MASTERARBEIT / MASTER'S THESIS

Titel der Masterarbeit / Title of the Master's Thesis

„*Climate protection à la carte: can the legal language of the ozone layer protection regime offer a recipe for success on climate protection?*"

verfasst von / submitted by

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angestrebter akademischer Grad / in partial fulfilment of the requirements for the degree of

Master of Science (MSc)

Wien, 2022 / Vienna 2022

Studienkennzahl lt. Studienblatt / degree programme code as it appears on the student record sheet:	UA 066 299
Studienrichtung lt. Studienblatt / degree programme as it appears on the student record sheet:	Interdisziplinäres Masterstudium Environmental Sciences
Betreut von / Supervisor:	Univ. Prof. Dr. Thilo Hofmann,

Acknowledgements

A tavola non s'invecchia.

(*At the table, no one grows old.*)

- Italian proverb

I dedicate this thesis to all those with whom I've ever shared a table. Those warmly familiar faces at the dynastic dining table. Those with whom I've overindulged in bacchanalian feasts of plenty. Those with whom I've locked eyes and shared words. Those who've regaled with tall tales and exceptional exploits. Those who've conversed, challenged, inspired, frustrated and amused. Those who've perched precariously at bars and on benches. Those who've been open, tender and vulnerable. Those who've flipped the table, those who've climbed onto it, and those who've slid under it. Those co-conspirators, who aided and abetted me in circumventing a national curfew to celebrate a significant birthday. Having been temporarily deprived of such simple pleasures for the greater good, may we always appreciate the levelling act and calming influence of taking a seat at a table, and the company and wisdom that comes from it.

From the loftily poetic to the decidedly prosaic: this thesis has had the gestation period of an elephant. Conceived in hope amid the tumult of an extended lockdown in Vienna, that was but a taste of the chaos to come, as it was equal parts nourished and neglected alongside professional opportunities in Vienna and New York City and personal commitments in Australia, before returning again to Vienna. Like all good children, its long anticipated and full-term birth still seemed hastily induced. And so we muddle on.

Thank you to Univ. Prof. Thilo Hofmann, for teaching me about water tables and for supervising this thesis.

To the indefatigably encouraging Univ. Prof. Harald Rieder, thank you for offering me great guidance while preparing this thesis and for offering a seat at your table at BOKU. You have been a source of steadfast support and encouragement, and contributed immeasurable improvements.

Thank you to Prof. Susan Solomon for generously agreeing to be interviewed as part of this thesis and whose insightful reflections on the development of ozone and climate science and the international regimes that govern them feature throughout.

To my grandma, Marie, and grandpa, Bob-Bob, posthumous thanks for your unwitting financial contribution to a 15,000 km big bike ride from China to Austria, a modest existence amidst master's studies in Vienna and scandalously un- and underpaid internships with the

United Nations. It has been quite a ride. I hope you would agree that this all represents several significant rungs on the ladder of life, despite foregoing more conventional climbs onto the rungs of a career or the private property ladder just yet.

To my trusty bicycle, Vincente, thank you for literally bringing me here along our own Silk Road across Eurasia, over the Pamir Highway, through snow, desert, relentless humidity and ferocious winds. One day we'll finish the last little bit to the Atlantic, and then perhaps Table Mountain in Cape Town…

To my dad, Murray, Claire, Georgie, Nick, and Leonie, Jess, Ollie and lots of other leading lights in my life, thank you for shaping me into the work in progress that I remain. I profoundly appreciate your love, support, capacity and readiness to listen, sage advice and effortless encouragement. I only hope I offer the same to you.

Finally, to empty chairs at empty tables and especially to my mum, Jane, I could have done with a good hug from you lately. Settle in at whichever table you now sit, because we have a lot to catch up on over a cuppa…

ARS

June 2022

Abstract

Following global alarm at the detection of the 'ozone hole' in 1985, relatively prompt international action succeeded in 'bending the curve' of anthropogenic emissions of ozone-depleting substances (ODS). The ozone layer now shows signs of 'healing'. Whatever its role in this success story, the international legal regime for ozone protection has been celebrated as an exemplar. By contrast, despite ever more scientific evidence of the causes and effects of human-induced climate change and a mature international regime for climate protection, global greenhouse gas (GHG) emissions continue their upward trajectory. This thesis investigates, compares and contrasts the international legal regimes for ozone and climate protection using different methods. First, the legal language in key agreements under each regime is closely analysed across key thematic areas common to both regimes, using 'text-as-data' and legal interpretation techniques. Second, the regime ratification rates are compared, in terms of the number of parties and their representative contribution to global emissions. Third, the proportionate emissions reductions required under each regime are inverted in a series of counterfactual scenarios; the ozone regime's required reductions are applied to GHG emissions since 1990, and the climate regime's emissions limitations are applied to ODS emissions from 1986. For the agreements under study, the ozone regime, both in the absolute number of terms with binding connotations and when having due regard to context, contains more binding and robust language than the climate regime. Although both regimes were established at a similar time, each has evolved in divergent directions, at different rates. By reference to regime theory, this suggests that the ozone regime consists of deeper, 'hard' contracts, while the climate regime consists of shallower, 'soft' pledges. This is reflected in the counterfactual scenario analysis. Most of the ozone regime scenarios achieve hypothetical GHG emissions close to 'net zero' by 2022, while the climate regime scenarios cause sustained growth in hypothetical ODS emissions, which only start to peak by 2022, with tremendous reductions in inferred stratospheric ozone levels. This is consistent with a number of studies in the literature which compare counterfactual or 'world-avoided' scenarios due to the ozone regime, but fills a gap in more directly comparing the two regimes.

Kurzfassung

Nach der weltweiten Besorgnis über die Entdeckung des „Ozonlochs“ im Jahr 1985 gelang es durch relativ rasches internationales Handeln, eine Trendumkehr in der anthropogenen Emission von ozonabbauenden Stoffen (ODS) einzuleiten. Die Ozonschicht zeigt nun Anzeichen einer „Heilung“. Unabhängig von seiner Rolle in dieser Erfolgsgeschichte wurde das internationale Regelwerk zum Schutz der Ozonschicht als Vorbild gefeiert. Im Gegensatz dazu, steigen die weltweiten Emissionen von Treibhausgasen (GHGs) trotz immer deutlicher wissenschaftlicher Erkenntnisse über die Ursachen und Auswirkungen des vom Menschen verursachten Klimawandels und einer ausgereiften internationalen Klimaschutzregelung weiter an. Diese Arbeit untersucht, vergleicht und kontrastiert die internationalen Rechtssysteme für Ozon- und Klimaschutz mit verschiedenen Methoden. Zuerst wird die Rechtssprache in den wichtigsten Abkommen der beiden Regime in wichtigen Themenbereichen, die beiden Regimen gemeinsam sind, unter Verwendung von „Text-als-Daten“- und Rechtsauslegungstechniken genau analysiert. Als zweites werden die Ratifizierungsraten der Regime im Hinblick auf die Anzahl der Vertragsparteien und deren repräsentativen Beitrag zu den globalen Emissionen verglichen. Als drittes werden die anteiligen Emissionsreduktionen, die unter jedem Regime erforderlich sind, in einer Reihe von kontrafaktischen Szenarien invertiert; die geforderten Reduktionen des Ozonregimes werden auf die Treibhausgasemissionen seit 1990 angewandt, und die Emissionsbegrenzungen des Klimaregimes werden auf die ODS-Emissionen seit 1986 angewandt. Unter den untersuchten Abkommen enthält das Ozonregime sowohl in der absoluten Anzahl der Begriffe mit verbindlichen Konnotationen als auch unter Berücksichtigung des Kontexts eine verbindlichere und robustere Sprache als das Klimaregime. Obwohl beide Regime zu einem ähnlichen Zeitpunkt entwickelt wurden, haben sie sich in unterschiedliche Richtungen und mit unterschiedlichem Tempo entwickelt. Unter Bezugnahme auf die Regimetheorie legt dies nahe, dass das Ozonregime aus konkreten, „harten“ Verträgen besteht, während das Klimaregime aus loseren, „weichen“ Zusagen besteht. Dies spiegelt sich auch in der Analyse der kontrafaktischen Szenarien wider. Die meisten Szenarien des Ozonregimes erreichen bis 2022 hypothetische Treibhausgasemissionen nahe Null, während die Szenarien des Klimaregimes zu einem anhaltenden Anstieg der hypothetischen ODS-Emissionen führen, die erst 2022 ihren Höhepunkt erreichen, wobei die abgeleiteten Ozonwerte in der Stratosphäre enorm sinken. Dies stimmt mit einer Reihe von Studien in der Literatur überein, in denen kontrafaktische oder durch das Ozonregime bedingte „Vermeidungsszenarien“ verglichen werden, füllt aber eine Lücke beim direkten Vergleich der beiden Regime.

Table of Contents

List of Figures

List of Tables

Glossary of Terms

The Amendments	The LDN1990, CPN1992, MON1997 and BEI1999, collectively
BEAs	Bilateral environmental agreements, agreed between two States
BEI1999	The Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer (adopted at the Eleventh MOP in Beijing on 3 December 1999)
CFCs	Chlorofluorocarbons
COP	The Conference of the Parties to the UNFCCC, or as context requires:
CMP	a) The COP serving as the meeting of the parties to the KP (CMP); or
CMA	b) The COP serving as the meeting of the parties to the PA (CMA).
CPN1992	The Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer (adopted at the Fourth MOP in Copenhagen on 25 November 1992)
Doha	The Amendment to the Kyoto Protocol (adopted at the Eighth CMP in Doha on 8 December 2012)
DU	Dobson Unit of stratospheric ozone concentration, where 1 DU is equal to a 0.01 mm thick layer of ozone at standard temperature and pressure (0 ºC, 1 atm)
HCFCs	Hydrochlorofluorocarbons
IPCC	The Intergovernmental Panel on Climate Change
KP	The Kyoto Protocol to the United Nations Framework Convention on Climate Change (concluded on 11 December 1997, entered into force 16 February 2005) 2303 UNTS 162
LDN1990	The Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer (adopted at the Second MOP in London on 29 June 1990)
MEAs	Multilateral environmental agreements, agreed between multiple States
MON1997	The Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer (adopted at the Ninth MOP in Montreal on 17 September 1997)
MON2007	The Adjustment to the Montreal Protocol on Substances that Deplete the Ozone Layer (adopted at the Nineteenth MOP in Montreal on 21 September 2007)

MOP	The meetings of the parties to the Montreal Protocol
MP	The Montreal Protocol on Substances that Deplete the Ozone Layer (generally)
MP1987	The Montreal Protocol on Substances that Deplete the Ozone Layer (concluded on 16 September 1987, entered into force on 1 January 1989) 1522 UNTS 3
MP2000	The Montreal Protocol, as amended or adjusted up until the year 2000 and incorporating all of the Amendments
ODP	Ozone-depleting potential of the various ODS controlled by the ozone regime, normalised to the ozone-depleting potential of CFC-11, such that 1 $t_{cfc\text{-}11}$ = 1 ODP t
ODS	Ozone-depleting substances, including ClO_x, CFCs, HCFCs, HO_x and NO_x
PA	The Paris Agreement (concluded on 12 December 2015, entered into force on 4 November 2016) 3156 UNTS
TCRE	The transient climate response to cumulative carbon emissions, see Chapter 6.6.2
UNEP	The United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change (concluded on 29 May 1992, entered into force 21 March 1994) 1771 UNTS 107
VCLT	The Vienna Convention on the Law of Treaties (concluded on 23 May 1969, entered into force 27 January 1980) 1155 UNTS 331
VCPOL	The Vienna Convention on the Protection of the Ozone Layer (concluded on 22 March 1985, entered into force on 22 September 1988) 1513 UNTS 293
VIE1995	The Adjustment to the Montreal Protocol on Substances that Deplete the Ozone Layer (adopted at the Seventh MOP in Vienna on 7 December 1995)
WMO	World Meteorological Organisation

1 Milestones in ozone science

No hat, no play

– Australian schoolyard sun protection mantra

The Montreal Protocol on Substances that Deplete the Ozone Layer (MP) is often celebrated as one of the most successful international environmental agreements (Annan 2000; Parson 2003; Sunstein 2007). However, its success was never guaranteed and the stakes certainly remain very high: the stratospheric ozone layer protects *all* biological life from harmful short wavelength ultraviolet (UV) radiation. Without international intervention, further anthropogenic ozone losses would risk hundreds of thousands of additional human skin cancers and widespread ecological damage (Parson 2003, 87–88).

First and foremost then, the MP's continued success has depended on rigorous science. A central component has been the international atmospheric monitoring effort, led by the World Meteorological Organisation (WMO), which has been in regular interaction with policymakers and the public, leading to the so-called 'adaptive management' of the issue (Parson 2003). Chapter 1 therefore briefly traces the history of ozone science, with a focus on the settled science of stratospheric ozone loss, and only a brief discussion of ongoing controversies to place the subsequent analysis in greater context.

1.1 Ozone origins

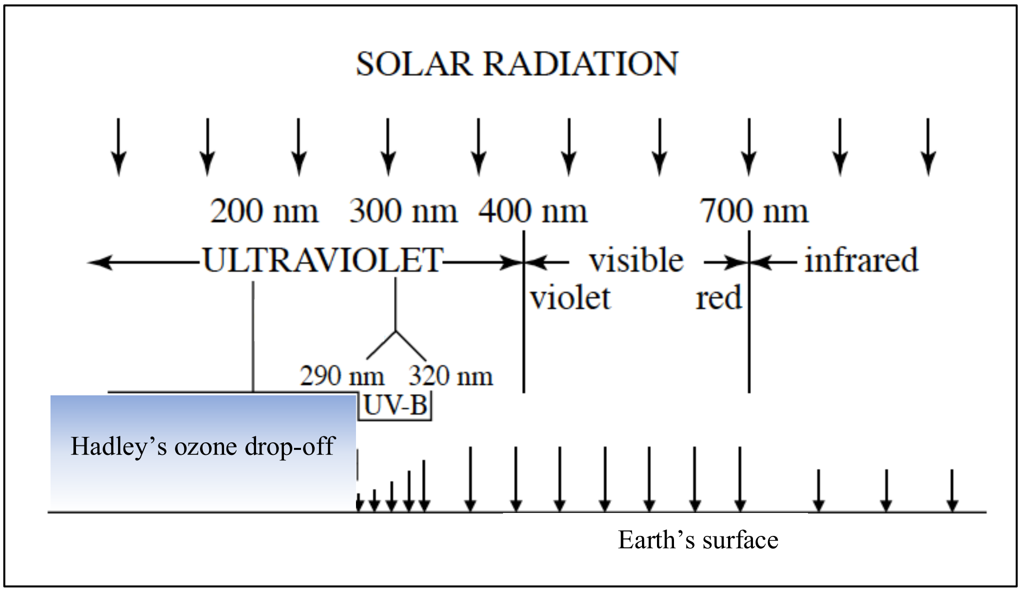
Even the Ancient Greeks mentioned a distinctive smell in the air after lightning storms (Rowland 1991; Stolarski 2001), but it was not recognised as ozone until 1839-40. In his laboratory in Basel, Switzerland, Christian Friedrich Schönbein identified ozone not as an 'electrical odour', but a separate substance and by-product of his experiments on the electrolysis of water (Schönbein 1840; Rubin 2001; Stolarski 2001). Schönbein named the gas ozone, after the Greek *ozein* ('to stink'), due to its pungent aroma (Schönbein 1840, 709; Rubin 2001; Stolarski 2001). Notably, Schönbein also speculated that ozone exists in the atmosphere (Schönbein 1840, 709–10; Rubin 2001), but further investigations at the time were inhibited by significant practical difficulties and debate about how to measure ozone (Rubin 2001; Stolarski 2001).

Subsequent efforts in the 1850s and 1860s focussed on determining ozone's chemical formula, O_3, and basic experiments to establish its chemical properties (Rubin 2001). Later, once ozone had been successfully isolated, laboratory experiments revealed that it undergoes photodegradation and that it is catalysed by chlorine, hydrogen and bromine (Griffith and McKeown 1926). However, the global consequences of even trace concentrations of such compounds in the atmosphere would not be fully appreciated for over fifty years.

1.2 Atmospheric science

Outside of laboratories such as that of Schönbein, the field of atmospheric ozone chemistry did not advance significantly until late in the 19th century. Experiments on UV light had revealed that certain wavelengths of the spectrum of incoming solar radiation were blocked by substances in the atmosphere (Stolarski 2001). However, it was British chemist Sir Walter Hartley in 1880-81 (Hartley 1881a; 1881b), who first attributed the drop off in incoming solar radiation below wavelengths of ~293 nm to the existence of ozone in the upper atmosphere (Rowland 1991; Stolarski 2001), as shown in Figure 1.

Figure 1: Total incoming UV radiation, drop-off in lower wavelength radiation due to atmospheric ozone, and residual spectrum of incoming UV radiation at Earth's surface



(Adapted from: Rowland 2006)

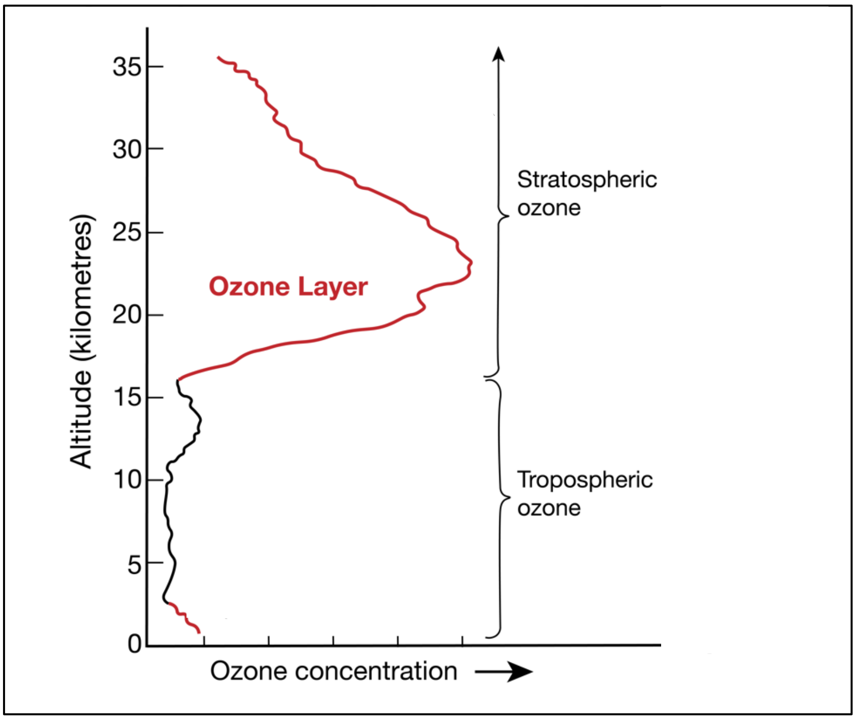
In the early 1900s, French meteorologist Léon Philippe Teisserenc de Bort and German meteorologist Richard Assmann were (independently) the first to discover the temperature inversion in the atmosphere (Emeis 2008); temperatures decrease with height in the troposphere,[1] before increasing towards a maximum temperature at ~35 km altitude in the

[1] The area of the atmosphere between the Earth's surface and a seasonally variable altitude of ~6-10km (over the poles), ~12 km (in mid-latitudes) to ~16 km (in the tropics) (Rowland 2006, 788; Ball et al. 2018).

stratosphere.[2] The temperature inflection point at the troposphere-stratosphere interface is known as the tropopause and the atmospheric temperature distribution reflects the distribution of ozone, of which 90% is present in the stratosphere (Ball et al. 2018), as shown in Figure 2.

In 1913, French meteorologists Fabry and Buisson were the first to accurately measure[1] atmospheric ozone concentrations (Fabry and Buisson 1913). They estimated that, if the total diffuse ozone in the atmosphere was compressed to sea level pressure and room temperature, it would form a layer approximately 5 mm thick (Stolarski 2001).

Figure 2: Typical atmospheric profile, showing distribution of ozone concentrations (unitless)



(Adapted from: Ritchie and Roser 2018)

In 1924, Fabry's spectrograph was improved by British meteorologist Gordon Dobson, who called it a spectrometer. The Dobson Unit (DU) of stratospheric ozone concentration, the conventional unit by which scientists report column ozone amounts today, is also named after Dobson. One DU is equal to a 0.01 mm thick layer of ozone at standard temperature and pressure (0 ºC, 1 atm) (Rowland 2006; Staehelin et al. 2018, 6576).

Dobson observed daily and seasonal fluctuations in ozone concentrations above Oxford, England, using his spectrometer device. He later established a series of measuring stations across Europe to test his theory that this was due to changes in atmospheric pressure (Stolarski 2001). One of those stations, at Arosa in the Swiss Alps, has produced the world's longest,

[2] The area of the atmosphere above the troposphere and extending to an approximate altitude of 50 km (Rowland 2006, 788). Teisserenc de Bort coined the terms 'troposphere' and 'stratosphere' in 1908 (Emeis 2008).

ongoing time series of total column ozone[3] measurements (Staehelin et al. 2018). This network expanded during the International Geophysical Year 1957-58, when Antarctic stations were established and the general global patterns in ozone distribution were revealed (Stolarski 2001):

1. tropical latitudes maintain relatively constant ozone concentrations;
2. the mid-latitude temperate zones contain relatively higher ozone concentrations, although with strong seasonal variability and peaks at the end of winter; and
3. polar latitudes contain maximum ozone concentrations, peaking in early spring.

1.3 Stratospheric ozone chemistry

In 1930, British mathematician and geophysicist Sydney Chapman theorised the formation of ozone from photolysis of atmospheric oxygen. His work laid the foundations of our understanding of stratospheric ozone chemistry, as shown in the following equations (Jacob 1999, 162–64).

Firstly, high energy, short wavelength incoming solar radiation is absorbed by oxygen molecules, breaking their covalent bonds:

$$O_2 + hv\ (\lambda < 242\ nm) \rightarrow\ O + O\ (1)$$

The liberated oxygen atoms lack a stable electron configuration and are therefore very reactive. In the presence of other constituents of air, represented here by molecule M, they react with other oxygen molecules to form ozone:

$$O + O_2 + M \rightarrow O_3 + M\ (2)$$

As altitude increases through the atmosphere, the partial pressure of oxygen decreases and UV radiation increases. As a result, the expected effect of the above two equations would be an ozone maximum and an oxygen minimum in the stratosphere. However, this is not borne out by atmospheric observations, where typical ozone concentrations are in the order of 3 parts per 10^7 molecules, rising as high as 1 part in 10^5 in the stratosphere, compared to ~21% oxygen (Rowland 2006, 770). This discrepancy is due to a negative feedback loop, as also theorised by Chapman and explained by the following two equations.

Firstly, the triple-bonded ozone molecules require less activation energy in order for their bonds to be broken. Thus, less energetic, longer wavelength incoming solar radiation is capable of photolyzing ozone, forming oxygen molecules and an excited oxygen atom:

$$O_3 + hv\ (\lambda < 314\ nm) \rightarrow O_2 + O\ (3)$$

[3] I.e., ozone concentrations distributed throughout the atmospheric column.

The reaction (3) products are capable of regenerating ozone via reaction (2), which results in no net ozone destruction. Chapman closed the ozone 'loop' by hypothesising a further reaction between the liberated O atoms and ozone, destroying ozone and forming oxygen:

$$O_3 + O \rightarrow 2O_2 \ (4)$$

Reactions (2) and (3) are much faster than reactions (1) and (4) (Jacob 1999, 164). Ultimately, the ozone layer's balance therefore lies between reactions (1) and (4), or between the abundance of 'even' (O_2) versus 'odd' (O^{2-}, O_3) forms of oxygen (Rowland 2006, 772). In other words, taking O_3 abundance as the focus, reaction (1) is considered to generate +2 molecules of O_3 and reaction (4) to remove -2 molecules of O_3, with reactions (2) and (3) considered neutral.

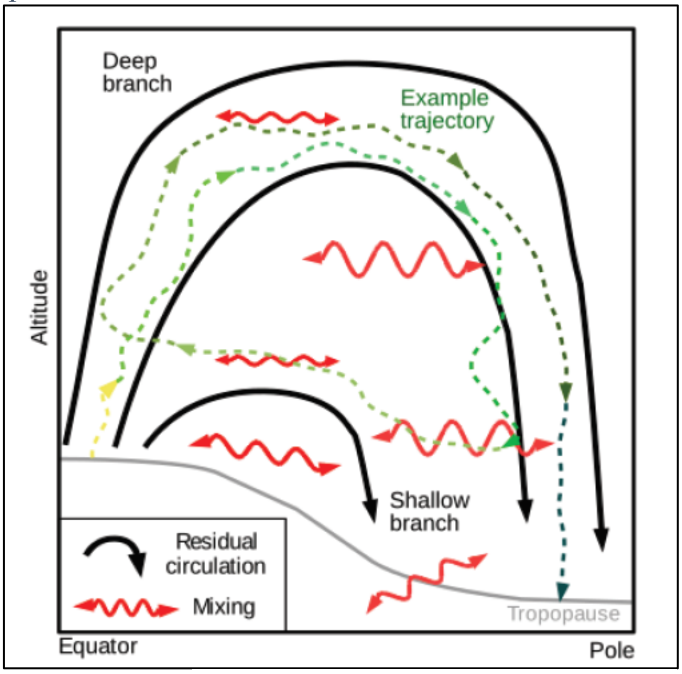
Meanwhile, the absorption of UV radiation in reactions (1) and (3) protects biological life on Earth from damaging short wavelength UV radiation (λ <300 nm). This is consistent with the 'drop off' in incoming solar radiation recognised by Hartley in 1881. Further, consistent with the first law of thermodynamics, transfer of heat to molecule M in reaction (2) explains the temperature inversion discovered by Teisserenc de Bort and Assmann, while also preserving the structure of the stratosphere (Rowland 2006).

Finally, Chapman's equations provided the basis for theorising the global distribution and circulation of ozone throughout the atmosphere. Despite the tropics having the highest UV radiation and hence the intuitive expectation that ozone concentrations would be highest in those areas due to reactions (1) and (3), the global distribution of ozone is exactly the opposite. The process driving this distribution was explained in work by Dobson and Alan Brewer, after whom it is named: the Brewer-Dobson Circulation (Stolarski 2001). The typical turnover is (Stolarski 2001):

1. air is transported upward by convection in the tropics and this air is ozone-rich due to abundant UV radiation;
2. once it rises to the stratosphere, the air then gradually moves back downward and poleward in the mid-latitudes; and
3. the air returns towards the troposphere at the poles, where the stratosphere reaches its deepest extent, concentrating ozone in these regions.

This general circulation pattern for one hemisphere is indicated in Figure 3 below.

Figure 3: Indicative pathways of stratospheric air parcels in the Brewer-Dobson Circulation



(Adapted from WMO 2019, 5.22)

Chapman's four ozone equations discussed above established and remained the explanation for the origins and concentrations of atmospheric ozone for several decades. However, over time, measurement techniques improved and global distribution of ozone was understood to be more heterogeneous (Rowland 2006). Further, Chapman's equations repeatedly overestimated the measured concentrations of stratospheric ozone (Parson 2003, 18). This stratospheric shortfall set the scene for several significant advances in our understanding of ozone chemistry: the catalysing role of trace gases in the stratosphere.

1.4 Catalytic stratospheric ozone loss

The first such advance was the discovery of hydrogen radicals' role in catalysing ozone destruction. In a preliminary paper, Bates and Nicolet (1950a) discuss the apparently limited relevance of water vapour in the stratosphere (average concentrations of <3 ppm, (Rowland 2006)), as opposed to the much more humid troposphere. However, water vapour-rich and vigorously energetic tropical storms, which are able to pierce through the tropopause, are an important conduit for other trace molecules being transported into the stratosphere (Rowland 2006). Further, despite being present in only negligible or trace concentrations, stratospheric water vapour and other trace gases are capable of disproportionately large catalytic impacts, due to regenerative reactions similar to those seen in Chapman's reactions (2) and (3).

In 1950, Bates and Nicolet (1950b) published a paper that revealed the important role of hydrogen oxides (OH^- and HO_2, collectively HO_x) in atmospheric chemistry. A significant source of HO_x is water vapour, which, like ozone, is photolyzed by UV radiation:

$$H_2O + hv\ (\lambda < 240\ nm) \rightarrow OH + H(5)$$

In addition, other hydrogenated molecules, particularly methane, CH_4, and molecular hydrogen, H_2, are further sources of HO_x. Methane can be photolyzed or otherwise oxidised:

$$CH_4 + hv \rightarrow CH_3 + H\ (6)$$

These hydrogen atoms readily combine with free oxygen atoms (e.g., reactions (1) and (3)) to form OH. Meanwhile, molecular hydrogen reacts with free oxygen atoms, forming more OH:

$$H_2 + O \rightarrow OH + H\ (7)$$

The reaction of photolyzed ozone in (3) with stratospheric water vapour is the ultimate source of stratospheric OH (Rowland 2006, 775):

$$O + H_2O \rightarrow OH + OH\ (8)$$

Regardless of the source, the net effect of reactions (5)-(8) is the production of OH, which is a prominent oxidant throughout the atmosphere, including in the destruction of ozone:

$$OH + O_3 \rightarrow HO_2 + O_2\ (9)$$

Moreover, OH is a catalytic ozone destroyer, because it is regenerated from the HO_2 product in reaction (9) by further reactions with free oxygen atoms, according to reaction (10):

$$HO_2 + O \rightarrow OH + O_2\ (10)$$

Reactions (9) and (10) also contribute significantly to atmospheric oxygen (Bates and Nicolet 1950b, 317), which regenerates the loop in reactions (1)-(4). In other words, reactions (9) and (10) form a catalytic cycle, which, to return to the calculus of 'odd' and 'even' oxygen, results in the further net loss of –1 molecule of O_3 per cycle (Rowland 2006, 772). This accounts for the majority of ozone loss in the lower stratosphere (Jacob 1999, 170).

The next breakthrough was the discovery that nitrous oxides (NO and NO_2, known collectively as NO_x) also catalyse ozone loss. In 1955, Nicolet had theorised the potential role of nitrous oxides in atmospheric chemistry, but he did not recognise its crucial catalytic role. This important discovery was instead made by Paul Crutzen in 1970, who clarified the catalytic effect of NO_x on ozone loss by the equations (Crutzen 1970):

$$NO + O_3 \rightarrow NO_2 + O_2\ (11)$$

$$NO_2 + O \rightarrow NO + O_2\ (12)$$

Unlike in the troposphere were NO_x is directly emitted through anthropogenic activity or formed via lightning, stratospheric NO_x originates from natural and anthropogenic surface emissions of nitrous oxide, N_2O, which is stable until it reaches the abundant UV radiation of the stratosphere, where it is photolyzed:

$$N_2O + hv \rightarrow N_2 + O \ (13)$$

Between 90-95% of atmospheric N_2O is removed in this way, forming unreactive nitrogen gas (Jacob 1999, 173; Rowland 2006, 774). However, some N_2O reacts with free oxygen atoms produced by various reactions given above:

$$N_2O + O \rightarrow NO + NO \ (14)$$

Reaction (14) represents the major source of stratospheric NO_x (Rowland 2006, 774). As with the HO_x cycle, reaction (14) therefore feeds a further catalytic cycle between reactions (11) and (12), leading to continued ozone loss. The NO_x catalytic cycle results in the further net loss of –1 molecule of O_3 per cycle (Rowland 2006, 772).

The third significant advance in catalytic ozone loss came in 1974, when Mario Molina and Frank Sherwood Rowland published their seminal paper about chlorofluorocarbons (CFCs) (Molina and Rowland 1974). CFCs are a family of wholly anthropogenic gases and, like N_2O, CFCs are stable throughout most of the atmosphere, but will photolyze in the abundant UV radiation of the upper stratosphere:

$$CCl_3F + hv \ (\lambda < 230 \ nm) \rightarrow Cl + CCl_2F \ (15)$$

Thus, Molina and Rowland (1974) warned of the potential impacts of such additional sources of stratospheric chlorine on ozone, due to chlorine oxide (ClO_x) chemistry:

$$Cl + O_3 \rightarrow ClO + O_2 \ (16)$$

$$ClO + O \rightarrow Cl + O_2 \ (17)$$

Reactions (16) and (17) represent a further catalytic cycle because the free Cl atoms are regenerated. As with the HO_x and NO_x cycles, the ClO_x cycle results in an additional net loss of –1 molecule of O_3 per cycle (Rowland 2006, 772).

Thus, the sum of the HO_x and NO_x 'natural' catalytic cycles accounts for the 'missing' O_3 from the overestimation in Chapman's equations (Rowland 2006, 772). However, anthropogenic enhancement of the NO_x and ClO_x cycles raised concerns about their depleting effects on the protective stratospheric ozone layer and therefore the grave risks to all living things on Earth from a broader spectrum of incoming UV radiation.

1.5 Ozone hole

In 1985, British meteorologists Joe Farman, Brian Gardiner and Jon Shanklin published their explosive paper on the discovery of a springtime ozone 'hole' over Antarctica (Farman, Gardiner, and Shanklin 1985). This was based on data from the Halley Bay research station established in the International Geophysical Year 1957-58 (Stolarski 2001) and caused widespread scientific concern because the catalytic loss cycles known could not explain it (Jacob 1999, 179).

The international concern about the ozone hole led to the 1985 *Vienna Convention for the Protection of the Ozone Layer* (VCPOL). This was quickly followed by two important international scientific reports: one by the World Meteorological Organisation (WMO 1986) and another by the US EPA (Titus 1986).

In 1986, the US National Oceanic and Atmospheric Administration (NOAA) sent an expeditionary team to Antarctica to investigate stratospheric ozone chemistry, seeking evidence of stratospheric chlorides (ClO and ClO_2). The team targeted these compounds due to the awareness that increasing trends in emissions (in the form of CFCs) was likely to be leading to increased stratospheric chlorine concentrations and, in the wake of the 'ozone hole' revelation, scientific suspicions focused on the following reaction (Solomon et al. 1986, 755–56):

$$ClO + NO \rightarrow Cl + NO_2 \ (18)$$

One of the scientists and the only woman in the NOAA team was Susan Solomon, who was interviewed as part of this thesis and whose observations provide valuable context throughout. The NOAA team's subsequent paper in *Nature* clarified the role of altitude and extremely cold polar stratospheric clouds in forming unique surface chemistry and phase conditions, which were the missing links in understanding the formation of the ozone hole (Solomon et al. 1986).

Firstly, a further catalytic cycle must be considered. Taking the products of reactions (2), (5), (7), (8), (10) and (17) results in the following:

$$OH + O_3 \rightarrow HO_2 + O_2 \ (19)$$

These species react with the products of reactions (15), (17) and (18) as follows:

$$ClO + O_3 \rightarrow ClO + O_2 \ (20)$$

The products of reactions (19) and (20) then further react to form HOCl, which photolyzes:

$$HO_2 + ClO \rightarrow HOCl + O_2 \ (21)$$

$$HOCl + hv \rightarrow OH + Cl \ (22)$$

The net result of (19) to (22) is the further loss of two O_3 molecules, generating three O_2 molecules (Solomon et al. 1986).

The abundance of the different chemical species involved in these ozone-depleting reactions is a function of altitude, with ClO and Cl species dominant at altitudes near 40km. But at lower altitudes (~20km), 'reservoir' species predominate, such as HCl and $ClONO_2$, which do not deplete ozone (Solomon et al. 1986). However, in certain conditions, HCl and $ClONO_2$ may react heterogeneously as follows:

$$HCl_s + ClONO_{2(g)} \rightarrow HNO_{3(s)} + Cl_{2(g)} \quad (23)$$

Further, given the mix of available reactants from the products of all of the reactions above, another possible heterogeneous reaction that results in the formation of HNO_3 is:

$$H_2O_{(s)} + ClONO_{2(g)} \rightarrow HNO_{3(s)} + HOCl_{2(g)} \quad (24)$$

It is at this point that the unique winter time conditions at the South Pole assume crucial importance. This is because the atmosphere at the South Pole is subject to uniquely cool winter conditions due to the formation of a very strong polar vortex that circumnavigates Antarctica (Rowland 2006, 780). Thus, during the Southern Hemisphere winter (July-September), when there is also no sunlight at the South Pole, temperatures grow extremely cold (ca. -80^{o}C), which is far colder than during any other season in the Antarctic (or Arctic) (Solomon et al. 1986). In these conditions, between the altitude of 10 to 20 km, polar stratospheric clouds are very common and, in the absence of sunlight, HNO_3 condenses in crystalline form. However, when sunlight returns in the spring (September-October), temperatures and photolysis rates rise and the reverse of chain reactions (22) and (23) begin until the polar vertex breaks up. The effect of these chemical reactions is a catastrophic loss of stratospheric ozone levels by October-November, when polar stratospheric ozone is 'replenished' by the Brewer-Dobson circulation (Solomon et al. 1986).

In 1987, stratospheric aeroplane flights between Chile and Antarctica found the 'smoking gun' in the ozone hole mystery: CFCs were leading to increased atmospheric chloride levels and, in turn, ozone loss. Also in 1987, Tolbert et al. (1987) further investigated the effects of polar stratospheric clouds, but the physicochemical processes driving the Antarctic ozone hole phenomenon had been clarified. This scientific consensus added to growing political pressure, which culminated in the Montreal Protocol being agreed in August 1987. One of the central parts of the ozone protection regime established by the Montreal Protocol was for regular international scientific ozone assessments to be conducted by the World

Meteorological Organisation. Such assessments have been conducted every 3-4 years since 1988,[4] with the next report due in 2022.

Since the Montreal Protocol was signed, it has become the first international agreement universally ratified by all 193 Member States of the United Nations. This milestone was reached in 2009, around the time that 'idealized sensitivity' studies were published about the 'World Avoided' by the MP (Morgenstern et al. 2008; Newman et al. 2009). These studies modelled stratospheric ozone concentrations under a range of scenarios: from a hypothetical 'no Montreal Protocol' scenario (the 'World Avoided' by the Protocol), through several of the amendments to the MP (London, Copenhagen, Beijing), to a scenario of full compliance with all relevant provisions of the MP (with amendments). Such studies are discussed further in sub-Chapter 3.4 below.

1.6 Unreported CFC-11 production and fugitive emissions

Despite encouraging progress in ozone science and the progressive development of the ozone regime, there was an 'unexpected and persistent' increase in CFC-11 emissions from 2012 suggesting that the observed decreasing trend in these emissions from 2002-2012 had slowed by up to 50% (Montzka et al. 2018). This upward trend in CFC-11 concentrations was detected at many of the long-term atmospheric monitoring sites established in the International Geophysical Year, particularly at Mauna Loa (Montzka et al. 2018), and through successive global experiments such as Advanced Global Atmospheric Gases Experiment (AGAGE) (Prinn et al. 2018).

Through monitoring the observed difference in mean concentrations between sites in the Northern and Southern Hemispheres, the increased emissions were traced to the Northern Hemisphere, with the strong implication that they had originated in eastern Asia (Montzka et al. 2018). This was subsequently confirmed by regional observations in Japan and South Korea, which showed an increase in average emissions from eastern China of about 7 Gg per year in the period 2014-2017, relative to the average emissions in 2008-2012 (Rigby et al. 2019). The increase in emissions was attributed primarily to the north-eastern provinces of Shandong and Hebei and no evidence of any significant increase was found in any of the available data from other eastern Asian countries (Rigby et al. 2019).

After the Chinese government announced that it was investigating and taking enforcement action, it was found that CFC-11 emissions had returned to expected rates of decrease by late 2018 and early 2019, based on both regional (Park et al. 2021) and global (Park et al.

[4] 1991, 1994, 1998, 2002, 2006, 2010, 2014, 2018, 2020.

2021) observations. However, the relatively modest volumes of unreported production revealed by the Chinese enforcement action suggested that other regions also contributed to the unexpected increase (Montzka et al. 2021, 430; Park et al. 2021, 434). This highlighted the continued importance of long-term atmospheric monitoring programs, such as AGAGE, on as broad a geographical scale as possible (Montzka et al. 2021, 430; Park et al. 2021, 436).

1.7 Ozone 'recovery'

The effect of human-induced ozone losses has been approximately 5-7% reductions in global total column ozone concentrations, which averages latitudinal differences in the troposphere and stratosphere, including much larger reductions in the Antarctic (Ball et al. 2018; WMO et al. 2019).

In recent years there have been encouraging signs that the Antarctic ozone hole is 'healing' and that it is on track to 'close over' by the middle of this century (Solomon et al. 2016). However, concerns have been raised more recently that the dramatic 'recovery' in Antarctic and upper stratospheric ozone masks slower recovery, or even continued declines, in ozone at lower altitudes and in different regions (Ball et al. 2018).

The concerns arise from discrepancies between recent ozone observations and modelled scenarios. Both observations and models confirm that upper stratospheric ozone is recovering, largely as a result of the MP's ban on CFCs (Steinbrecht et al. 2018; Ball et al. 2018). However, none of the relevant models is capable of reproducing the observed losses in middle- and lower stratosphere ozone in the mid-latitudes (Ball et al. 2020; Dietmüller et al. 2021). This therefore remains an active field of research, with attention in the atmospheric research community focussed on transport-driven vs chemical-driven ozone changes and the confounding effects of natural variability (Ball et al. 2020; Dietmüller et al. 2021).

Meanwhile, observed losses in the tropical lower stratosphere ozone have been attributed to enhanced tropical upwelling to the upper stratosphere. This is due to an intensifying Brewer-Dobson circulation, which is one of the anticipated effects of anthropogenic global warming (Steinbrecht et al. 2018; Ball et al. 2018; Dietmüller et al. 2021). Thus, research efforts are also focussed on the interactions between ozone depletion and global warming (Dietmüller et al. 2021).

2 From ice ages to hothouse Earth

The development of climate science echoes the development of ozone science. As in the previous chapter on ozone, any attempt to provide a brief review of the development of climate science will inevitably necessitate the selection and prioritisation of certain milestones achieved during recent decades. This is an altogether more daunting task here, given that anthropogenic climate change is a much broader issue than anthropogenic ozone depletion. Thus, the following is a whistle-stop tour of certain key milestones in climate science, which emphasises similarities between the two atmospheric phenomena that are the subject of this thesis.

2.1 Origins of climate science

Most accounts of the history of climate science begin with the conundrum presented to 19th century Earth scientists, who strived to explain the drivers behind the growing and compelling evidence of glacial expansion and retreat in Earth's history (Weart 2008, chap. 1; Treut et al. 2007, 106). The problem was mainly one of causation; what could cause the very slow, but landscape-shaping oscillation between periods of glaciation and deglaciation? As detailed below, the answer is a multifaceted one, involving several interacting and often reinforcing phenomena: greenhouse gases, changes in solar insolation, changes in global ocean circulation, and fluctuations in Earth's orbit.

As early as the 17th and 18th centuries, scientists such as Mariotte (1681) and Saussure (1760s) had experimented with glass and observed that it transmitted visible light, but retained other non-visible radiation and grew warmer (Treut et al. 2007, 103). However, in the absence of a more tangible barrier such as glass, the absorptive potential of gases was overlooked. Then, in 1824, Joseph Fourier built on Saussure's work and argued that the Earth's surface must emit invisible radiation (Weart 2008, 2–3; Treut et al. 2007, 103). When he applied this theory though, his calculations resulted in sub-zero average surface temperatures for the Earth. He therefore postulated that the atmosphere must play a role in warming the Earth (Treut et al. 2007, 103), reasoning by analogy to the earlier experiments that the atmosphere must act like a planetary pane of glass (Weart 2008, 3). Pouillet further developed Fourier's theory in 1836, hypothesising that the atmosphere absorbed more terrestrial radiation than incoming solar radiation, which it largely transmitted (Treut et al. 2007, 103).

It was not until the 1850s that the atmosphere's radiation absorbing capacity was empirically attributed to particular gases. In 1856 Eunice Foote, experimenting with glass tubes containing no air (evacuated), compressed air, moist air and dry air, and observed the different properties of each. She noted that water vapour and 'carbonic acid', as carbon dioxide (CO_2) was then referred to, absorb radiation and made the direct link between these atmospheric gases and the potential for climate change (Jackson 2020, 109). This was more completely elucidated by John Tyndall in 1859, who found that various atmospheric gases, including water vapour, carbon dioxide and methane, readily absorb longer wavelengths of radiation at a variety of temperatures and pressures (Tyndall 1861; Jackson 2020). Notably, this was some 20 years before Hartley identified a similar property of ozone, but with shorter wavelength radiation.

The 'gap' between the various atmospheric gases' absorption spectra investigated by Foote and Tyndall, through which terrestrial radiation is eventually transmitted to space (Simpson 1928), would come to be known as the 'atmospheric window'. As considered in more detail in Sections 2.2, 2.3 and 2.5 below, the idea of a 'window' is a useful heuristic in understanding why additional anthropogenic GHG emissions are cause for concern.

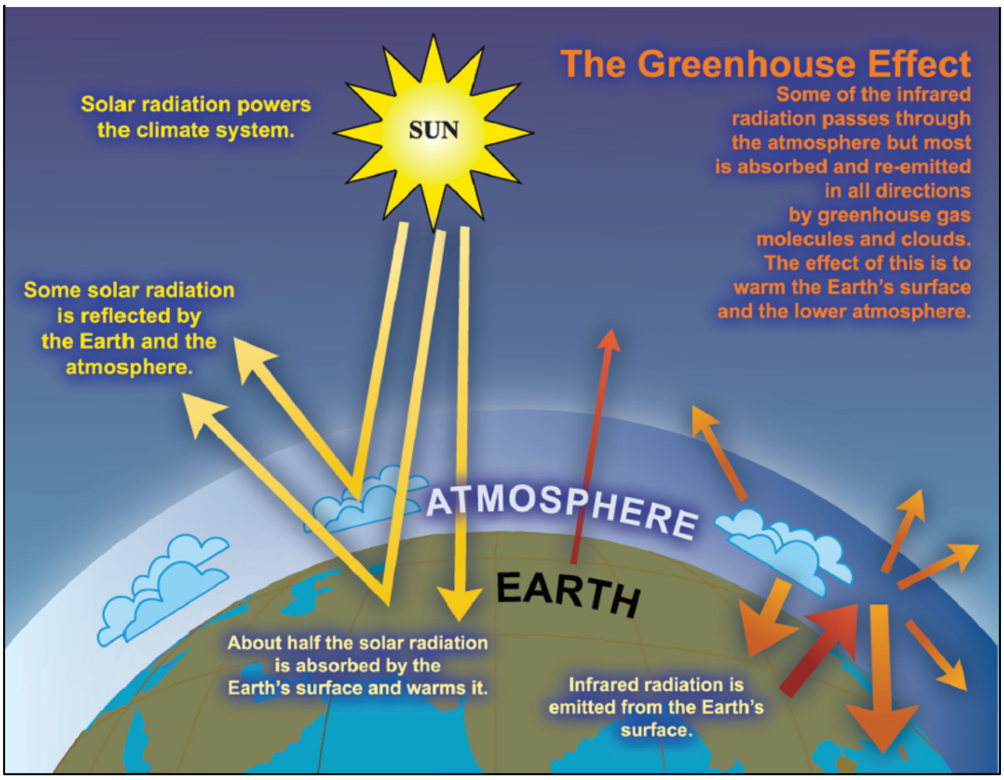
2.2 The Greenhouse Effect

From experiments with panes of glass to experiments on the absorption spectra of atmospheric gases, an underlying assumption is that the Earth's climate system is driven by incoming radiation from the sun. Due to the first law of thermodynamics, or the law of conservation of energy, this insolation must be balanced by reemission of radiation from the Earth back into space. However, as a much cooler body than the sun, the Earth re-emits the incoming shortwave radiation in the form of longer wavelength infrared radiation (Simpson 1928). This basic radiative balance driving the Earth's climate system is shown in simplified form in Figure 4 below.

There are basically three ways to change Earth's radiation balance (Treut et al. 2007, 96):

1. Changes in total incoming radiation, whether as a result of 'wobbles' in the Earth's orbit around the sun every ~40,000 years, or as a result of ~11 year cycles in sunspot activity on the surface of the sun itself;
2. Changes in the amount of incoming radiation that gets reflected (also known as 'albedo') before reaching the Earth's surface, whether by clouds, atmospheric aerosols, or changes in surface vegetation cover; or
3. Changes in the amount of longwave radiation emitted from the Earth surface and eventually re-emitted back into space.

Figure 4: A simplified diagram of the Earth's Greenhouse Effect



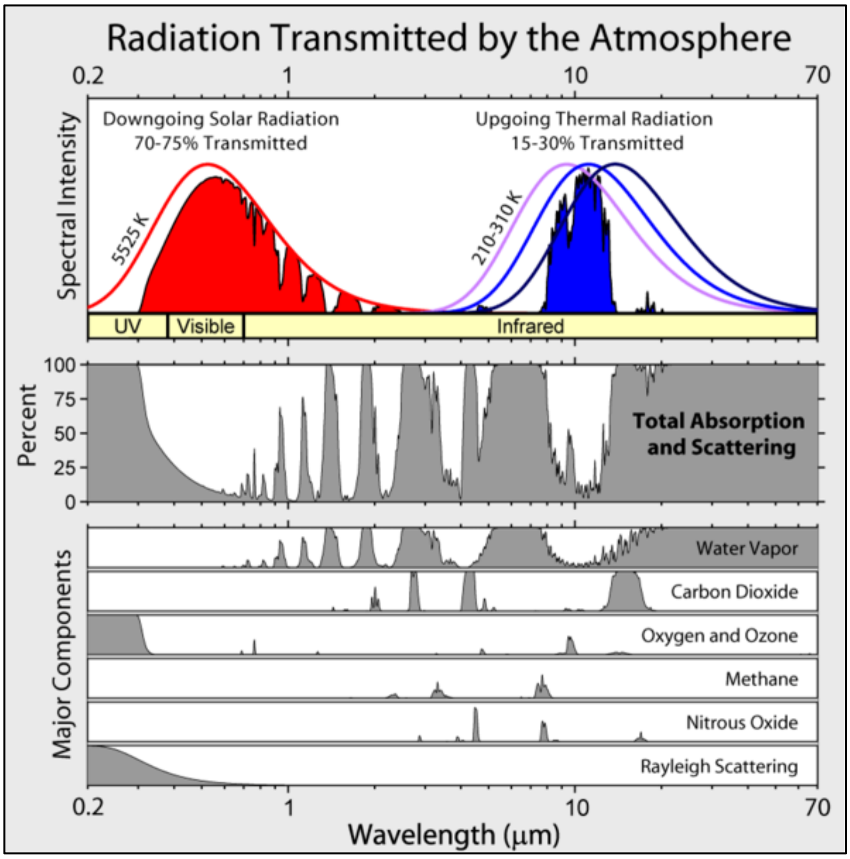
(Treut et al. 2007, 115)

The remainder of this chapter focusses on the last of the above three factors, but the reader should note that there are important interlinkages between all three factors, some of which are considered briefly in sub-Chapter 2.5 below.

In relation to the third factor, the extent to which the atmosphere is capable of re-emitting terrestrial radiation to space is affected by the concentration of particular gases in the atmosphere, so-called 'greenhouse gases'. As proven by Foote, Tyndall and Simpson, these gases intercept the outgoing radiation from the Earth's surface by absorbing it and then become chemically excited. The molecules then relax back into their normal state by re-emitting longwave radiation, trapping more energy in the atmosphere in the form of this radiated heat than would otherwise radiate out to space. This is why the resultant warming of the atmosphere caused by greenhouse gases is known as the 'greenhouse effect', which is vital for maintaining conditions conducive to life on Earth at average temperatures ~13^{o}C (Treut et al. 2007, 115).

More particularly, as investigated by Hettner (1918) and Simpson (1928), the greenhouse effect can be understood by reference to the different absorption spectra of greenhouse gases. As shown at left in Figure 5, greenhouse gases *transmit* the majority of short wavelength (λ = <1 μm) *incoming* solar radiation, approximately 70-75% of which reaches the Earth. On the other hand greenhouse gases, predominately water vapour and carbon dioxide, *absorb* the majority of longer wavelength *outgoing* radiation (λ = 8-12 μm) emitted by the Earth's surface, 15-30% of which reaches space. This is shown to the right of Figure 5, although the effect of different temperatures and pressures adds to the spread of the spectra, particularly for more abundant gases, like water vapour and carbon dioxide (Hettner 1918; Simpson 1928). Note that Figure 5 also shows, as discussed in Chapter 1, that oxygen and ozone absorb a narrow but vitally important spectral sliver of incoming radiation at short wavelengths.

Figure 5: 'Atmospheric windows' for various greenhouse gases



(Rohde 2016)

The greenhouse effect therefore depends on the efficiency of a basic radiative flux between the atmosphere and space, with greenhouse gases acting as a key conduit.

2.3 Closing the atmospheric window

The idea that human activities could increase atmospheric greenhouse gas concentrations is not new. Having opened the 'atmospheric window' in the laboratory and as ever more was discovered about the warming 'blanket' of greenhouse gases that encircles the Earth, climate scientists were also speculating about the potential for human-induced change as a result of emissions of greenhouse gases from human activities.

In 1896 Arrhenius, citing the work of Högbom, identified human activities as capable of contributing significant quantities of carbon dioxide to the atmosphere. In his paper, Arrhenius calculated the contribution of carbon dioxide to the greenhouse effect and estimated that doubling atmospheric carbon dioxide concentrations could cause an average global temperature increase of 5-6°C (Arrhenius 1896). Subsequent scientists, such as Ångström, rebutted Arrhenius. They argued (correctly) that water vapour was a far more potent greenhouse gas than carbon dioxide, but erroneously concluded that small changes in carbon dioxide concentrations therefore had little global significance (Weart 2008, 7). A key idea was that existing concentrations of atmospheric water vapour and carbon dioxide already absorbed a maximum of terrestrial radiation; that is, the radiation absorption potential of these gases were already 'saturated' at their existing quantities in the atmosphere (Weart 2008, 7). Unfortunately, these ideas were mistaken, but took hold and delayed progress on climate science for decades.

In 1931, Hulburt refuted Ångström, arguing that changes in atmospheric carbon dioxide concentrations could account for the oscillation between ice ages. He estimated that if carbon dioxide concentrations were doubled, it would cause a 4°C increase in global average temperatures (Hulburt 1931). However, Hulburt's article was published in a physicists' journal, the Physical Review, so did not come to widespread prominence amongst meteorologists and geologists (Mason 2012).

In 1938, Callendar estimated that humans had already emitted 150,000 Mt of carbon dioxide. He theorised that this was causing human-induced warming and estimated that doubling atmospheric carbon dioxide levels would result in 2°C global average temperature rise from increased radiation absorption alone. It shall be noted that Callendar did not consider the effects of increased convection and identified, but did not quantify the potentially mitigating effect of the oceans. He concluded that the effect of this warming would be banal and emphasised the potential benefits (Callendar 1938). Despite delivering his paper at the Royal Meteorological Society, in front of Simpson and other luminaries of climate science, Callendar was a steam power engineer and so, like Hulburt, his ideas were not embraced by the meteorological establishment (Weart 2008, 2).

In 1955, Hans Suess revealed the effect of humans' mass use of fossil fuels: the isotopic signature of atmospheric carbon dioxide was changing, with radioisotope carbon-14 (^{14}C) being depleted in atmospheric carbon dioxide, relative to 'normal' carbon-12 (^{12}C), due to fossil fuel burning (Suess 1955). Fossil fuels are depleted in ^{14}C, which undergoes radioactive decay, due to being millions of years old and hence any such radiocarbon is substantially decayed (Libby 1946). Given widespread combustion of fossil fuels for various human activities, this was compelling evidence of human-induced changes in the atmosphere's composition. However, debate continued as to the effects of additional anthropogenic carbon dioxide.

In 1956, Plass overturned the longstanding assumption that the 'atmospheric windows' for carbon dioxide and water vapour were saturated. He pointed out that the apparently overlapping absorption spectra of water vapour and carbon dioxide were merely nearly coincident and did not in fact overlap, when analysed carefully. Further, the partial pressure of water vapour, although a potent greenhouse gas, falls away with altitude, whereas carbon dioxide is well mixed throughout the atmosphere (Plass 1956, 304). Thus, Plass realised that additional carbon dioxide in the upper layers of the atmosphere would lead to additional absorption of longwave radiation and hence warming in all lower layers (Weart 2008, 23). As described in Section 2.2, this is due to the process of absorption and re-emission of terrestrial radiation and particularly the effect of changes in temperature and pressure, which serve to broaden the absorption spectra of greenhouse gases and hence the warming potential of these gases. Like Hulburt and Callendar before him, Plass' ideas were all the more remarkable given that he had a hobby interest in climate science alongside his work in infrared radiation research for weapons systems (Weart 2008, 22–24).

Plass' work recapitulated the theories of Högbom and Arrhenius, as further developed by Hulburt and Callendar. He presented a compelling case that the problem with human emissions of carbon dioxide is that this leads to more terrestrial radiation being absorbed and so less radiation emitted into space, which ultimately causes warming. At the same time, more atmospheric warming means that more water vapour is also evaporated into the atmosphere, which reinforces the warming cycle started by the additional carbon dioxide. The absorption spectra of these two gases and the other greenhouse gases are a 'louvred window', which transmits only ~15-30 % of terrestrial radiation (Section 2.2). As Plass sought to argue, additional carbon dioxide emitted by human activities risked closing additional 'louvres' in these spectra and so warm the Earth.

Meanwhile, in 1975, inspired by Molina and Rowland's work on CFCs and their potential impacts on the ozone layer, Ramanathan considered CFCs' potential as greenhouse gases. He found that, similar to their dominant role in catalysing ozone destruction, CFCs have disproportionately large radiation absorptive potential despite their trace concentrations in the atmosphere (Ramanathan 1975). Moreover, the strongest absorption bands for CFCs are located within range of 8–13 μm (Ramanathan 1975), which is almost directly coextensive with the largest gap in the 'atmospheric window' (refer Figure 5), so their increasing abundance risked further 'closing' the window and enhancing warming.

From Arrhenius to Ramanathan, the discoveries summarized above represent key theoretical milestones in climate science. However, as Plass noted in the prophetic final sentence of his paper, compelling evidence of increasing greenhouse gas emissions and measured temperature increases were the last remaining pieces of the puzzle (Plass 1956, 315–16):

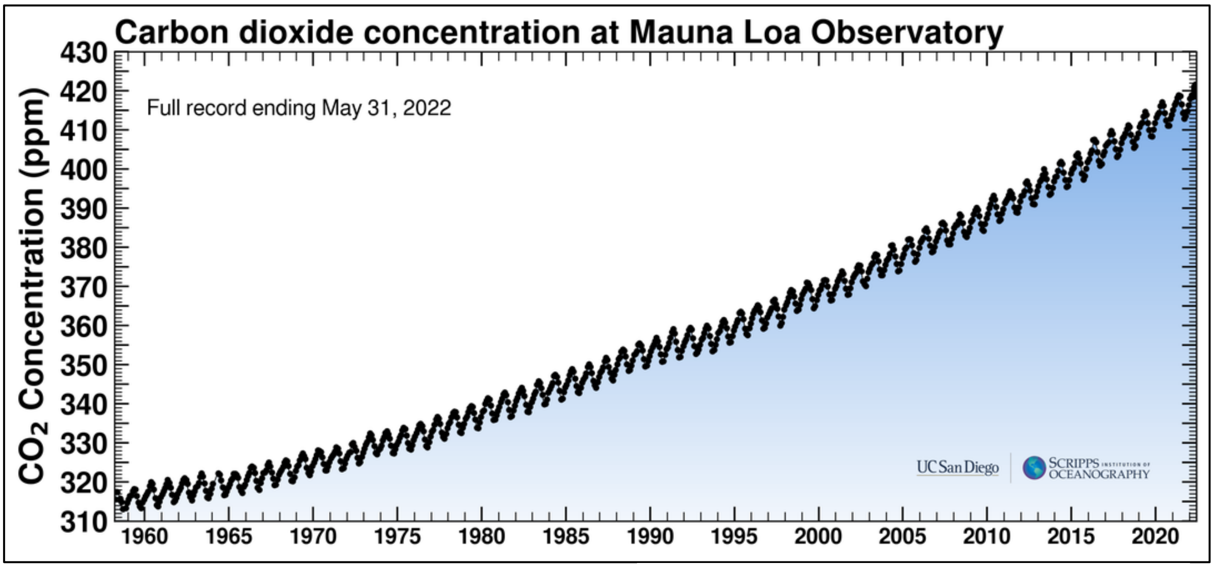
> '*If at the end of this century the average temperature has continued to rise and in addition measurement also shows that the atmospheric carbon dioxide amount has also increased, then it will be firmly established that carbon dioxide is a determining factor in causing climatic change*.'

Thus, attention then turned to historical climates and establishing regular measurements of atmospheric carbon dioxide levels.

2.4 Increasing carbon dioxide

In 1958, Charles Keeling and the Scripps Institution of Oceanography, led by Roger Revelle, started measuring atmospheric carbon dioxide concentrations at Mauna Loa, Hawaii. Keeling had been inspired by Plass' work (Weart 2008, 24) and his carbon dioxide project secured funding as part of the International Geophysical Year 1957-58 (Weart 2008, 34), which had also funded an expanded global network of ozone measurement stations. In 1976, Keeling et al. published what has come to be known as the 'Keeling curve', based on their measurements of carbon dioxide concentrations at Mauna Loa, which showed a clear rising trend (with significant interannual variability due to the Northern Hemisphere growing season) (Keeling et al. 1976). The Keeling curve continues to show a clear upward trend in carbon dioxide concentrations today, as a result of continued anthropogenic emissions (see Figure 6).

Figure 6: 'Keeling Curve' – atmospheric CO_2 measured at Mauna Loa as at 31 May 2022



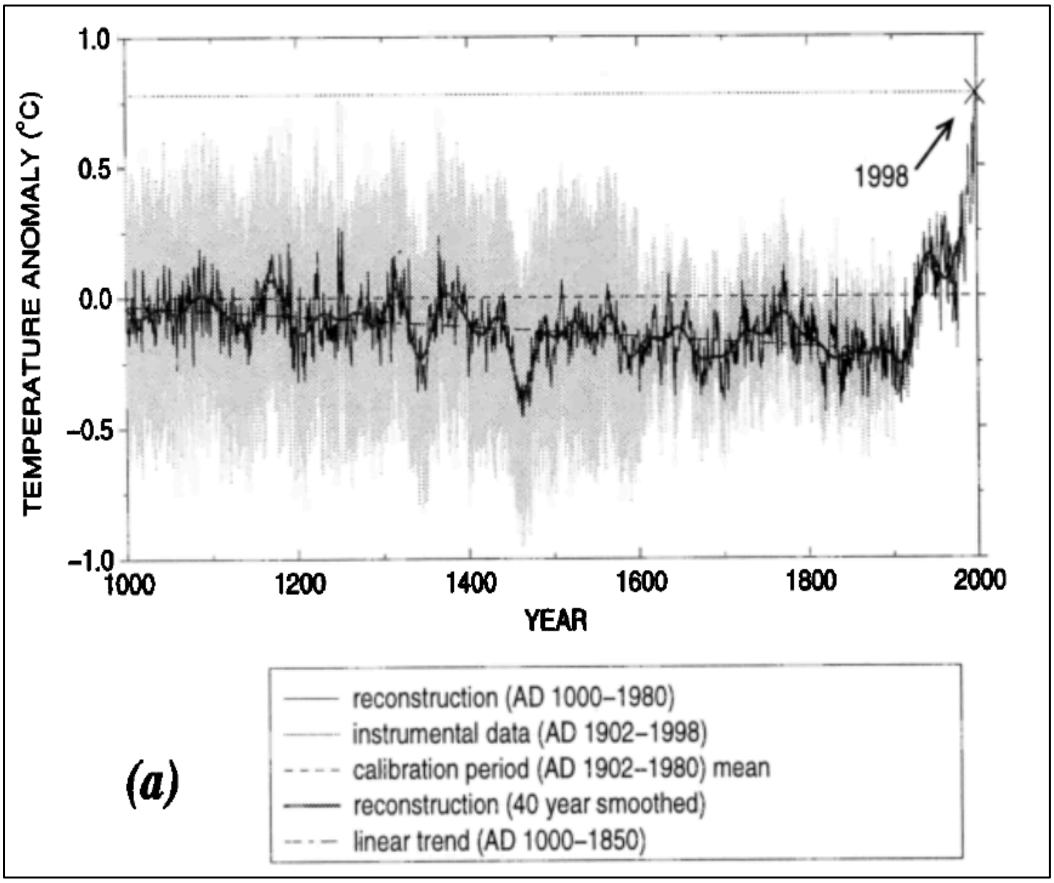
(Monroe 2022; Keeling et al. 2005)

The iconic Keeling curve was compelling additional evidence for the human imprint on contemporary climate change (Treut et al. 2007, 100). However, systematic instrumental records only extend so far back into the past and so other methods were required to infer past carbon dioxide levels and therefore past climates, in order to put the danger of rising human greenhouse gas emissions in broader historical perspective. These include a variety of proxies for historical atmospheric carbon dioxide concentrations, such as studies of ice cores, speleothems (stalagmites and stalactites in caves) and tree rings, from which historical temperatures can be inferred. However, the large reliance on assumptions, as well as significant practical difficulties often contribute to large uncertainties in such studies. By way of example, a brief history of ice core studies is instructive.

Funding for the first ice core study also came from the International Geophysical Year 1957-1958 and required logistical support from the US military in inhospitable conditions on the Greenland ice cap (Weart 2008, 70). The first core was extracted in 1961, but the team did not reach bedrock (at a depth of 1.4 km) until 1966. At the same time, there were fundamental difficulties in methodologies and interpretation of the results, e.g., the bottom of a core was often distorted due to extreme pressure and glacial flow (Weart 2008, 71–72). Initially, the best method was to compare isotopic fractionation between $^{16}O/^{18}O$ (Dansgaard 1954), similar to Suess' method with $^{12}C/^{14}C$. It was not until 1980 that a more reliable method was devised for measuring historical atmospheric carbon dioxide levels, which could be measured in bubbles of air trapped within annual layers of ice (Delmas, Ascencio, and Legrand 1980).

Eventually, as successive refinements were made in the methodologies of such proxy studies, this led to another prominent climate science curve: the 'hockey stick' graph of Mann, Bradley and Hughes (1999) shown in Figure 7, with its abrupt recent increase in annual global temperature anomalies. The inherent challenges and methodological difficulties in establishing the record are clear from the large grey-shaded uncertainty intervals in Figure 7, which were discussed at length by Mann, Bradley and Hughes (1999). Despite these uncertainties, such studies of composite proxy and instrumental records revealed that from approximately 10,000 years ago up until 1750 CE, globally averaged atmospheric CO_2 concentrations fluctuated around 280 ppm (± 20 ppm) (Indermühle et al. 2000; Treut et al. 2007, 100). Since the Industrial Revolution, atmospheric carbon dioxide concentrations have risen exponentially to 367 ppm by 1999, then 379 ppm by 2005 (Treut et al. 2007, 100) and, at the time of writing, globally averaged carbon dioxide concentrations are ~421 ppm, as was shown in Figure 6.

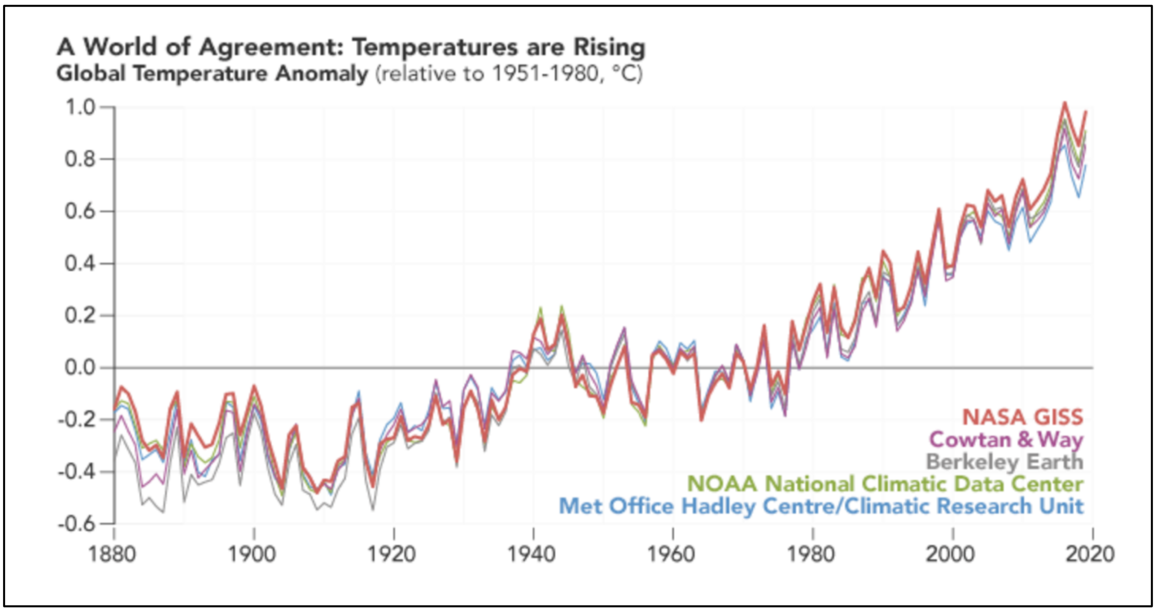
Figure 7: 'Hockey stick' graph of proxy and instrumental records of past climates



(Mann, Bradley and Hughes 1999)

At the same time, instrumental temperature records show that average global temperatures are anomalously ~1°C warmer relative to the pre-industrial period, as seen in Figure 8. Taken together, modern instrumental records and proxy-based climate reconstructions strongly suggest that modern global warming is well beyond the bounds of natural variability for thousands of years (Mann et al. 2008; Lüthi et al. 2008; IPCC 2013a). These multiple lines of evidence all seemed to resoundingly confirm the earlier theories of an artificially enhanced greenhouse effect through human emissions of greenhouse gases.

Figure 8: Global temperature records from multiple climate science institutions since 1880



(NASA 2020)

2.5 Human fingerprint confirmed (again)

All of the above represent compelling evidence for the detection of human-induced climate change. However, as with the issue of the ozone hole and the 'smoking gun' of elevated stratospheric chloride concentrations detected by aeroplane in 1987, climate scientists also sought evidence to firmly attribute the observed warming to human emissions and the enhanced greenhouse effect. Since there is only one Earth, with insurmountable ethical and practical challenges to any attempts at planetary scale experiments, attribution studies had to rely instead on computer modelling to simulate the effect of anthropogenic greenhouse gases on Earth's climate system. Modellers also had to contend with the confounding effects of various processes, such as absorption of carbon dioxide by the oceans, clouds and aerosols.

Atmospheric modelling began in the 1950s, with the first reasonable replication of regional weather achieved in 1955 and the first three-dimensional model capable of solving basic atmospheric equations in 1965 (Weart 2008, 91–92). A model of the global ocean circulation followed in 1969 (Manabe and Bryan 1969). In 1967, Manabe and Wetherald began developing the first three-dimensional global climate model, which attempted to couple ocean-atmosphere interactions. This was finally achieved in 1975 (Manabe, Bryan and Spelman 1975; Bryan, Manabe and Pacanowski 1975; Manabe and Wetherald 1975; Wetherald and Manabe 1975).

By 1990, climate models showed that the observed warming between 1867 to 1982 could not be explained by natural variability alone (Wigley and Raper 1990). The diverse effect of clouds, which both reflect and absorb radiation, was also increasingly well reproduced by models (Senior and Mitchell 1993). In 1992, a team led by Jim Hansen successfully modelled the effect of atmospheric sulphate aerosols from volcanoes, based on contemporary observations in the aftermath of the Mt Pinatubo eruption in the Philippines (Hansen et al. 1992; Treut et al. 2007, 98; Weart 2008, 163). Within a few years, once the aerosols had been washed out of the atmosphere by precipitation, average global temperatures continued to steadily increase together with rising greenhouse gas emissions (Weart 2008, 168). These examples demonstrate how the models improved, growing closer to the goal of discerning the enhanced greenhouse effect from natural climate variability and other confounding factors.

By 1995, three independently developed global circulation models each succeeded in replicating observed 20th century warming (Weart 2008, 164). In November 1995, at a colloquium organised by Charles Keeling held at the American National Academy of the Sciences, modelling results were presented that 'provide convincing evidence for a discernible human influence on global climate' (Wigley, Jones, and Raper 1997, 8320). Very similar language was ultimately adopted, after a political stoush (Oreskes and Conway 2010, 200–207), in the 1995 Second Assessment Report by the Intergovernmental Panel on Climate Change (IPCC), which stated: '*The balance of evidence suggests a discernible human influence on global climate*' (Houghton et al. 1996, 4).

As climate models improved and various confounding factors could be isolated from the effects of carbon dioxide, by the mid- to late 1990s the human fingerprint on contemporary climate change had become clear. The weight of evidence had already indicated that greenhouse gas emissions and global average temperature were rising in lockstep. Crucially, repeated model runs showed that neither natural variability alone, nor any reasonable parameters for the various confounding factors (Canty et al. 2013), could account for the observed temperature increase; it was only when greenhouse gas emissions from human activities were included that the models showed good agreement with the observed trends.

Summary of the physical science

As has been discussed in the preceding chapters, ozone science and climate science have developed in parallel, as summarised in Table 1 below.

Table 1: Summary of parallel developments in ozone and climate science

Milestones in ozone science		Milestones in climate science	
1840	Schönbein identifies pungent gas product of the electrolysis of water; names it 'ozone'	**1856 – 1859**	Foote (1856) and Tyndall (1959) investigate the role of H_2O, CO_2 and CH_4 in absorbing certain wavelengths of radiation
1850 – 1860	Ozone's chemical formula and chemical properties determined experimentally	**1896**	Arrhenius estimates global average warming of 5-6°C, if atmospheric CO_2 is doubled
1881	Hartley attributes 'drop-off' in incoming solar radiation below λ ~293 nm to ozone	**1918 – 1928**	Hettner (1918) and Simpson (1928) clarify the relationship between atmospheric gases' absorption spectra and the greenhouse effect
1900s	de Bort and Assmann independently discover the atmospheric temperature inversion	**1931**	Hulburt argues that changes in atmospheric CO_2 could account for Earth's oscillation between ice ages
1913	Fabry and Buisson accurately measure atmospheric ozone concentrations	**1938**	Callendar theorises human-induced enhancement of the greenhouse effect
1924	Dobson develops his ozone spectrometer	**1955**	Suess reveals the isotopic human signature of fossil fuel combustion
1930	Chapman theorises the photolysis of atmospheric oxygen, through which ozone is created and destroyed by further photolysis	**1956**	Plass confirms that human combustion of fossil fuels is closing the 'atmospheric window', raising atmospheric temperatures
1950	Bates and Nicolet publish paper on the role of HO_x in atmospheric ozone chemistry	**1958**	Keeling starts direct atmospheric CO_2 measurements at Mauna Loa, Hawaii
1970	Crutzen publishes paper on the role of NO_x in atmospheric ozone chemistry	**1975**	Ramanathan investigates CFCs' potential as greenhouse gases
1974	Molina and Rowland publish paper on the role of CFCs in atmospheric ozone chemistry	**1976**	Keeling publishes the first 'Keeling curve', showing clear rise in atmospheric CO_2 concentrations

1985	Farman et al. publish paper on the appearance of an ‘ozone hole’ in the Antarctic spring	**1980**	Reliable method developed for inferring past atmospheric CO_2 concentrations from ice cores
1985	Vienna Convention for the Protection of the Ozone Layer	**1988**	Intergovernmental Panel on Climate Change established
1986	US scientific expedition to Antarctica investigates atmospheric chlorine chemistry	**1990**	IPCC publishes its First Assessment Report
1987	Airborne sampling provides proof of the role of CFCs in ozone loss	**1990**	Climate models show that observed warming between 1867 and 1982 could not be accounted for by natural variability alone
1987	Montreal Protocol on Substances that Deplete the Ozone Layer	**1992**	Rio Earth Summit; adoption of the United Nations Framework Convention on Climate Change (UNFCCC)
1988	First World Ozone Assessment by the World Meteorological Organization	**1995**	IPCC publishes its Second Assessment Report, concluding that there is a ‘discernible’ human signature to recent warming
2009	Newman et al. publish their ‘World Avoided’ study, showing the effect of the MP	**1997**	Kyoto Protocol (KP)
2016	Solomon et al. publish paper showing the observed and projected further ‘healing’ of the ozone layer by 2050	**1999**	Mann, Bradley and Hughes publish their ‘hockey stick’ graph of historical atmospheric CO_2 concentrations, based on composite proxies and modern instrumental records
		2001	IPCC publishes its Third Assessment Report
		2007	IPCC publishes its Fourth Assessment Report, concluding that human-induced warming is ‘unequivocal’
		2014	IPCC publishes its Fifth Assessment Report
		2015	Paris Agreement (PA)
		2021	IPCC publishes its Sixth Assessment Report

3 The Two Legal Regimes

'… it's easy to say they have a lot in common scientifically. You know, both sets of gases, most of the major ones anyhow, have very, very long lifetimes so the accumulation problem from year after year of emissions is very serious in both cases. It's easy to say that both are global problems… and of course the ozone Protocol came first, which meant that… many of the same diplomats that worked on the ozone agreement thought 'oh it worked so great for ozone– why don't we just translate those ideas into climate change?''

- Professor Susan Solomon, 27 July 2021

The issues of anthropogenic ozone destruction and anthropogenic climate change are not only linked physically and chemically, but also in the design of the respective responses in international law. Professor Susan Solomon has been intimately involved in the science of both human-induced ozone destruction and human-induced climate change. She has also interacted closely with policymakers throughout her long career in the USA, at the National Oceanic and Atmospheric Administration and more recently at the Massachusetts Institute of Technology, and internationally, as a former co-chair of the IPCC's Working Group I during the development of the Fourth Assessment Report. Her insights provided verbally in an interview in July 2021 greatly inform the discussion of the results of this thesis, contained in Chapter 6, but her opening monologue extracted above succinctly summarises another point of intersection between the two issues: the similarities in the design of the regimes for ozone and climate protection under international law.

As mentioned in the preceding chapters, ozone science and climate science remain active and dynamic fields of research today, with several contemporary conundrums to be resolved and a future rife with uncertainties:

'*… frankly, the science of ozone is more exciting right now than ever and I think the same thing is going to happen with climate… because as the world gets hotter, there will continue to be phenomena that we don't understand and as the governments… try to evaluate 'are people really meeting their commitments?'…, which they have all agreed that they will do, there will be many, many challenges on measurements of emission and interpretation of those measurements will involve physical science. There will be feedbacks in the biogeochemistry that we probably haven't even dreamed of yet.*'

- Professor Susan Solomon, 27 July 2021

While the future is far from settled for ozone and climate science, the focus of the rest of this thesis is directed at the letter of the law used in the international regimes governing the scientific problems. Having introduced the essential scientific ingredients, this chapter proceeds to introduce the key features and point out certain similarities in the architecture of the respective international legal regimes. The chapter then proceeds to review the relevant literature and identify existing knowledge 'gaps', before defining the thesis' aims and hypotheses.

3.1 Overview of both regimes

The ozone and climate regimes are characterised by a similar structure, as shown in Figure 9 below. Both regimes are established by framework conventions, which are broad agreements with few detailed binding obligations. Under such a framework, many of the concrete commitments towards the overall objectives are left to be imposed by way of implementing agreements or protocols (UNEP 2007, 38–39). Here, the two relevant framework conventions are the VCPOL, for the ozone regime, and the 1992 *United Nations Framework Convention on Climate Change* (UNFCCC), for the climate regime.

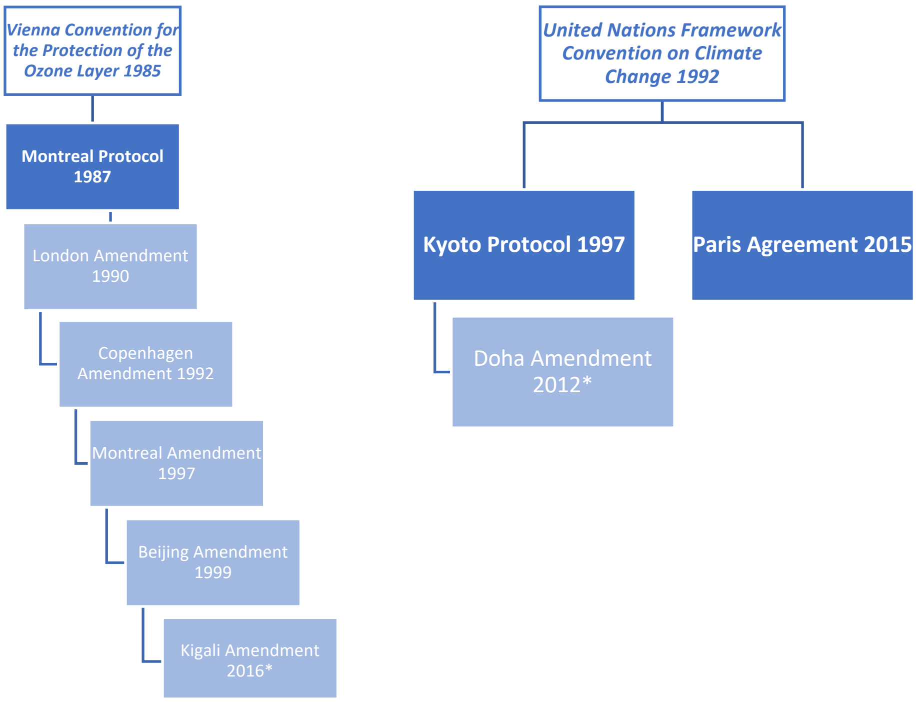
The ozone regime has been substantially implemented by the *Montreal Protocol 1987*[5] (MP1987). The MP1987 has been amended five times since it entered into force in 1989: by the London (LDN1990),[6] Copenhagen (CPN1992),[7] Montreal (MON1997),[8] Beijing (BEI1999)[9] and Kigali[10] Amendments. The relationship between the different international agreements and the development of the ozone regime over time are shown in Figure 9. The MP has also been 'adjusted' a number of times. 'Adjustments' are distinguished from 'amendments', since the former involve minor changes (e.g. revised emissions reduction deadlines), whereas the latter involve substantive changes to the MP (e.g., addition, deletion or substitution of an article or paragraph). In either case, the changes must be adopted by an appropriate decision of the parties to the MP at a duly convened meeting of the parties (MOP), but an 'amendment' is subject to more onerous procedural requirements.[11] There are also a series of decisions of the MOP to the MP, which further modified the ozone regime,[12] but analysis of these documents is beyond the scope of this thesis.

Meanwhile, the climate regime has been implemented through the *Kyoto Protocol 1997* (KP), together with its *Doha Amendment 2012* (Doha), and the separate *Paris Agreement 2015* (PA). The relationship between the different international agreements and the

[5] The Montreal Protocol on Substances that Deplete the Ozone Layer, concluded at Montreal on 16 September 1987.
[6] Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer, London, 29 June 1990.
[7] Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer, Copenhagen, 25 November 1992.
[8] Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer, Montreal, 15-17 September 1997.
[9] Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer, Beijing, 3 December 1999.
[10] Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer, Kigali, 15 October 2016.
[11] See VCPOL Articles 9 and 10.
[12] See Handbook to the MP (Ozone Secretariat 2020, sec. 2).

development of the climate regime over time are shown in Figure 9. There is no similarly extensive history of amendments under the climate regime, in contrast to the ozone regime. However, there is a long list of relevant decisions of the Conference of the Parties to the UNFCCC (COP),[13] which have supplemented the agreements and clarified certain details about the climate regime,[14] but analysis of these documents is beyond the scope of this thesis.

Figure 9: Overview of the structure of the ozone and climate regimes



**NB: the text of the Kigali and Doha Amendments have not been considered in further detail as part of this thesis.*

3.2 Overall regime objectives

'…defining what is "dangerous". You know, it's always been clear that what is "dangerous" is not a scientific question, right? It involves you know "dangerous to who?" and "how much risk is too much?" So it involves values, as well as science…'

\- Professor Susan Solomon, 27 July 2021

At the outset and noting the method of interpretation required[15] by the 1969 *Vienna Convention on the Law of Treaties* (VCLT), it is important to understand the overall objective of each convention, before considering the implementing agreements in detail. Note that detailed analysis of the text of the framework conventions is beyond the scope of this thesis.

[13] Serving as both the Conference of the Parties to the UNFCCC and, as applicable, the equivalent body under the KP or PA. See 'COP' in Glossary of Terms.
[14] See, for example, decision 1/CP.21 made under the PA, which adopted the Paris Agreement, while also referring to several contentious issues for which there was no consensus within the main agreement (e.g., on the Green Climate Fund), so these were relegated to the decision of the COP instead.
[15] See VCLT Art 31.

Table 2: The overall objectives of the regime framework conventions

VCPOL	UNFCCC
The Parties shall take appropriate measures in accordance with the provisions of this Convention and of those protocols in force to which they are party to protect human health and the environment against adverse effects resulting or likely to result from human activities which modify or are likely to modify the ozone layer. – Article 2(1) of the VCPOL	*The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.* – Article 2 of the UNFCCC

The following elements are particularly noteworthy from Article 2(1) of the VCPOL. First, the 'objective' is bound up with other 'general obligations' and so is drafted in the language of active obligation ('shall'), by compelling 'the Parties' to take action to protect human and environmental health. Second, 'adverse effects' are defined by reference to '*significant deleterious effects'* in Article 1(2). Third, these 'adverse effects' are linked to the modification, or the *possible* modification, of the ozone layer,[16] while also linking this to their source ('*resulting*'), or even the possibility of their source ('*likely to result from*'), in human activities. Fourth, it specifically contemplates 'protocols' made under the VCPOL.[17] Finally, the remainder of Article 2 (not extracted above) requires the Parties to take other action to cooperate in accordance with their available 'means' and 'capabilities',[18] and requires that the application of this article shall be based on 'relevant scientific and technical considerations'.[19]

[16] Defined in VCPOL Article 1(1) as 'the layer of atmospheric ozone above the planetary boundary layer'.
[17] See also the definition of 'protocol' in VCPOL Article 1(7).
[18] Refer VCPOL Article 2(2).
[19] Refer VCPOL Article 2(4).

Meanwhile, having regard to the six elements of the VCPOL objective above, the important takeaways from Article 2 of the UNFCCC are as follows. First, the ultimate objective is drafted in the language of ambition (‘*to achieve*’) and without a subject (i.e., using the passive voice). Second, the goal is expressed by reference to the ‘*stabilization’* of atmospheric concentration of greenhouse gases, but that level remains unspecified other than by reference to ‘natural’ adaptation; ‘*dangerous’* is not defined either, while ‘*climate system*’ is defined very broadly.[20] Third, the link to human activity is mentioned (‘*anthropogenic interference*’), but the causative link is less overt. Fourth, the ultimate objective is defined for the purposes of both the UNFCCC and any ‘*related legal instruments*’ adopted by the COP. Finally, the second sentence seeks to balance temporal considerations with environmental (‘*ecosystems*’), social (‘*food production*’) and economic (‘*economic development*’) considerations.

Thus, already the differences between the overall objectives hint at some of the broader themes that characterise the comparison and analysis of the two regimes. It is telling that the VCPOL objective is directed at its parties and their actions, whereas the UNFCCC’s ultimate objective is drafted passively. Further and without proceeding to engage in too much analysis of the ‘parent’ framework conventions, note that while most other operative provisions of the VCPOL require action simply by ‘*the Parties*’,[21] the UNFCCC refers to ‘*the Parties*’, or distinguishes between ‘*developed’* and ‘*developing country Parties*’.[22] Moreover, the location of the objective of the VCPOL among other ‘general obligations’ in Article 2 immediately links it to operative paragraphs.[23] By contrast, the UNFCCC sets out its ‘objective’,[24] then ‘principles’[25] and then ‘commitments’[26] in separate articles and appears to impose more general obligations[27] on parties than the more specific VCPOL. As discussed in Chapter 6, these trends in the different regime objectives are reflected in closer analysis of the two regimes.

It should also be noted that the UNFCCC repeatedly acknowledges the existence of the ozone regime and seeks to avoid duplicating control of emissions of GHGs that are also ODS, through repeated references to ‘*all greenhouse gases not controlled by the Montreal Protocol*’. This phrase is also used consistently in the KP to maintain the separation between the two regimes, but no such references to the ozone regime appear in the PA.

[20] Refer UNFCCC Article 1(3), which includes the ‘atmosphere, hydrosphere, biosphere and geosphere and their interactions’.
[21] Refer VCPOL Articles 2, 3, 4 and 5.
[22] See, for example, UNFCCC Article 4.
[23] Refer VCPOL Article 2(2)(b).
[24] In UNFCCC Article 2.
[25] In UNFCCC Article 3.
[26] In UNFCCC Article 4.
[27] Refer UNFCCC Article 4(1).

3.3 The implementing agreements

Having considered the overall objectives of the framework conventions, a number of key similarities and differences between the main implementing agreements (MP, KP and PA) under the ozone and climate regimes are summarised in Table 3. These include: an overarching framework convention and objective to be achieved through implementing agreements, defined atmospheric pollutants, established reference ODS consumption / GHG emissions baselines, required reductions or targets relative to those baselines, regulation of relevant trading activities, technology transfer, financing, ongoing monitoring and review, non-compliance measures and entry into force provisions subject to 'double pre-conditions'.[28]

Table 3: Comparative 'anatomy' of the MP, KP and PA

<table>
<tr><th>Feature</th><th>Montreal Protocol</th><th>Kyoto Protocol</th><th>Paris Agreement</th></tr>
<tr><td rowspan="2">Purpose</td><td rowspan="2">Determined to protect the ozone layer by taking precautionary measures to control equitably total global emissions of substances that deplete it, with the ultimate objective of their elimination on the basis of developments in scientific knowledge, taking into account technical and economic considerations and bearing in mind the developmental needs of developing countries
- Preambular paragraph 6</td><td>In pursuit of the ultimate objective of the Convention as stated in its Article 2,
Recalling the provisions of the Convention,
Being guided by Article 3 of the Convention
- Preambular paragraphs 2-4</td><td>In pursuit of the objective of the Convention, and being guided by its principles, including the principle of equity and common but differentiated responsibilities and respective capabilities, in the light of different national circumstances
- Preambular paragraph 3</td></tr>
<tr><td colspan="2">[Article 3 of UNFCCC refers, among others, to the principles of common but differentiated responsibilities, respective capabilities, special situation of developing countries, the 'precautionary principle' and low cost, sustainable development, supportive and open international economic system]</td></tr>
</table>

[28] In terms of both the number of parties and those parties' representative percentage of ODS consumption/GHG emissions.

Feature	*Montreal Protocol*	*Kyoto Protocol*	*Paris Agreement*
Defined atmos-pheric pollutants	Over 76[29] 'controlled substances' with 'ozone-depleting potential', as listed in a series of Annexes to the MP.	6 gases in Annex A: 1. Carbon dioxide (CO_2) 2. Methane (CH_4) 3. Nitrous oxide (N_2O) 4. Hydrofluorocarbons (HFCs) 5. Perfluorocarbons (PFCs) 6. Sulphur hexafluoride (SF_6)	Refers repeatedly to 'greenhouse gases' and adopts[30] the definition in UNFCCC Article 1(5): '*those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and re-emit infrared radiation*'.
Control mecha-nisms	1. Emissions baseline 2. 'Control measures' consisting of progressive national emissions cuts 3. Trade restrictions (import/export bans) 4. Technology transfer 5. Multilateral Fund	1. Emissions baseline 2. National GHG inventories & mitigation measures 3. 'Clean Development Mechanism', 'Joint Implementation' & emissions trading 4. Technology transfer 5. Financing	1. Global average temperature goals 2. Maintains national GHG inventories system 3. 'Nationally determined contributions' pledges 4. Enhanced transparency framework & 'global stocktake' 5. Technology transfer 6. Financing
Reference baseline (year / multiyear average)	1986 (NA5[31]) 1995-1997 (A5[32]) Annex A (CFCs, halons)	1990	Varies nationally, according to each country's 'nationally determined contribution'

[29] Not including many other HCFC/HBFC isomers listed in Annex C.
[30] See the chapeau to PA Article 1.
[31] NA5 = non-Article 5 parties (i.e., developed country parties)
[32] A5 = parties operating under MP Article 5 (i.e., developing country parties)

Feature	***Montreal Protocol***		***Kyoto Protocol***	***Paris Agreement***
	1989 (NA5) 1998-2000 (A5)	Annex B (Other fully halogenated CFCs, carbon tetrachloride, methyl chloroform)		
	1989 (NA5) 2009-2010 (A5)	Annex C (HCFCs, HBFCs, bromochloromethane)		
	1991 (NA5) 1995-1998 (A5)	Annex E (methyl bromide)		
Emissions reduction targets / measures	Various reduction schedules, depending on the 'controlled substance' and Annex - Arts 2A to 2I, Annexes A-C, E		All Annex I (developed parties) parties to achieve reduction of ~5% of 1990 levels in the 'commitment period' (2008-2012) - Art 3, Annex B	1.5°C / 2°C 'global average temperature goal'; size of reduction and timeframe dependent on each 'nationally determined contribution' - Arts 2(1)(a), 3, 4
Regulation of trade	Depends on the 'controlled substance', but most 'control measures' include a ban on imports and exports of ODS to/from non-parties.		Enables parties to voluntarily trade certified emissions reductions (i.e., 'carbon credit' schemes). - Art 12	Enables parties to trade 'internationally transferred mitigation outcomes' on a voluntary, cooperative basis. - Art 6

Feature	*Montreal Protocol*	*Kyoto Protocol*	*Paris Agreement*
	(Later extended to allow for products containing ODS and even those made using ODS, but not containing them in final product, to be subject to control measures). - Art 4		
Technology transfer	MP 1987: developed country parties had to 'undertake' to facilitate access to substitute substances / technology for developing country parties. - Art 5(2), (3) MP 2000: developed country parties required to take 'every practical step' to ensure best available substitutes and technologies were transferred to developing country parties. - Art 10A	All parties required to 'cooperate' on transfer of technologies. - Art 10(c) Developed country parties required to provide financing for technology transfer. - Art 11(2)	All parties must 'strengthen' cooperation on technology development and transfer. Developing country parties must be financially supported for such cooperation, but PA does not necessarily require that developed country parties provide that support. - Art 10(6)
Financing	Establishes a financial mechanism, which includes a Multilateral Fund funded by developed country parties to meet the 'agreed incremental costs' incurred	Developed country parties to provide new and additional funding for the 'agreed full costs' of developing country parties establishing GHG inventories. Also for the	Developed country parties must provide financial resources to developing country parties. Also, developed country parties should 'take the lead' in mobilising 'climate

Feature	*Montreal Protocol*	*Kyoto Protocol*	*Paris Agreement*
	by developing country parties, and to assist with technical cooperation and capacity-building. - Art 10	'agreed full incremental costs' of various technology transfer, capacity-building and cooperation activities. - Art 11(2)	finance' from a wide range of sources and this should 'represent a progression beyond previous efforts'. - Art 9(1), (3)
Monitoring & review	Overall review: every 4 years, by panel of experts from 'scientific, environmental, technical and economic' fields. - Art 6 Following such a review, ozone-depleting potentials of listed ODS may be adjusted, or the 'scope, amount and timing' of reduction schedules may be changed by a meeting of the Parties. ODS may also be added/removed from Annexes, but this requires an amendment. - Art 2(9), (10)	Overall review: Conference of the Parties (COP) to 'periodically review' the KP in light of 'best available' science on climate change and its impacts, as well as relevant 'technical, social and economic' information. COP has broad powers to 'take appropriate action' following such a review. - Art (9)(1) The COP must also regularly review the implementation of the KP and may exercise various functions or powers to enhance implementation. - Art 13(4) Annual national GHG inventory reports are subject to 'thorough and comprehensive' expert review. The review team	Overall review: COP to also conduct 'global stocktake' every 5 years, which will track progress on implementation towards the PA's long-term goals. The global stocktake should also inform parties in updating NDCs. - Art 14 COP to regularly review implementation of PA and make decisions to promote its effective implementation, including the establishment of any subsidiary bodies and exercise of any other functions as may be required. - Art 16(4) PA also establishes an 'enhanced transparency framework' for national communications, to track progress towards NDCs, and other priorities including adaptation,

Feature	*Montreal Protocol*	*Kyoto Protocol*	*Paris Agreement*
		will report to the COP and Ozone Secretariat, for consideration at the next COP. - Art 8	finance, technology transfer and capacity-building. - Art 13
Non-compliance	No substantive provisions; delegated to first meeting of the Parties. - Art 8	No substantive provisions; first COP to approve an 'appropriate and effective' mechanism. - Art 18	Establishes an implementation and compliance mechanism, in the form of an expert committee that must function in a 'transparent, non-adversarial and non-punitive' manner. - Art 15
Conditions for entry into force (EIF)	On 1 Jan 1989, provided: a) 11 (or more) parties have ratified it; and b) these parties represent at least two-thirds of global 1986 ODS consumption. - Art 16	EIF 90 days after: a) not less than 55 parties have ratified it; and b) these 55 parties must incorporate enough Annex I parties to account for more than 55% of 1990 GHG emissions. - Art 25	EIF 30 days after: a) at least 55 parties to the UNFCCC have ratified it; and b) these parties account for at least 55% of GHG emissions as at 12 Dec 2015.[33] - Art 21

The preliminary observations about the overarching objectives of the regimes and the above comparison between key structural elements of the two regimes will assume greater prominence in the more detailed textual analysis discussed in Chapter 6.

[33] See 'special meaning' defined in PA Art 21(2), decision 1/CP.21 and Annex I to UNFCCC secretariat report FCCC/CP/2015/10.

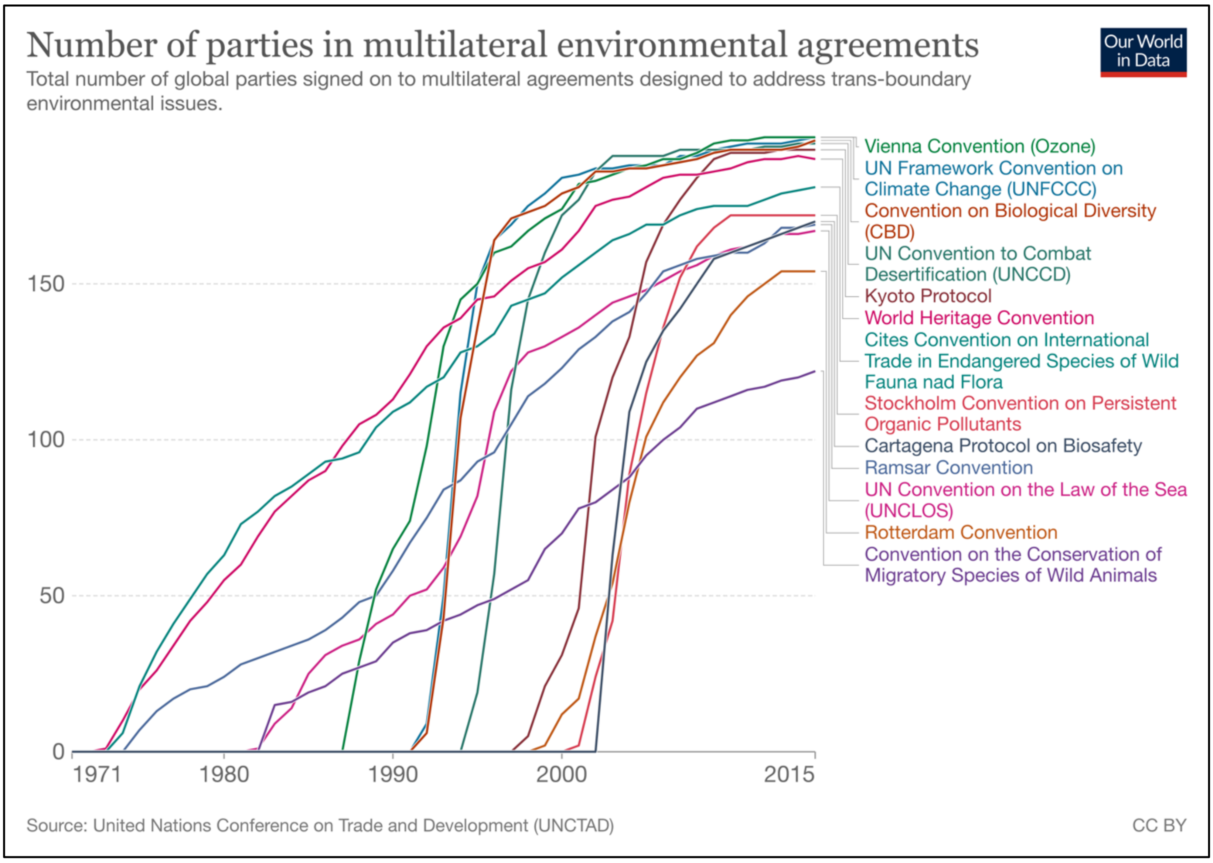
3.4 Literature review

The ozone and climate regimes represent the convergence of a long history of environmental law. A common human societal concern for the environment has its origins in some of the oldest continuous human cultures, where meticulous land management and 'care for country' served as the central organising principle of environmental lore for Indigenous Australians (Gammage 2011, chaps 4 & 5). More recently, there were references in Roman Antiquity to legal rules governing common concerns recognisable as what might be termed 'environmental law', including rules for the exploitation or ownership of natural resources, and cooperation for common protection against natural dangers (Colognesi 2017, 38).

Modern international environmental law has its origins in the form of bilateral environmental agreements (BEAs), such as riparian (river access) or marine fisheries rights treaties between European countries from the mid-1300s (Mitchell 2022). This trend in fisheries and riverine treaties continued over the following centuries until multilateral environmental agreements (MEAs) were agreed, which sought to encourage international cooperation for the protection of resources from external influences, such as a landmark convention agreed to protect European vignerons against an introduced vineyard pest (*Phylloxera Convention* 1881). Further BEAs and MEAs were agreed at the turn of the 20th century amid increasing internationalisation and later recorded under the formal system of treaty registration introduced under the auspices of the League of Nations (League of Nations 1927). However, in the post-World War II era, alongside the establishment of the United Nations and continued 'globalisation', modern BEAs and MEAs greatly accelerated in terms of number and diversity of topics (Mitchell et al. 2020, 105–7). In particular, the landmark 1972 UN Conference on the Human Environment in Stockholm is often regarded as a great catalyst for the proliferation in MEAs, as shown in Figure 10 below. However, Mitchell et al. (2020, 106) found that States had agreed at least 250 BEAs and MEAs by 1972 and they show that this trend began as early as the 1950s.

Regardless of when exactly the trend began, the broader growth in international conferences, often resulting in MEAs, reflects parallel trends in the development and internationalisation of ozone and climate science discussed in Chapters 1 and 2. The close connection between international conference negotiations and MEAs has been a prolific area of study (Tolba 1998; Underdal 2012; Kemp 2015), particularly in the context of the development of the ozone and climate regimes (Litfin 1994; Benedick 1998; Depledge 2000; Miles 2002).

Figure 10: Growth in the number of parties to MEAs since the 1970s



(Ritchie and Roser 2018a)

International lawyers have considered the form and substance of various MEA regimes. This has included careful consideration of the 'shallow'-'deep' dichotomy in terms of the depth of an MEA, together with detailed analysis of circumstances conducive to more flexible political 'pledges' versus more rigid, binding agreements (Abbott and Snidal 2000, 429–30; Raustiala 2005). A State is taken to prefer a 'deeper' and 'hard' or more binding arrangement under four conditions. Firstly, where the potential benefits of international cooperation are great, but the costs of rogue states acting opportunistically to take advantage of the situation (i.e., a prisoner's dilemma) are also very high. Secondly, if non-compliance with an agreed obligation would be hard to detect (e.g., arms control). Thirdly, when a binding agreement could be used by like-minded parties to coalesce around a common area of concern to the 'club' (e.g., the EU or North Atlantic Treaty Organisation). Fourthly, the executive arm of a government may wish to impose obligations on the other (e.g., legislative or judicial) arms of government, or competing political groups (Abbott and Snidal 2000, 429–30; Raustiala 2005, 592). The risk of opportunism is often decisive (Raustiala 2005, 593), as it is for ozone and climate issues here, where the risk of, for example, indiscriminate increased skin cancers or greater climate instability present the most compelling reason for states to consider a more binding agreement.

On the other hand, a 'soft law' political commitment or 'pledge' may be appealing in other circumstances, such as in the face of domestic political constraints. This is particularly relevant in the context of the climate regime and the PA, due to the history of climate politics in the USA. By unanimous resolution (98-0) dated 25 July 1997, the US Senate effectively told President Clinton that the Senate would withhold its advice and consent to the ratification of the KP or 'any such protocol or other agreement' under the UNFCCC, as would otherwise be required for a 'treaty' (*U.S. Const.* 1788, Art. II § 2). The Senate resolution cited the failure of the KP to impose binding obligations on both developed and developing country parties as a significant reason why the Senate would withhold its consent. For this reason, the Obama Administration advocated strongly for pledges in the lead up to COP21 in Paris, as a binding 'protocol' would fall foul of the Senate's resolution (Van Calster and Reins 2021, 106). Ultimately, since the PA as agreed contains common obligations for both developed and developing country parties, this suggests that the 'dead hand' of the Senate resolution has now been lifted from the climate regime (Van Calster and Reins 2021, 84). Nevertheless, as President Trump's action in withdrawing the US from the PA shows (Secretary-General of the United Nations 2019), this 'work around' solution is more precarious than a treaty ratified by the Senate. In the face of such uncertainty, let alone any that may be inherent in the subject matter of the regime (e.g. large scientific uncertainties), States tend to grow more inclined towards pledges as uncertainty rises (Raustiala 2005, 600).

Many attempts have been made to empirically assess the 'effectiveness' of MEAs (as a dependent variable). 'Effectiveness' has been interpreted differently across disciplines. In the social sciences, long-term MEA effectiveness research programmes have been conducted by Miles et al. (2002) using 37 case studies, and Mitchell et al. (2020). Mitchell, in particular, has striven for quantitative approaches using data on State membership of the regime and changes in observable State behaviour, since becoming a member, in the area of activity targeted by the particular regime. Mitchell's studies are based on data from a manually coded large database of international environmental agreements (Mitchell 2002; 2003; Mitchell et al. 2020). Social science effectiveness studies have provided a number of insights (Young 2011), including corroborating empirical evidence of the broad dichotomy inherent in MEA negotiations between a 'shallow and weak' but broadly inclusive agreement, versus a 'deep and demanding' one, often at the expense of participation (Raustiala 2005; Young 2011). Such studies also indicate that formal compliance and enforcement procedures, typically lacking in international regimes, are not essential and management, transparency or other accountability mechanisms may also prove effective (Young 2011, 19857). Contextual factors are also often critical to regime success, with particular relevance for attempts to apply lessons from the ozone regime in the context of the climate regime (Young 2011, 19855).

Much careful attention has also been given to the issue of legal 'bindingness'. This includes fundamental discussions about what is meant by that term, particularly in the context of criticism of the PA, where surprisingly disparate views have been (often wrongly) expressed (Raustiala 2005, 589; Bodansky 2016, 142; Mayer 2021, 117). However, despite repeated attempts to empirically prove whether and in what circumstances enhanced 'bindingness' results in overall 'effectiveness', evidence has remained elusive (R. Stavins et al. 2014, 1020; Bodansky 2016, 149). Public opinion and civil society perceptions that 'binding is best' appear to have muddied the waters (Raustiala 2005, 596–98; Bodansky 2016, 149), but this much is clear from the literature:

1. an international agreement can be legally binding without all of its provisions necessarily being binding– what matters is whether the parties intended the agreement to be legally binding (Bodansky 2016);

2. 'vague' or standard-based language in international agreements is not necessarily tantamount to 'non-binding' (Rajamani 2016a);

3. the lack of formal compliance procedures does not make a provision 'non-binding' (though may limit its effectiveness) and other factors, such as reputational risks, can serve to promote compliance (Raustiala 2005, 589; R. Stavins et al. 2014, 1020);

4. legally binding language is neither a necessary, nor a sufficient indicator of State behaviour (Raustiala 2005, 590); and

5. 'all else being equal' approaches are of limited practical utility, because of the strength of contextual factors and arbitrary distinctions between 'hard' and 'soft' law are thus often unhelpful in this context (Raustiala 2005, 610; R. Stavins et al. 2014, 1020; Rajamani 2016a).

Comparing the ozone and climate regimes

There have been numerous studies of the development of ozone science alongside negotiations to establish the ozone regime. Seminal texts include the account by the lead negotiator of the US delegation, Richard Benedick (Benedick 1998) and the detailed analysis by Parsons (2003). A further detailed and considered historical analysis of the development of the ozone regime was conducted by Grundmann (2002). The language of the ozone regime has even been studied using a 'discursive approach' in the political sciences (Litfin 1994). Meanwhile, Yoshida (2001) traced the development of the international legal regime for ozone protection, from its negotiation history, to its continuous amendment alongside evolving scientific knowledge, national implementation (in Japan) and the regime's interactions with international trade law.[34] Similarly, the Ozone Secretariat, which is hosted within UNEP and administers the ozone regime, produces regular and very detailed Handbooks for both the VCPOL (Ozone Secretariat 2019) and the MP, as amended (Ozone Secretariat 2020). The ozone regime has also been studied quantitatively, with atmospheric scientists modelling the benefits that the ozone regime has already achieved using a chemical transport model (Chipperfield et al. 2015). Projecting the ozone regime's impact into the future, several other studies used coupled chemical-climate models to compare ODS emissions pathways assuming full compliance with the ozone regime against counterfactual pathways assuming partial or no compliance with the regime, to estimate the dystopian 'world avoided' by the ozone regime (Morgenstern et al. 2008; Newman et al. 2009). These studies motivated the development of the counterfactual regime scenarios described in Chapter 4 and the comparison detailed in Chapter 5.

At the same time, the development of climate science and the climate regime has also been the subject of extensive study, from a 'history of global warming' (Weart 2008), to the expansion in international cooperation on climate science (Zillman 2009), the study of science-policy interactions within the IPCC (Skodvin 2003) and political and economic theories underlying international environmental agreements on climate change (Carraro 1999). Key components of the climate regime have also been extensively studied by international lawyers and political scientists, including Article 2 of the UNFCCC (Oppenheimer and Petsonk 2005), procedural justice rights under the UNFCCC (Tomlinson 2015) and close textual analysis of Article 6.2 of the PA in the context of previous carbon trading and emissions offsets schemes (M. A. Mehling 2018). Rajamani (2016a; 2016b) has closely considered the text of the PA to assess its 'unique' mix of 'hard', 'soft' and non-binding obligations. Although much has been said about the 'grand bargains' needed for an agreement (Benedick 1998, chap. 13), less has been said about subtleties of language and the drafting devices that have often helped to get fraught negotiations over the line, particularly during climate regime negotiations (Biniaz 2016). There is also a clause-by-clause textual history of the KP over the course of its negotiation (Depledge 2000) and there are at least two comprehensive, clause-by-clause legal commentaries on the PA (Klein et al. 2017; Van Calster and Reins 2021). Similar to Litfin's (1994) study of the ozone regime, Peck (2016) even ethnographically analysed the discourse

[34] This was more recently updated to incorporate commentary on the Kigali Amendment, among other developments since the first edition (Yoshida 2019).

around ‘carbon’ in international climate governance. The climate regime has also been studied quantitatively, with countless attempts to model potential future GHG emissions scenarios (van Vuuren et al. 2011; Riahi et al. 2011) and, more recently, the effects of different NDCs under the PA and their impacts on climate (Salawitch et al. 2017, chap. 3; Rogelj et al. 2019; Meinshausen et al. 2022). A history of predictions have also been made by political scientists and international lawyers about ‘where next?’ for the climate regime (Michaelowa, Tangen, and Hasselknippe 2005; Victor 2011; R. N. Stavins and Stowe 2016). Some of these ideas, such as a ‘carbon club’ and enhanced integration with international trade law as advocated by Victor (2011) and Carraro (2016), remain the subject of continued discussion and debate (Benson, Janardhan, and Reinsch 2022). Others have advocated for less rigid structures and more ‘clumsy’ climate governance solutions in the face of seemingly intractable issues and political differences (Verweij et al. 2006), which is arguably what the PA represents.

There has also been a great deal written about the similarities and differences between the ozone and climate regimes, including the extent to which the former could be an exemplar for the latter (Lang 1991; Morrisette 1991; Gillespie 2006; Sunstein 2007; Biniaz 2017; Grundmann 2018). Gillespie (2006) tracked the development of three international regimes for atmospheric protection, from the 1979 *Convention on Long Range Transboundary Air Pollution* to the ozone regime and finally the climate regime, from dual scientific and legal perspectives. Savaşan (2019) compared the historical development, cases of non-compliance and effects of the compliance mechanisms under the two regimes. In addition, the negotiating positions and national circumstances of key countries have also been closely studied (Grundmann 2002, chap. 4; Sunstein 2007; Kemp 2015). Analysis of the different economic circumstances and the availability of alternative technologies have been featured prominently too (Gareau 2010). Most of these detailed case study analyses turn on contextual factors (Young 2011, 19855) and certain key differences between the two regimes in their attempts to explain why the ozone regime has ‘worked’, while any comparable level of progress remains to be seen under the climate regime (Sunstein 2007; Gareau 2010; Grundmann 2018). However, there have also been attempts to quantify the interrelated impacts of the regimes, such as the unintended climate benefits of the ozone regime (Velders et al. 2007). The study by Velders et al. (2007) used ODS emissions and consumption data to determine the MP’s impacts in terms of avoided $CO_{2\text{-eq}}$ emissions and compared these significant climate benefits against the relatively modest quantitative reductions required under the KP.

Having regard to all of the above, the following ‘gaps’ in the literature can be identified:

1. There appears to be no close case study comparison between the 'binding' language used in the operative clauses of both the ozone and climate regimes, as opposed to those case studies that consider these regimes individually;

2. There appears to be a lack of analysis of the respective regime ratification data, both in terms of the number of parties and the representative contribution to overall emissions regulated by each regime; and

3. With the limited exception of the Velders et al. (2007) study, there does not appear to be much consideration of the quantitative interactions between the regimes, nor the counterfactual situations in which:

   a. the problem of anthropogenic climate change would have been tackled by the modest required reductions under a series of progressively more rigorous implementing protocols, such as was achieved under the ozone regime, by reference to the climate regime's 1990 baseline; and

   b. conversely, if the problem of stratospheric ozone depletion would *not* have been dealt with as promptly as it was and instead a series of less rigorous required reductions was imposed, by reference to the ozone regime's 1986 baseline.

These identified gaps led to the development of the following aims and hypotheses for further investigation by this thesis.

4 Aims & Hypotheses

4.1 The Montreal Protocol as a blueprint

The MP has been praised an 'extraordinary and even spectacular success story' in international environmental law (Sunstein 2007), but this success was not inevitable. After seminal studies by Bates and Nicolet (1950b), Crutzen (1970) and Molina and Rowland (1974), the VCPOL was agreed in March 1985. Urgent international action soon followed, after the staggering discovery of the 'ozone hole' by Farman et al. (1985) and further scientific investigation into stratospheric ozone depletion (Titus, EPA, and UNEP 1986), which led to the MP1987 in September 1987. The Protocol has since been amended five[35] times in line with evolving scientific understanding and the state of available alternative chemical compounds to replace ODS in industrial applications. Encouragingly, ODS emissions have decreased significantly, ODS concentrations peaked around the turn of the century (WMO et al. 2019) and observations now suggest that the ozone layer is 'healing' (Solomon et al. 2016).

Meanwhile, over a comparable timeline, scientific evidence has accumulated for an anthropogenic enhancement of the greenhouse effect due to the emission of well-mixed greenhouse gases (Callendar 1938; Keeling et al. 1976). The ozone and broader climate issues are not only linked by physico-chemical processes (Newman 2018); the architecture of the international climate protection regime has developed by analogy with the ozone protection regime (Sunstein 2007). Since the UNFCCC was concluded in 1992, further milestones have been achieved with the KP in 1997 and the PA in 2015. However, in contrast to the ozone protection regime, the climate protection regime does not show a comparable level of success to date in reducing emissions of non-ODS greenhouse gases (GHG), particularly CO_2 (Sunstein 2007).

This thesis will therefore investigate the language used in the operative provisions of each regime, in an attempt to shed light on the mixed success of the regimes. Such close analysis should enable a deeper, critical comparison between the regimes, particularly when discussed in the context of the different factual matrix surrounding each regime.

4.2 Ratification rates

Inspired by Sunstein's (2007) simple observations about the inverted roles played by powerful States (i.e., the USA and EU Member States) in the origins of the ozone and climate

[35] 1990 London Amendment; 1992 Copenhagen Amendment; 1997 Montreal Amendment; 1999 Beijing Amendment; 2016 Kigali Amendment.

regimes, part of this thesis considers the ratification rates under each regime to investigate whether there are more nuanced patterns in the ratification data for each regime that may shed further light on their mixed 'effectiveness'. This seems particularly relevant given the significant 125% increase in UN Member States since 1990, which parallels the period of establishment and further development of these regimes.

Alongside the number of party ratifications to the implementing agreements, analysis of those parties' proportionate relative contribution to global consumption of ODS and emissions of GHG, respectively, may reveal further insights about the relative efficacy of these regimes.

Finally, analysing the ratification data in terms of the pattern of development and interval between agreements under each regime should serve as a useful analogy for the future development of the climate regime, given its new trajectory under the PA.

4.3 Text-as-data analysis

Together with the ratification data and inspired by Sunstein's (2007) comparison once again, in the context of a growing literature in comparative text analysis using machine learning techniques, this thesis will also investigate the degree of variance between the two regimes using text-as-data techniques. However, as context is often essential in textual analysis of legal documents (Spirling 2012), manual close textual comparison and legal analysis will be the primary techniques used, with the text-as-data analysis playing a complementary role.

4.4 Implementation of Paris Agreement

There is a need to place recent developments in the implementation of the Paris Agreement into broader context. The election of the Biden Administration and the USA's re-signing of the PA has reinvigorated waning hopes for the PA under the previous administration. In the lead up to COP26 to the UNFCCC in Glasgow, many developed countries submitted updated NDCs and significant political momentum was amassed among developed countries committing to 'net zero' GHG emissions by 2050. As implementation of the PA continues and ahead of its first 'global stocktake' due to be conducted in 2023, this is therefore an opportune time to compare progress. Having regard to the regimes' differing degrees of success discussed in 4.1 above, a novel opportunity presents itself to compare and contrast the reductions achieved in ODS consumption under the ozone regime with those achieved in GHG emissions under the climate regime. Further, comparison with the regimes' historical ratification data may put the PA's five-year NDC schedule into perspective, amid calls by the UN

Secretary-General for countries to rapidly speed up this process to a system of annual pledges until the 1.5°C global average temperature goal is achieved (Sengupta 2021).

4.5 Research questions and hypotheses

For all of the above reasons, the following research questions and hypotheses have been devised and will be investigated in detail in this thesis.

1. How do the operative clauses of the Montreal Protocol (with its London (1990), Copenhagen (1992), Montreal (1997) and Beijing (1999) amendments) compare to the Kyoto Protocol and Paris Agreement?

   H_0: The Montreal Protocol and its amendments (in 1) contain more rigorous and binding obligations over time than the Kyoto Protocol and Paris Agreement.

2. How does the party ratification rate, in terms of number of parties but also parties' share of global ODS / GHG emissions, compare between the Montreal Protocol (with amendments in 1), and the Kyoto Protocol and Paris Agreement?

   H_0: Party ratification rates differ widely between the Montreal Protocol (with amendments in 1) and the Kyoto Protocol and Paris Agreement, in terms of both the number of ratifying parties and their share of global ODS / GHG emissions.

3. How would global GHG emission trajectories develop under 'theoretical' emission rates comparable to the ODS emissions reductions achieved under the Montreal Protocol (with amendments in 1)?

   H_0: Global GHG emissions would drop sharply over the next three decades and lead to compliance with the primary goals of the Paris Agreement.

4. How would global ODS emissions have otherwise evolved, assuming (counterfactual) similar ratification rates and emissions as observed for GHGs under the Kyoto Protocol and Paris Agreement?

   H_0: Global ODS emissions would have increased, leading to widespread stratospheric ozone loss on a global scale.

5 Methods

This thesis investigated the ozone and climate protection regimes as a comparative case study using mixed methods, as detailed further below. The analysis consisted of three broad stages: legal textual analysis, supported by text-as-data methods; analysis of party ratification rates and representative emissions data, and; emissions scenario development and analysis.

5.1 Legal analysis

Firstly, the texts of the relevant agreements were analysed using the accepted interpretation practices of international law, based on Section 3 of the *Vienna Convention on the Law of Treaties 1969* (VCLT). This was necessarily contingent on the fundamental presumption that all of the agreements under study here, particularly the PA,[36] satisfied the definition of a 'treaty' under the VCLT (1969, Art 2(1)(a)). As such, every treaty is 'binding upon the parties to it and must be performed by them in good faith' (VCLT 1969, Art 26). However, this does not mean that every clause in a treaty must be interpreted as binding (Bodansky 2016). Rather, the nature of States' obligations under a treaty are a function of the nature of any given provision, which must be determined by interpretation (Ghaleigh 2021, 81). Further, the essential nature or character of any provision is substantially a function of the particular verb deployed (Ghaleigh and Verkuijl 2021, 102; Bodansky 2016).

Having made these preliminary assumptions, the VCLT provided for the following approach to interpretation, in accordance with the provisions of Articles 31 to 33:

1. The treaties were interpreted in good faith, in accordance with the ordinary meaning of the terms used in the treaty, having regard to context and in light of the treaty's object and purpose. This is the general rule of treaty interpretation and it is 'very deliberately' intended to be a single rule in which equal use is made of the 'ordinary meaning', 'context' and 'object and purpose' in interpreting any treaty (Ghaleigh 2021, 78; ILC 1966, 219–20).

2. Supplementary means of interpretation, including reference to the preparatory materials (*travaux préparatoires*) and other contemporary records from the time that the agreements were negotiated, were considered only in the event of ambiguity. However, it was noted that such materials can be incomplete or misleading (ILC 1966, 220). In reality, to the extent that these materials were consulted, this was for the purpose of informing discussion of the results, rather than in undertaking the primary interpretive task.

[36] Despite previous conjecture, it is now settled that that PA is a 'treaty' for the purposes of the VCLT (Ghaleigh 2021, 84; Bodansky 2016).

3. Despite Article 33 of the VCLT, only the English language versions of the ozone and climate regime treaties were compared. This was simply due to the linguistic limitations of the author and it was not intended to elevate the English version above any of the six equally authentic versions in the official languages of the United Nations.[37] To that end and in the context of Article 4(2) of the PA, Mayer (2021, 126) notes an interesting discrepancy in the use of commas in at least two of the six official language versions of the PA, which highlights a potential limitation of this approach.

Meanwhile, to enable comparative analysis across the different regimes and treaties, a hierarchy of verbs was developed, based on verbs frequently used in the agreements under study and in other international agreements. Consistent with widespread theory and practice, this adopted a 'sliding scale' of prescriptiveness or 'bindingness' (Bodansky 2016, 145; M. A. Mehling 2018, 32–33; Ghaleigh and Verkuijl 2021, 102), as shown in Table 4 below. This extends from the use of verbs that are prescriptive ('undertake', 'shall'), to the more recommendatory ('should', 'encourage'), to the permissive ('may') and finally to the aspirational ('will', 'can', 'strive') (Bodansky 2016, 145; Garner 1995; Ghaleigh and Verkuijl 2021, 102).

Table 4: Hierarchy of verbs used in comparative legal analysis

		Regime agreement and Article reference (example)		
More binding	**Verb**	**MP**	**KP**	**PA**
	undertake	Art 4(5)	(not used)	Art 3
	shall	Art 2A(1)	Art 3(1)	Art 4(1)
	should (recommendation)	Art 2(9)	Art 10(e)	Art 4(4)
↓	encourage	Art 10(6)	(not used)	Art 4(4) ('are encouraged')
	may (provided that)	Art 2(5)	Art 3(4)	(not used)
	may (permissive)	Art 2(11)	Art 6(3)	Art 7(9)
Less binding	will	Art 6	Art 12(3)(a)	Art 4(3)
	can (capable of)	PP3, 7	(not used)	Art 4(7)
	can (permissive)	(not used)	Art 12(10)	(not used)
	strive	(not used)	Art 2(3)	Art 4(19)

[37] Nor was it intended to further concentrate study of the climate regime in the authorship of a small subset of affected parties, not reflective of the full diversity of negotiating groups and geographical regions within the UN system (Mehling 2018, 30).

This hierarchy was taken to be the default 'ordinary and natural meaning' of these verbs, for the purposes of the three-pronged approach to interpretation described above. However, when applied together with the two other interpretive techniques described above, namely the 'context' and 'object and purpose', it was clear that the meanings suggested by this hierarchy were not fixed. This only served to reinforce the importance of treating the three prongs as equally important tools in the interpretative process.

Having regard to all of the above, particularly the general rule to interpret a treaty in good faith based on the ordinary meaning of its terms, the provisions of the treaties of the ozone and climate regime were then analysed accordingly.

5.2 Text-as-data methods

In recent years, advances in programming and machine learning have led to a growing field in 'text-as-data' and 'natural language processing' studies (Gentzkow, Kelly, and Taddy 2019). This has identified the law as a field that warrants further investigation using such methods (Gentzkow, Kelly, and Taddy 2019, 568–69) and has spurred the development of applied 'natural language processing' tools for use in legal practice (Bommarito II, Katz, and Detterman 2018). Of particular relevance in the field of legal analysis are the studies of international trade and investment agreements by Alschner and Skougarevskiy (Alschner and Skougarevskiy 2015; 2016b; 2016a; Alschner, Seiermann, and Skougarevskiy 2017), which recently culminated in a new database (Alschner, Elsig, and Polanco 2021). Those studies analyse and compare the text of international trade agreements in search of patterns in the language used to determine whether a 'stronger' trading partner has managed to bring their preferred language to bear in the final agreement, i.e., whether a country is a 'rule-taker' or a 'rule-maker' (Alschner and Skougarevskiy 2016a). More specifically, those studies compare the 'Jaccard distance' between the agreements under study, developed by Paul Jaccard to compare distributions of alpine flower species (Jaccard 1901). In simple terms, the method involves comparing the number of observations common to two (or more) samples, with the total number of observations in either (or all). 'Jaccard similarity' can be expressed as:

$$J_{(A,B)} = \frac{|A \cap B|}{|A \cup B|}$$

Similarly, the 'Jaccard distance' is simply $1 - J_{(A,B)}$. The result (in either 'similarity' or 'distance') ranges from 0 to 1, where a Jaccard distance score closer to 0 indicates greater similarity between texts and a score closer to 1 indicates greater dissimilarity, with the score signal reversed for 'similarity' results (Alschner and Skougarevskiy 2015, 9; 2016a, 6).

All of these techniques rely on the 'tokenisation' or vectorisation of every word in the text of an agreement, often using a 'bag-of-words' approach, which creates a 'document-term matrix' (DTM) of all words ('tokens') across all of the input documents (Manning, Raghavan, and Schütze 2009, 117; Grimmer and Stewart 2013, 7–8).

However, inputs must be carefully managed to avoid the removal of frequently used keywords that are essential to interpreting legal context (Alschner and Skougarevskiy 2015, 11). When used to define certain strings of characters in a text with *x*-length and/or compared against the text of national template agreements and negotiating drafts, this technique can be used to infer the 'consistency' and 'innovation' (i.e., change) in a country's use of language across time (Alschner and Skougarevskiy 2015, 5–6; 2016a, 6).

As at the date of this thesis, no similar comparative initiative appears to have been made in the field of international environmental law, despite a large (and growing, refer Figure 10) corpus of MEAs. Several extensive databases could provide the full-text data for a similarly comprehensive comparative research project, such as the *Ecolex*[38] and *InforMEA*[39] databases, the *Environmental Conventions Index* (Escobar-Pemberthy and Ivanova 2020), or the International Environmental Agreement Database (IEADB) (Mitchell et al. 2020).

The above techniques were utilised to generate basic 'text-as-data' results using the 'text mining' package in the data mining software Orange® (v3.32.0) (Demšar et al. 2013), which uses the Python programming language (Van Rossum and Drake Jr 1995). Orange was chosen for its user-friendly interface and the applicable 'Workflow' (in '.ows' format) used to generate the text-as-data results in Chapter 6 is available at the following link: https://phaidra.univie.ac.at/o:1536359. The Workflow file requires the plain text of the original agreements to first be downloaded and converted to plain text ('.txt'). The texts of the original MP1987 and all of the Amendments (LDN1990, CPN1992, MON1997 and BEI1999) were obtained from the Handbook to the MP (Ozone Secretariat 2020, secs. 5.2, 5.4-5.7). For the purposes of a clean comparison with the MP1987, the consolidated text of the MP as amended by the Amendments up until the year 2000 (MP2000) was also obtained and converted to plain text. The plain text for the MP2000 was obtained from UNEP (2000). Meanwhile, the plain text for the KP and the PA were obtained from the *EcoLex* database. Relevant links are provided in the description to the '.ows' Workflow file: https://phaidra.univie.ac.at/o:1536359.

[38] Jointly administered by the International Union for the Conservation of Nature, United Nations Environment Programme, and the Food and Agriculture Organisation of the United Nations.
[39] https://www.informea.org/en.

In generating these data, a custom list of 'stopwords' for removal from the text 'corpus' was used, which consisted of Orange's standard list of English stopwords based on the Natural Language Toolkit (NLTK) list of English stopwords (Bird, Klein and Loper 2009). However, this list was adapted to the context of these agreements (e.g. to remove internal references within each agreement, such as 'article', 'agreement', 'convention', 'entry' 'into' 'force' and 'signature', as well as days, dates, months, years, locations etc.). The full list of 'stopwords' is available in the file 'Remove.txt' at this link: https://phaidra.univie.ac.at/o:1536383.

5.3 Party ratification rates

Ratification date data for each of the agreements (and amendments) under study here were obtained from tables on the *EcoLex* database,[40] as detailed in the data description at this link: https://phaidra.univie.ac.at/o:1536414. Only entry into force (EIF) and ratification date data were extracted, as 'Signature date' data were incomplete and, in any event, of limited legal effect.[41] The tabulated EIF and ratification dates were then imported to Microsoft Excel (refer 'Consolidated Ratification Data.xlsx' at the link above).

The *EcoLex* data for *EIF dates* were in the format 'Mon DD, YYYY' (e.g. Jun 17, 2004). As such, Excel did not recognise these data as a date and so the '=DATEVALUE()' formula was used, as follows:

1. '=DATEVALUE(MID(XX,5,1)&'-'&LEFT(XX,3)&'-'&RIGHT(XX,4))' (for a date with a single (1) digit day date); and
2. '=DATEVALUE(MID(XX,5,2)&'-'&LEFT(XX,3)&'-'&RIGHT(XX,4))' (for a date with a double (2) digit day date),

where XX indicate the relevant reference cells.

Meanwhile, the *ratification dates* were in the format 'Jun 17, 2004 [2]', where the number in square brackets, '[2]', indicated one of the four different modes of ratification available to States.[42] Since Article 2(1)(b) of the VCLT provides that any of these forms of ratification are equally effective, this reference was removed using the Excel 'Text to Columns' tool. With ratification dates then in the format '| Mon | DD | YYYY |', these data across 3 columns were converted to a single column/cell, using the formula: '=XX&'/'&YY&'/'&ZZ', where XX = |Mon|, YY = |DD| and ZZ = |YYYY| columns. These data were then in the same format as the EIF dates and converted as above using the '=DATEVALUE()' formula.

[40] https://www.ecolex.org/.
[41] See, for example, the US' bare signature of the KP, but its failure to ever ratify that agreement.
[42] Being 'ratification', 'acceptance', 'approval' and 'accession', refer Article 2(1)(b) of the VCLT.

In the case of the PA, the EIF and ratification date data were cross-checked against the UN Treaty Series database,[43] since recent ratifications by Iraq and Turkey had not yet been reflected in the *EcoLex* database. These data were manually added once imported to Excel.

The corresponding baseline emissions data (see 5.4 below) were then copied into the same Excel spreadsheet, alongside the relevant regime dates. That is, the 1986 ODS consumption data were copied into a new column after the ozone regime EIF and ratification dates; then the 1990 GHG emissions data after the KP dates; and finally, the 2015 GHG emissions data after the PA dates. With the data in this format, a PivotTable could then be created for every year from 1988 to 2021, showing the number of countries that had ratified each agreement in a given year and the corresponding cumulative percentage of ODS consumption, across all agreements. This PivotTable is included in the Worksheet labelled 'Pivot_Ratifications' in the 'Consolidated Ratification Data.xlsx' file.[44]

The PivotTable data were then used to isolate the corresponding cumulative emissions data, as a percentage, and the count of ratification dates, by year and across the agreements. Since each of these datasets were expressed per year and were non-cumulative, the running totals were calculated in separate tables and the results were graphed in Figure 16.

5.4 Emissions data

For the data discussed in sub-Chapters 5.4 and 5.5 below, refer to the 'Scenarios_consolidated_final.xlsx' file, available at this link: https://phaidra.univie.ac.at/o:1536416.

5.4.1 ODS consumption data

The ozone regime regulates ODS production and consumption,[45] imposing agreed reduction schedules on each class of ODS over multiple years. Under the reporting requirements established by the MP, every party must estimate its baseline 1986 ODS consumption figures, together with data for every subsequent year since it ratified the MP. Accordingly, a reasonable dataset exists with an established regime baseline, which can be used as a proxy for ODS emissions (Liang et al. 2008, 3), using emissions factors (EF) and release factors (RF) from 'banks' of ODS in refrigeration units, insulation foams etc (Lickley et al. 2020).

Data on ODS consumption were downloaded from the United Nations Environment Programme (UNEP) and Ozone Secretariat's data centre.[46] The data are available in ozone-depleting potential (ODP) tonnes or CO_2-eq tonnes and can be downloaded in various formats

[43] https://treaties.un.org/Pages/AdvanceSearch.aspx?tab=UNTS&clang=_en.
[44] Available at this link: https://phaidra.univie.ac.at/o:1536414.
[45] Which itself is defined to include 'production'.
[46] https://ozone.unep.org/countries/data-table

using the data centre filter tools. The data were downloaded in three tranches as totals, in ODP tonnes, for the following groups from 1986 to 2020: annual global totals, annual totals for Article 5 (developing country) parties and annual totals for Non-Article 5 (developed country) parties. Appropriate filters were selected to limit the data variously to: the timeframe '1986-2020' (data for the 1986 baseline year were included, as well as the continuous time series from 1989 to 2020); the global total and the totals for the two classes of parties ('Article 5' [developing country] parties and 'Non-Article 5' [developed country] parties).

All data were downloaded in ODP tonnes[47] and the output was grouped by Annex group (i.e., by ODS), from A/I to E/I. Annex F data (which relates to hydrochlorofluorocarbons (HFCFCs) regulated by the Kigali Amendment to the MP) were deleted. In cross-checking the sum of the A5 and NA5 totals against the global total, an inexplicable discrepancy of +67.5 ODP tonnes was discovered in the year 2020 (i.e., the individual A5 and NA5 data summed to 67.5 ODP tonnes more than the global total). This represents an error of just ~0.7% (compared to either total) and as it was confined to the 2020 data only, it was ignored.

There were several countries that featured in both the list of Article 5 (developing) and Non-Article 5 (developed) country parties over the length of the extracted time series (1986, 1989-2020). These countries are listed, together with their recategorization on the basis of which class they belonged to for the majority of the time series according to their ODS consumption reports, in Table 5 below.

The ODS consumption data were then imported to Microsoft Excel and manipulated to develop the party ratification rate and counterfactual emissions scenarios data, as described in 5.5 below. Consistent with the recategorization above, a new column was added to the ODS consumption data series and the countries were labelled as A5/NA5 parties accordingly.

Table 5: List of countries recategorized for purposes of ODS consumption data

Country	Recategorized to class (A5 / NA5)
Armenia	NA5
Brunei	A5
Bahrain	A5
Cyprus	A5
Georgia	A5
Kuwait	A5

[47] A single filter option offers two forms of output: 'ODP tonnes or in CO2-eq tonnes'. Reasoning by deduction, comparing the output data with comparable data in the literature and noting the conversion factor of 1 ODP tonne = 4750 CO2-eq tonnes (for CFC-11)(http://www.ozonaction.org/GWPODPCalculator/), it was deduced that the data were in ODP tonnes.

Country	Recategorized to class (A5 / NA5)
Kyrgyzstan	NA5
Malta	A5
Moldova	A5
Palau	A5
Saudi Arabia	A5
Singapore	A5
Slovenia	NA5
South Africa	A5
Republic of Korea	A5
Turkey	A5
Turkmenistan	NA5
United Arab Emirates	NA5

5.4.2 GHG emissions data

Data on global GHG emissions, in $MtCO_{2\text{-eq}}$, were downloaded from the Global Carbon Atlas[48] for the period 1964 to 2019 (Friedlingstein et al. 2020). The data were limited to this period to minimise the impact of any confounding effects from the ongoing COVID-19 pandemic, the disruptive effects of Brexit on common EU GHG emissions/ODS consumption reporting, as well as the US withdrawal from and re-entry to the Paris Agreement.

The GHG emission data were imported to Microsoft Excel and were manipulated as follows. The data were transposed with rows as country names and columns as years. Country names were rationalised using a common sense approach that was consistent with the 193 recognised Member States of the UN, while also striving for consistency with Article 29 of the VCLT.[49] Accordingly, data from non-UN Member State countries and overseas territories were re-allocated and added to the annual totals reported for the most relevant 'parent' State, as shown in Table 6 below.

[48] http://www.globalcarbonatlas.org/en/CO2-emissions.

[49] VCLT Art 29: '*Unless a different intention appears from the treaty or is otherwise established, a treaty is binding upon each party in respect of its entire territory.*'

Table 6: GHG emissions re-allocated from countries to recognised UN Member States

Country*	**UN Member State to whom country emissions re-allocated**
Anguilla	UK
Aruba	The Netherlands
Bermuda	UK
Bonaire, Saint Eustatius and Saba	The Netherlands
British Virgin Islands	UK
Curaçao	The Netherlands
Faeroe Islands	Denmark
French Polynesia	France
Greenland	Denmark
Hong Kong SAR China	UK+; later China#
Macao	Portugal
Montserrat	UK
New Caledonia	France
Occupied Palestinian Territory	Israel
Saint Helena	UK
Saint Pierre and Miquelon	France
Taiwan	China
Turks and Caicos Islands	UK

*In re-allocating these emissions to the relevant UN Member State in the column at right, the author does not purport to 'take a side' in ongoing territorial tensions between countries, nor seek to legitimise neo-colonial or occupation policies of the relevant UN Member State.

+HK SAR data reallocated to UK from 1960 to 1996 and then 50% of 1997 emissions. This reflects the Handover from the UK to China, effective at midnight on 1 July 1997.

#HK SAR data reallocated to China: 50% of 1997 emissions and then from 1998 to 2019. This reflects the Handover from the UK to China, effective at midnight on 1 July 1997.

In addition, the following countries, for which no data were reported, were removed from the list: Cayman Islands, Falkland Islands/Malvinas, French Guiana, Gibraltar, Guadeloupe, Kosovo, Martinique, Réunion, Wallis and Futuna Islands, and Western Sahara.

5.5 Development of hypothetical emissions scenarios

To quantitatively visualise and to compare and contrast the 'effectiveness' of the ozone and climate regimes, two hypothetical and counter-factual emissions simulations were developed. In essence, these simulations set out to consider:

1. *How would global GHG emission trajectories develop under 'theoretical' emission rates comparable to the reductions in ODS consumption achieved under the MP (with Amendments)?*

2. *How would global ODS consumption (and ultimate emissions) have otherwise evolved, assuming (counterfactual) similar ratification rates and emissions as observed for GHGs under the KP and PA?*

These hypothetical alternative emissions simulations, consisting of several different emissions scenarios based on the reduction schedules imposed by the respective regimes, were developed as follows.

5.5.1 GHG emissions simulation

This simulation applied the *ozone regime's* scheduled reductions in global ODS consumption relative to the 1986 baseline, to *global GHG emissions* relative to the 1990 baseline. In doing so, global ODS consumption figures were used as a proxy for ultimate global ODS emissions and the reductions achieved in ODS consumption relative to 1986 figures were simply applied, as a proportionate change, to GHG emissions. The scenario data are included in the 'NA5 Scenarios' and 'A5 Scenarios' Worksheets in the 'Scenarios_consolidated_final.xlsx' file.[50]

The ozone regime imposed reductions by class of ODS, or annex-by-annex, over time. These reductions are summarised in Table 22 and Table 23 below for NA5 (developed) and A5 (developing) parties, respectively. Since the ozone regime imposed its respective reductions on the parties in these two distinct classes, with differing baselines and reduction schedules, the scenarios were developed separately for the NA5 parties and the A5 parties, and then combined into overall, regime-wide scenarios. Nevertheless, the dynamic development of the ozone regime inspired a general approach that was common to all scenarios. The general approach is explained first, with certain other factors unique to a particular scenario then clarified below.

[50] Available at this link: https://phaidra.univie.ac.at/o:1536416.

5.5.2 General approach

Firstly, a hypothetical 'no regime' worst case scenario was developed as a reference point for all scenarios. First, the 1986 baseline ODS consumption data for each class of party (A5/NA5) was imported to Excel. Data were grouped by the nine MP Annexes / classes of ODS in separate rows and extended over time in separate columns from 1989 to 2040.[51]

The general approach was to take the 1986 baseline data and apply growth assumptions similar to Velders et al. (2007). Thus, the CFCs (Annex A, Group I) were increased by between 3% and 7% annually, while all other ODS were increased by up to 3% annually (Velders et al. 2007). However, the essence of the ozone regime is that it has evolved over time. This dynamic development can be simplified in broad terms as follows: new substances were developed by the chemical industry; these new substances found industrial applications (e.g., in fridges, foams); the substances were released to the atmosphere; atmospheric scientists found that the new substances had ozone-depleting potential; scientists and policymakers worked to calculate the ODP of the new ODS and develop realistic reduction or phaseout pathways with industry.[52] Thus, additional ODS were added to the ozone regime in additional MP Annexes over time.

By reference to the 1986 baseline, this means that some ODS, which would later be produced in large volumes, were produced only in small volumes or not at all in 1986. As a work-around in developing the 'worst case scenario', the maximum ODS consumption value for each Annex / class of ODS was located within each time series. Where this maximum occurred at the start of the time series (i.e., in 1986 or 1989), this value was simply increased for the reasons above by between 100% and 107% from 1986/1989 until 2040, using the '=RANDBETWEEN()' formula in Excel.[53] These cells are shown shaded in grey in the screenshot in Figure 11, below. However, where there was a 'gap' between 1986 and the year of maximum ODS consumption, the 1986 figures were increased linearly until the maximum. These cells are shown shaded in white in Figure 11, below. Then, in the year after the maximum and every year after that until 2040, the values were increased by between 100% and 107%, as above.

[51] No data 1987-1988. For the agreements under study here, the latest required reduction for A5 parties was the 1997 Vienna Adjustment's required net zero reduction in Annex C Group I substances by 1/1/2040 (later brought forward by the 2007 Montreal Adjustment). Accordingly, all other scenarios were extended to this year (2040) to optimise scenario comparison.
[52] In reality, these sequential steps were often occurring simultaneously and dynamically, as the different ODS were developed.
[53] The formula requires lower and upper bounds to be specified, within which Excel will randomly generate numbers. Accordingly, for CFCs, the lower bound was 103% and the upper bound was 107% of the immediately preceding cell, starting from the 1986/1989 ODS consumption figure and extending until 2040. For any other ODS, the lower bound was the immediately preceding cell (i.e., 100%) and the upper bound was 103% of that cell.

Figure 11: Screenshot from 'NA5_NR' scenario development

	A	B	C	D	E	F	G	H	I	J	K
36	**NA5_NR**			**1986**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**
37	3-7% increase (total)	**Total:**		**1138526**	**1398692.3**	**1491489**	**1574527**	**1657464**	**1766001**	**1858035**	**1935967**
38											
39	Velders et al. (2007)	**Annex Group**	**Annex Group Nam**	**1986**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**
40	3-7% / yr increase	A/I	Chlorofluorocarbo	957557.9	1009065	1047242	1102683	1166787	1230651	1308937	1371221
41	3% / yr increase	A/II	Halons	180963.8	184800	190057	190167	195515	198360	203286	206706
42	Linear to max. + 3% / yr increase	B/I	Other Fully Haloge	0	3987.5	4032	4115	4127	4202	4311	4381
43	Linear to max. + 3% / yr increase	B/II	Carbon Tetrachlor	0	261966.8	263700	268869	275428	278197	278780	282028
44	Linear to max. + 3% / yr increase	B/III	Methyl Chloroform	0	61020.5	61366	61398	62261	62980	63568	64131
45	Linear to max. + 3% / yr increase	C/I	Hydrochlorofluoro	2.8	4128.128571	8256.257143	12384.38571	16512.51429	20640.64286	24768.77143	28899.7
46	Linear to max. + 3% / yr increase	C/II	Hydrobromofluoro	0	0.4	0.8	1.2	1.6	2	2.4	2.8
47	Linear to max. + 3% / yr increase	C/III	Bromochlorometha	0	0.653846154	1.307692308	1.961538462	2.615384615	3.269230769	3.923076923	4.576923077
48	Linear to max. + 3% / yr increase	E/I	Methyl Bromide (M	1.5	11503	23006	34510.5	34947	35629	36685	37539
49		**Total:**		**1138526**	**1536472**	**1597661**	**1674130**	**1755582**	**1830665**	**1920342**	**1994913**

Note that whereas Velders et al. (2007) applied fixed 103% or 107% increases, the use of the '=RANDBETWEEN()' function in the manner described above resulted in random increases, in the range of 103-107% (for CFCs) and 100-103% (for all other ODS).

The 'no regime' data were then copied into the cells for all subsequent scenarios as a 'default' value, unless replaced by other data for the reasons detailed below. As such 'default' data, all subsequent entries of these data points were greyed out in the subsequent scenarios (refer Figure 12, below).

The next step was to impose the ozone regime's required reductions under each agreement, amendment or adjustment on the worst case scenario data. This involved applying the relevant reduction in ODS consumption, by reference to the relevant baseline figure, in the relevant reduction year. That is, for each scenario, the required reductions from Table 22 or Table 23 were converted to a proportion (e.g. 80% = 0.8) and multiplied by the corresponding baseline ODS production figure for each Annex / class of ODS (e.g. Annex A, Group I, CFCs). Each result was entered in a cell corresponding to the reduction year, representing the minimum required reduction in consumption of that ODS by that year under the ozone regime.

All data preceding this required reduction were simply the 'default' values from the 'no regime' worst case scenario. Thus, a distinction was made between data *preceding* a reduction year and data *following* a reduction year. Note that the MP1987 originally required reductions on and from various dates partway through the reduction year. This was changed to full calendar years in the 1990 London Amendment[54] (and all subsequent amendments). Given that the ODS consumption data is annualised, all required reductions across all scenarios were adjusted to apply to the data for the full year in which the reduction was to take effect.

The distinction between reduction years is indicated by the black borders dividing the cells in each scenario (see Figure 12 below, at the boundary between 1986-1989 and 1991-1992 for the MP1987 scenarios). The required reductions are indicated as the figures in bold on the *right hand side* of the regime 'border'. Over time and across scenarios, the 'border'

[54] Refer Table 22 and Section 5.3 of the *Handbook to the Montreal Protocol* (Ozone Secretariat 2020, 866).

representing the development of the ozone regime encroaches further into the ‘no regime’ data, reducing cumulative ODS consumption figures in each successive scenario. Meanwhile, the data to the right of the ‘border’ (and therefore regulated by the regime) were typically subjected to linear reductions between required reductions, with exceptions to that general rule, as further discussed in relation to each scenario below.

Figure 12: Screenshot from NA5_MP1987 scenario development

36	MP (1987) scenario	Annex Group	Annex Group Nam	1986	1989	1990	1991	1992	1993	1994	1995
37	1986	A/I	Chlorofluorocarbon	***957557.9***	**957557.9**	909680.005	861802.11	813924.215	**766046.32**	716542	347349
38		A/II	Halons	***180963.8***	192949	197638	189295	**180963.8**	47663	159171	99190
39		B/I	Other Fully Haloger	***0***	687	3877	3486	528	3797	894	464
40		B/II	Carbon Tetrachloric	***0***	251895	162796	271251	158879	221882	14675	185907

Finally, as more information came to light to better inform the policymaking process, further agreements were negotiated under the ozone regime. To reflect this dynamic state of knowledge and evolution of the regime, real world consumption data were added to each successive scenario, on the *left hand side* of the regime ‘border’ (refer bold and italicised black font in column ‘1986’, in Figure 12). The added real world data is shown in ***bold italic*** font to distinguish it from the simulated[55] data points, which is shown in grey font.

The amount of real world data added depended on the date of the agreement that was the subject of that scenario. Only that real world data that would have been available at the time of the relevant agreement was used. Despite evidence of unexplained discrepancies and historical revisions being made to UNEP’s ODS consumption data (McCulloch 2005), this necessarily assumed that all States provided accurate and timely national data for the year preceding the date of the agreement.[56] It follows that for the ‘CPN_1992’ scenarios, for example, only the real world consumption data up until the end of 1991 were added.[57] The effect of adding this real world ODS consumption data is to further reduce the cumulative ODS consumption figures in each successive scenario. This is because the real data tended to achieve much greater reductions in ODS consumption than either the ‘maximum’ simulated in the ‘no regime’ scenario, or the ‘minimum’ reduction required by the ozone regime.

Taken together, these three broad steps in the scenario development process serve to ‘model’ the development of the ozone regime. The 1986 baseline data and the assumptions of Velders et al. (2007) simulate how expansive ODS consumption could have been from 1989 to 2040. Then the dual effect of adding real world data to fill in the knowledge ‘gap’, as it

[55] Regardless of how this data is generated, following the assumptions of Velders et al. (2007) or linearly or randomly inter- and extrapolated, all such data is shown in grey.
[56] The ozone regime requires all State parties to report production, import and export data for each controlled ODS no later than nine months after the end of the year to which the data relate (see Article 7(2) of the MP1987). Notwithstanding the nine month deadline and the fact that the London Amendment was dated 29 June 1990, it is assumed that all national data for 1989 were available during the negotiation of that agreement.
[57] Despite the Copenhagen Amendment being dated 25 November 1992, it is assumed that no portion of the data for 1992 was available at the negotiations on that agreement.

would have become available, and expanding the 'border' of the ozone regime in response to that knowledge leads to progressively greater reductions in total ODS consumption, as the scenarios develop in time and relative to one another. In other words, more information about ODS consumption became available and new (or further) limits were placed on the different ODS, accordingly. This was the manifest purpose and much vaunted process (Benedick 1998) through which the ozone regime developed over time.

Dynamic data

An important consequence of the use of the '=RANDBETWEEN()' formula in Excel is that the resulting datapoints are dynamic. Every time that the document is saved or edited, all of the randomly generated datapoints shift within their defined ranges. Thus, all ODS scenario data, except for those based on real-world data, are in a state of flux and the results therefore represent a 'snapshot' of the scenarios at a particular time. This must be kept in mind in discussing the results. For consistency, a 'snapshot' of the data was taken at 16:45 on Wednesday 11 May 2022 and saved as a new Excel spreadsheet ('Scenarios_consolidated_final.xlsx'[58]). This dataset is used throughout the results and discussion in Chapter 6.

Approach to NA5 scenarios

Once again, the relevant baselines and required reductions for NA5 parties are summarised for each Annex / class of ODS and each relevant agreement of the ozone regime in Table 22. Applying these reductions using the general approach described above resulted in eight scenarios for the NA5 parties, as further described below.

Each scenario envisaged the required reductions as 'gates' governing the subsequent trajectory of the scenario. It follows that, once the first 'gate' had been imposed, this determined the upper boundary for the scenario's subsequent trajectory. Likewise, the lower boundary of the trajectory was determined by reference to the next required 'gate', if applicable, in which case a linear decrease was generally applied between 'gates'. However, if no subsequent 'gate' was imposed (e.g., after 1993 for Annex A/I ODS in the MP1987 scenario), then the lower boundary was simply set to zero and values were randomly generated between zero and the maximum imposed by the last reduction 'gate'.

The 'Notes' column in the summary tables included for each scenario below indicate whether a particular scenario resorted to linear or random inter- and extrapolation, and for

[58] Available at this link: https://phaidra.univie.ac.at/o:1536416.

what time intervals (years) these techniques were used. If random generation was used, the lower and upper bounds are stated by reference to ODS consumption values in a given year.

1. '***NA5_reality***'

This is simply the real ODS consumption data for the period 1989-2020, as a reference scenario. It includes the 1986 baseline data, but there is no national data for 1987 and 1988.

2. '***NA5_NR***'

This is the counterfactual 'no regime' worst case reference scenario, consistent with regime effectiveness theory (Young 2011). It starts with 1986 baseline data and extends to 2040, applying similar assumptions to Velders et al. (2007), as was described above.

3. '***NA5_MP1987***'

This scenario takes substantially the same data as the 'No Regime' scenario, but makes certain additional assumptions and then simulates the reductions required by the original 1987 MP, and then extended out to 2040 using random number generation, as noted in Table 7 below.

Table 7: Summary of NA5_MP1987 scenario reductions

Annex/ Group	Baseline year	Reduction years	Notes
A/I	1986	1989, 1993	Baseline: real 1986 ODS consumption data. 1990-1992: linear interpolation. >1994: random (lower = 0, upper = 1993 'cap')
A/II	1986	1992	Baseline: real 1986 ODS consumption data. >1993: random (lower = 0, upper = 1992 'cap')

4. '***NA5_LDN1990***'

This scenario takes substantially the same data as the 'NA5_MP1987' scenario, but uses linear interpolation to avoid unrealistic abrupt reductions from default 'no regime' data values (e.g., between 1989 – 1993). It adds 'known' real ODS consumption data for 1989 and imposes the additional reductions required by the 1990 London Amendment to the MP. Note that this scenario includes a permitted *increase* in Annex A/I (CFCs) from mid-1991 to December 1992 of up to 150%.[59] As with the NA5_MP1987 scenario, this was adjusted to apply across full calendar years (1991 and 1992). To further distinguish this scenario from subsequent scenarios, values were also deliberately driven into the permitted increase range of 100-150% for those two years. Reductions were extended out to 2040. This is detailed in the summary table below.

[59] Refer Table 22 and Section 5.3 of the *Handbook to the Montreal Protocol* (Ozone Secretariat 2020, 866).

Table 8: Summary of NA5_LDN1990 scenario reductions

Annex/ Group	Baseline year	Reduction years	Notes
A/I	1986	1989, 1995, 1997, 2000	Baseline: real 1986 ODS consumption data.
			1990: random (lower = 1995, upper = 1989 'cap') 1991-1992: random (lower = 1989 'cap', upper = 150% of 1989 'cap'). 1993: random (lower = 1995, upper = 1989 'cap') 1994, 1996, 1998-2000: linear interpolation.
			2000: zero.
A/II	1986	1992, 1995, 2000	Baseline: real 1986 ODS consumption data.
			1993-1994, 1996-1999: linear interpolation
			2000: zero.
B/I	1989	1993, 1997, 2000	Baseline: real 1989 ODS consumption data.
			1990-1992: linear interpolation (to reduction year). 1994-1996, 1998-1999: linear interpolation.
			2000: zero.
B/II	1989	1995, 2000	Baseline: real 1989 ODS consumption data.
			1989-1995: linear interpolation (to reduction year). 1993-1999: linear interpolation (to zero).
			2000: zero.
B/III	1989	1993, 1995, 2000, 2005	Baseline: real 1989 ODS consumption data.
			1994, 1996-1999, 2001-2004: linear interpolation.
			2005: zero.

5. '***NA5_CPN1992***'

This scenario takes substantially the same data as the 'NA5_LDN1990' scenario, but adds 'known' real ODS consumption data until 1991, and then simulates the *additional* reductions required by the 1992 Copenhagen Amendment to the MP out to 2040. This is detailed in the summary table below. Unlike the LDN1990 scenario, Annex A/I (CFCs) data is not *driven* into the 100-150% range in 1991-1992, but random number generation leaves open such a 'permissive' increase in these two years for CPN1992 and all subsequent scenarios.

Table 9: Summary of NA5_CPN1992 scenario reductions

Annex/ Group	Baseline year	Reduction years	Notes
A/I	1986	1994, 1996	Baseline: real 1986 ODS consumption data. 1990: random (lower = 1994, upper = 1989) 1991-1992: random (lower = 1994, upper = 1.5*1989) 1993: random (lower = 1994, upper = 1989) 1995: linear interpolation. 1996: zero.
A/II	1986	1994	Baseline: real 1986 ODS consumption data. 1992-1993: linear interpolation (to reduction year). 1994: zero.
B/I	1989	1993, 1994, 1996	Baseline: real 1989 ODS consumption data. 1995: linear interpolation. 1996: zero.
B/II	1989	1995, 1996	Baseline: real 1989 ODS consumption data. (1992-1994: no change to linear interpolation from LDN1990 – already very varied time series) 1996: zero.
B/III	1989	1993, 1994, 1996	Baseline: real 1989 ODS consumption data. 1995: linear interpolation. 1996: zero.
C/I	1989 (compo-site)[60]	1996, 2004, 2010, 2015, 2020, 2030	Baseline: real 1989 ODS consumption data for CFCs (3.1%) + HCFCs (100%). 1996-2029: linear interpolation. 2030: zero.
C/II	1989	1996	Baseline: real 1989 ODS consumption data. 1996: zero.
C/III	1989	1995	Baseline: real 1989 ODS consumption data. >1996: random extrapolation (lower = 0, upper = 1995 ‘cap’)

6. ‘***NA5_VIE1995***’

This scenario takes substantially the same data as the ‘NA5_CPN1992’ scenario, but adds ‘known’ real ODS consumption data up until 1994 and then simulates quicker *additional*

[60] Refer Table 22.

reductions in Annex E/Group I substances required by the 1995 Vienna adjustment to the MP (VIE1995), and extended out to 2040 (see summary Table 10 below).

Table 10: Summary of NA5_VIE1995 scenario reductions

Annex/ Group	Baseline year	Reduction years	Notes
E/I	1991	1995, 2001, 2005, 2010	Baseline: real 1991 ODS consumption data.
			1996-2009: linear interpolation.
			2010: zero.

7. '***NA5_MON1997***'

This scenario takes substantially the same data as the 'NA5_VIE1995' scenario, adds 'known' real ODS consumption data up until 1996 and then simulates quicker *additional* reductions in Annex E/Group I substances required by the 1997 Montreal Amendment to the MP, as detailed in the summary table below. The effects of this faster reduction schedule are seen in the years 1995 to 2009, but the VIE1995 and MON1997 scenarios are otherwise the same before (1986-1994) and after (2010-2040).

Table 11: Summary of NA5_MON1997 scenario reductions

Annex/ Group	Baseline year	Reduction years	Notes
E/I	1991	1995, 1999, 2001, 2003, 2005	Baseline: real 1991 ODS consumption data.
			1996-2004: linear interpolation.
			2005: zero.

8. '***NA5_BEI1999***'

This scenario takes substantially the same data as the 'NA5_MON1997' scenario, adds 'known' real ODS consumption data to 1998 and then simulates the *additional* reductions required by the 1999 Beijing Amendment to the MP, as detailed in the summary table below. The MON1997 and BEI1999 scenarios are the same from 1986-1996, but the combination of the addition of 1997-1998 real world data for Annex C/III ODS and a faster reduction schedule in Annex C/I ODS after 1996 cause the BEI1999 scenario to diverge from 1997-2040.

Table 12: Summary of NA5_BEI1999 scenario reductions

Annex/ Group	Baseline year	Reduction years	Notes
C/I	1989 (composite)[61]	1996, 2004, 2010, 2015, 2020, 2030	Baseline: real 1989 ODS consumption data for CFCs (3.1%) + HCFCs (100%).
			1997-2029: linear interpolation.
			2030: zero.
C/III	(none)	2002	Baseline: none.
			2002: zero.

Approach to A5 scenarios

The development of the ODS consumption scenarios for the A5 parties followed substantially the same process as described for the NA5 parties above. The substantive distinction between the two classes of parties was that A5 parties were given an additional 10 years to comply with any relevant reduction.[62] The relevant required reductions are set out in Table 23.

Note that many of the baselines for A5 parties are multi-year averages, rather than a single (e.g. 1986) baseline, and that since almost none of these baselines would have been known at the time the regime was imposed, the averages are taken from the 'A5_NR' projections.

Also note that the ozone regime imposes two different bases for A5 parties' reductions in ODS consumption: by the relevant reduction year, the A5 parties must reduce their ODS consumption either by the required proportion of the multiyear baseline, or a maximum calculated level of consumption of 0.3 kg per capita, whichever is the lower.[63] For simplicity, this 'failsafe' per capita requirement was substantially ignored in developing the scenarios. Only as a final cross-check were the 'No Regime' worst case A5 scenario totals and 0.3 kg per capita figures compared using historical[64] and projected[65] population data for the 'Less developed regions'[66] (UNDESA 2019). The per capita 'cap' would only appear to be at risk of exceedance in the years 2030,[67] 2035[68] and 2040[69] (being years for which UN population

[61] Refer Table 22.
[62] See Article 5(1) of the MP1987 and MP2000.
[63] See, for example, Article 5(1) of the MP1987.
[64] Total Population - Both Sexes (XLSX, 2.4 MB), Description: 'Total Population - Both Sexes. De facto population in a country, area or region as of 1 July of the year indicated. Figures are presented in thousands.'
[65] Total Population (XLSX, 281 KB), Description: 'Total Population (Both Sexes): Median, 80% and 95% prediction intervals.'
[66] Accordingly, it was assumed that the 'Less developed regions' data corresponds to 'A5' party membership, but this is a highly abstract and crude assumption.
[67] Projected population: ~7.26E+09 people; projected A5 ODS consumption: ≥ 2.18E+09 kg.
[68] Projected population: ~7.60E+09 people; projected A5 ODS consumption: ≥ 2.28E+09 kg.
[69] Projected population: ~7.91E+09 people; projected A5 ODS consumption: ≥ 2.37E+09kg.

projections are available), but none of the other scenarios would exceed this 'cap' at any time in the time series.[70] (See calculations to the right of the 'A5_NR' data in the 'A5 Scenarios' Worksheet, in the 'Scenarios_consolidated_final.xlsx' file, at the link above.) Accordingly, and since the 'A5_NR' scenario by definition excludes any ozone regime restrictions anyway, the 0.3 kg per capita 'cap' was ignored in all A5 scenarios.

Once again, the relevant baselines and required reductions for A5 parties are summarised for each Annex / class of ODS and each relevant agreement of the ozone regime in Table 23. Applying these reductions using the general approach described above resulted in nine scenarios for the A5 parties, as further described below.

1. '***A5_reality***'

This is simply the real ODS consumption data for the period 1989-2020, as a reference scenario. It includes the 1986 baseline data, but there is no national data for 1987 and 1988.

2. ***'A5_NR'***

This is the counterfactual 'no regime' worst case reference scenario, consistent with regime effectiveness theory (Young 2011). It starts with 1986 baseline data and extends to 2040, applying similar assumptions to Velders et al. (2007), as was described above.

3. '***A5_MP1987***'

This scenario takes substantially the same data as the 'A5_NR' scenario, including for the purposes of calculating the average 1995-1997 baseline, and then simulates the reductions required by the original 1987 MP. It is extended to 2040 using random number generation as detailed in the summary table.

Table 13: Summary of A5_MP1987 scenario reductions

Annex/ Group	Baseline year	Reduction years	Notes
A/I	1995-1997	1999, 2003, 2008	Baseline: average 1995-1997 'A5_NR' projected values.
			2000-2002, 2004-2007: linear interpolation.
			>2009: randomly generated (lower = 0, upper = 2008 'cap')
A/II	1995-1997	2002	Baseline: average 1995-1997 'A5_NR' projected values.
			>2003: randomly generated (lower = 0, upper = 2002 'cap')

[70] At most, in 1998, all other scenarios still result in total ODS consumption figures an order of magnitude too small (1E+08 kg).

4. ‘***A5_LDN1990***’

This scenario takes substantially the same data as the ‘A5_MP1987’ scenario, but adds ‘known’ real ODS consumption data for 1989 and imposes the *additional* reductions required by the 1990 London Amendment to the MP. For the purpose of these reductions, it takes the projected ‘A5_NR’ values for the average 1998-2000 baselines (Annex B). Note that this includes a permitted *increase* in Annex A/I CFCs from mid-1991 to December 1992 of up to 150%[71] and as with the A5_MP1987 scenario, this was adjusted to apply across both calendar years (1991 and 1992). Like the ‘NA5_LDN1990’ scenario, the data were driven into the 100-150% range. After imposing zero reductions on all other Annexes up until 2015, data for Annexes C and E from 2016-2040 are common to ‘A5_NR’ and ‘NA5_MP1987’.

Table 14: Summary of A5_LDN1990 scenario reductions

Annex/ Group	Baseline year	Reduction years	Notes
A/I	1995-1997	1999, 2001, 2005, 2007, 2010	Baseline: average 1995-1997 ‘A5_NR’ projected values. 2000: random (lower = 2005, upper = 1999 ‘cap’) 2001-2002: random (lower = 1999 ‘cap’, upper = 150% of 1999 ‘cap’). 2003: random (lower = 1995, upper = 1999 ‘cap’) 2004, 2006, 2008-2009: linear interpolation. 2010: zero.
A/II	1995-1997	2002, 2005, 2010	Baseline: average 1995-1997 ‘A5_NR’ projected values. 2003-2004, 2006-2009: linear interpolation 2010: zero.
B/I	1998-2000	2003, 2007, 2010	Baseline: average 1998-2000 ‘A5_NR’ projected values. 2004-2006, 2008-2009: linear interpolations. 2010: zero
B/II	1998-2000	2005, 2010	Baseline: average 1998-2000 ‘A5_NR’ projected values. 2001-2004: linear interpolation (to reduction year). 2006-2009: linear interpolation. 2010: zero.
B/III	1998-2000	2003, 2005, 2010, 2015	Baseline: average 1998-2000 ‘A5_NR’ projected values. 2004, 2006-2009, 2011-2014: linear interpolation. 2015: zero.

[71] Refer Table 22 and Section 5.3 of the *Handbook to the Montreal Protocol* (Ozone Secretariat 2020, 866).

5. ‘*A5_CPN1992*’

This scenario takes substantially the same data as the ‘A5_LDN1990’ scenario, but adds ‘known’ real ODS consumption data until 1991, makes certain additional assumptions and then simulates the *additional* reductions required by the 1992 Copenhagen Amendment to the MP out to 2040. This is detailed in the summary table below. Unlike the LDN1990 scenario, Annex A/I (CFCs) data is not *driven* into the 100-150% range in 2001-2002, but the random number generator leaves open the option of this ‘permissive’ increase during these two years for this and all subsequent scenarios. Otherwise this scenario is the same as ‘A5_LDN1990’, as the CPN1992 did not introduce more stringent requirements for A5 parties and so does not differ as substantially as for NA5 parties.

Table 15: Summary of A5_CPN1992 scenario reductions

Annex/ Group	Baseline year	Reduction years	Notes
A/I	1995-1997	1999, 2003, 2008	Baseline: average 1995-1997 ‘A5_NR’ projected values
			2000: random (lower = 2005, upper = 1999) 2001-2002: random (lower = 2005, upper = 1.5*1999) 2003: random (lower = 2005, upper = 1999) 2004: linear interpolation All other values as in ‘A5_LDN1990’ scenario
			2010: zero (as in ‘A5_LDN1990’)
C/II	(none)	1996	1996: zero.
E/I	1995-1998	2005	Baseline: average 1995-1998 ‘A5_NR’ projected values
			>2006: random extrapolation (lower = 0, upper = 2005 ‘cap’)

6. ‘*A5_VIE1995*’

This scenario takes substantially the same data as the ‘A5_CPN1992’ scenario out to 2040, adds ‘known’ real ODS consumption data until 1994, and then simulates the *additional* reductions required in ODS listed in Annexes C/I and E/I by the 1995 Vienna Adjustment to the MP.

Table 16: Summary of A5_VIE1995 scenario reductions

Annex/ Group	Baseline year	Reduction years	Notes
C/I	2015	2016, 2040	Baseline: 2015 'A5_NR' projected value
			2017-2039: linear interpolation
			2040: zero
E/I	1995-1998	2002	Baseline: average 1995-1998 'A5_NR' projected values
			>2003: random extrapolation (lower = 0, upper = 2002 'cap')

7. '***A5_MON1997***'

This scenario takes substantially the same data as the 'A5_VIE1995' scenario out to 2040, but adds 'known' real ODS consumption data to 1996 (which slightly reduces the 1995-1998 baseline for Annex E/I) and then simulates the *additional* reductions required by the 1997 Montreal Amendment to the MP. Since the addition of the real world data reduces the average 1995-1997 baseline for Annex A/I ODS, the subsequent interpolation was revised accordingly, with otherwise no changes to the required reductions imposed in previous scenarios.

Table 17: Summary of A5_MON1997 scenario reductions

Annex/ Group	Baseline year	Reduction years	Notes
A/I	1995-1997	(no change)	Baseline: real-world data 1995-1996, 'A5_NR' data 1997
			1999-2009: revised interpolation
			2010: zero (no change)
A/II	1995-1997	(no change)	Baseline: real-world data 1995-1996, 'A5_NR' data 1997
			>2002: revised linear interpolation
E/I	1995-1998	2002, 2005, 2015	Baseline: 1995-1998 (mix of real data for 1995-1996 and 'A5_NR' data for 1997-1998)
			2003-2004, 2006-2014: linear interpolation
			2015: zero

8. '***A5_BEI1999***'

This scenario takes substantially the same data as the 'A5_MON1997' scenario, but adds 'known' real ODS consumption data to 1998, and then simulates the reductions required by the *additional* reductions required by the 1999 Beijing Amendment to the MP out to 2040.

Although the BEI1999 did not impose any changes to the reductions required to Annexes B/I-III and E/I under MON1997, the effect of the addition of real world data until 1998 is to revise down their baselines and hence further reduce overall ODS consumption through the revised linear interpolation. (NB: the revised baseline does not change the Annex B/II data baseline because 1998 was also the maximum production year for the Annex B/II ODS and so this was the same datapoint already fixed in the 'A5_NR' scenario.)

Table 18: Summary of A5_BEI1999 scenario reductions

Annex/ Group	Baseline year	Reduction years	Notes
A/I	1995-1997	(no change)	Baseline: all real-world data 1995-1997. 1999-2009: revised interpolation. 2010: zero (no change).
A/II	1995-1997	(no change)	Baseline: all real-world data 1995-1997. >2002: revised linear interpolation. 2010: zero (no change).
B/I	1998-2000	(no change)	Baseline: real-world data 1998, 'A5_NR' data 1999-2000. No change in required reductions; revised linear interpolation values only.
B/II	1998-2000	(no change)	
B/III	1998-2000	(no change)	
C/III	(none)	2002	2002: zero.
E/I	1995-1998	(no change)	Baseline: all real-world data 1995-1998. 2003-2014: revised linear interpolation. 2015: zero (no change).

9. ***'A5_MON2007'***

This scenario takes substantially the same data as the 'A5_BEI1999' scenario, adds 'known' real ODS consumption data until 2006 and then simulates *additional* reductions required by the 2007 Montreal Adjustment to the MP out to 2040. In addition to revised interpolation due to 'complete' real-world average baselines (Annex B: 1998-2000), the MON2007 imposed *new additional* reductions[72] on Annex C/I ODS, for which 'A5_NR' data were used.

[72] The MON2007 reductions are expressed by reference to separate *consumption* and *production* baselines, but since the timeframe and required relative percentage cuts are the same, only the consumption reductions are simulated in this scenario. Refer Table 23 for comparison between consumption/production reduction schedules.

Table 19: Summary of A5_MON2007 scenario reductions

Annex/ Group	Baseline year	Reduction years	Notes
B/I	1998-2000	(no change)	Baseline: all real-world ODS consumption data 1998-2000.
B/II	1998-2000	(no change)	
B/III	1998-2000	(no change)	Revised interpolation data.
C/I	2009-2010	2013, 2015, 2020, 2025, 2030	Baseline: average 2009-2010 'A5_NR' data.
			2014, 2016-2019, 2021-2024, 2026-2029: linear interpolation.
			2030: zero.

Regime-wide scenarios

Each of the data series corresponding to the scenarios described above were defined with appropriate names in Excel (e.g., 'NA5_NR' and 'A5_MON1997'). These were then added to a new Worksheet, named 'ODS_Scenarios' in the same 'Scenarios_consolidated_final.xlsx' file,[73] and listed by class of parties (NA5 and then A5). Each data series from the NA5 scenarios was then added together with the corresponding data series from the A5 scenarios using their defined names in consecutive rows (refer Table 20). This resulted in regime-wide scenarios for the evolution of ODS consumption over time. The year-on-year proportionate change relative to the total 1986 ODS consumption (baseline) was then calculated for each of the resultant regime-wide scenarios. The regime-wide proportionate change data series were then given new defined names. All of this is summarised in Table 20 below, together with the average annual percentage change across the length of each time series.

[73] Available at this link: https://phaidra.univie.ac.at/o:1536416.

Table 20: Overall scenarios for both A5 and NA5 parties under the ozone regime

	Scenario name (regime-wide)	Constituent scenarios	Change from 1986 (%)	Timestep (years)	Average annual change (%)
1.	'NR_'	=(NA5_NR)+(A5_NR)	+1200	52	23
2.	'Reality'	=(NA5_reality)+(A5_Reality)	-100	33	-3
3.	'MP1987_'	=(NA5_MP1987)+(A5_MP1987)	(no net change)	52	0
4.	'LDN1990_'	=(NA5_LDN1990)+(A5_LDN1990)	-83	52	-1.6
5.	'CPN1992_'	=(NA5_CPN1992)+(A5_CPN1992)	-94	52	-1.8
6.	'VIE1995_'	=(NA5_VIE1995)+(A5_VIE1995)	> -99	52	-1.9
7.	'MON1997_'	=(NA5_MON1997)+(A5_MON1997)	> -99	52	-1.9
8.	'BEI1999_'	=(NA5_BEI1999)+(A5_BEI1999)	-100	52	-1.92
9.	'MON2007_'	=(NA5_BEI1999)+(A5_MON2007)[74]	-100	42	-2.38

Application of scenarios to GHG emissions data

The ODS consumption and GHG emission datasets have different baselines (1986 and 1990, respectively) and span different lengths of time. In addition, the ODS consumption data has a conspicuous 'gap' between the 1986 baseline and the continuous time series starting in 1989. Thus, in order to apply the ODS scenarios to the GHG emissions data, the ODS data had to be standardised as a proportion of the 1986 baseline (as described above) and the two year 'gap' between 1986 and 1989 in the ODS time series had to be overcome. The solution here was to equate the two baselines (1986 ODS = 1990 GHG) and then apply the proportionate time series from 1993. To bridge the 'gap', the '=RANDBETWEEN()' formula was once again deployed, with the lower bound set to the 1990 value and the upper bound set to the 1993 value within each separate scenario time series.

Interpretation of counterfactual GHG emissions data

To place the simulated GHG emissions results in their broader real-world context, the total cumulative emissions were calculated for each scenario time series. These were then compared with the Global Carbon Project's (GCP) calculated 'remaining carbon budget'[75] for 2022.

[74] Since the 2007 Montreal Adjustment did not impose any additional reductions on NA5 parties, the reductions required under the 1999 Beijing Amendment ('NA5_BEI1999') were re-used in the overall 'MON2007' scenario.
[75] See IPCC (2021a, Appendix VII: Glossary) and IPCC (2021b, 28–29).

As at 2021, the 'consumed carbon budget' was estimated to be 2475 $GtCO_2$ up until the end of 2021. Thus, from 2022 onwards, the corresponding 'remaining carbon budgets', representing a 50% likelihood of limiting the global average temperature increase to 1.5°C, 1.7°C and 2.0°C above the pre-industrial average, were estimated to be 420 $GtCO_2$ (1.5°C), 770 $GtCO_2$ (1.7°C) and 1270 $GtCO_2$ (2.0°C), respectively.[76]

To compare the counterfactual GHG emissions data, both the consumed and remaining 'carbon budgets' were backdated to 1990. This was calculated by taking the difference between the GCP's real-world GHG emissions data for the period 1990 to 2021[77] and the relevant budget. Thus, the GCP cumulative 1990-2021 emissions total was *subtracted* from the GCP's 'consumed' 2022 budget and *added* to the GCP's 'remaining' 2022 budgets, with the results shown in the table below.

Table 21: Consumed and remaining carbon budgets, backdated to 1990

Consumed carbon budget as at 1990 ($GtCO_2$)	**Remaining 1.5°C budget as at 1990 ($GtCO_2$)**	**Remaining 1.7°C budget as at 1990 ($GtCO_2$)**	**Remaining 2.0°C budget as at 1990 ($GtCO_2$)**
1567	1328	1678	2178

The cumulative scenario totals were then subtracted from the backdated 1990 carbon budgets in Table 21.

[76] These subsidiary remaining carbon budgets are smaller than those estimated by the IPCC, which estimates 500 $GtCO_2$ (1.5°C), 850 $GtCO_2$ (1.7°C) and 1350 $GtCO_2$ (2.0°C), respectively (IPCC 2021b, 38). However, since all data used here is from the GCP, for consistency, those budgets were preferred.
[77] I.e., the GCP's estimates of global GHG emissions for 2020 and 2021 were added to the 1990-2019 time series used here.

Table 22: Ozone regime's required reductions for NA5 (developed country) parties

ODS Group / Annex	Montreal Protocol (MP1987)	London Amendment (LDN1990)	Copenhagen Amendment (CPN1992)	Vienna Adjustment (VIE1995)	Montreal Amendment (MON1997)	Beijing Amendment (BEI1999)
Group I Annex A (1986 baseline)	1. 100% 1/8/89	1. 150% - 1/7/91 to 31/12/92	1. 150% - 1/7/91 to 31/12/92			
	2. 80% 1/7/93*	2. 50% 1/1/95	2. 25% 1/1/94			
	3. 50% 1/7/98*	3. 15% 1/1/97	3. 0% 1/1/96			
	*LDN1990 adjusted to whole calendar years	4. 0% 1/1/00				
Group II Annex A (1986 baseline)	100% 1/2/92	1. 100% 1/1/92	0% 1/1/94			
		2. 50% 1/1/95				
		3. 0% 1/1/00				
Group I Annex B (1989 baseline)		1. 80% 1/1/93	1. 80% 1/1/93			
		2. 15% 1/1/97	2. 25% 1/1/94			
		3. 0% 1/1/00	3. 0% 1/1/96			
Group II Annex B (1989 baseline)		1. 15% 1/1/95	1.15% 1/1/95		**(No change)**	
		2. 0% 1/1/00	2. 0% 1/1/96			
Group III Annex B (1989 baseline)		1. 100% 1/1/93	1. 100% 1/1/93			
		2. 70% 1/1/95	2. 50% 1/1/94			
		3. 30% 1/1/00	3. 0% 1/1/96			
		4. 0% 1/1/05				
Group I Annex C (1989 baseline - consumption)			1. (3.1% of CFC consumption + 100% HCFCs) 1/1/96			
			2. 65% 1/1/04			
			3. 35% 1/1/10			
			4. 10% 1/1/15		**(No change)**	
			5. 0.5% 1/1/20			
			6. 0% 1/1/30			

ODS Group / Annex	Montreal Protocol (MP1987)	London Amendment (LDN1990)	Copenhagen Amendment (CPN1992)	Vienna Adjustment (VIE1995)	Montreal Amendment (MON1997)	Beijing Amendment (BEI1999)
Group I Annex C (<u>1989</u> baseline - <u>production</u>)						1. (2.8% of CFC consumption + 100% HCFCs consumption) + (2.8% of CFC production + 100% HCFCs production) 1/1/04
Group II Annex C			0% 1/1/96		**(No change)**	
Group III Annex C						0% 1/1/02
Group I Annex E (<u>1991</u> baseline)			1. 100% 1/1/95	1. 100% 1/1/95	1. 100% 1/1/95	
				2. 75% 1/1/01	2. 75% 1/1/99	
				3. 50% 1/1/05	3. 50% 1/1/01	**(No change)**
				4. 0% 1/1/10	4. 30% 1/1/03	
					5. 0% 1/1/05	

Table 23: Ozone regime's required reductions for A5 (developing country) parties

ODS Group / Annex	Montreal Protocol (MP1987)	London Amendment (LDN1990)	Copenhagen Amendment (CPN1992)	Vienna Adjustment (VIE1995)	Montreal Amendment (MON1997)	Beijing Amendment (BEI1999)	Montreal Adjustment (MON2007)
Group I Annex A (<u>avg 1995-1997</u> baseline)	1. 100% 1/1/99	1. 100% 1/1/99					
	2. 80% 1/1/03*	2. 50% 1/1/05					
	3. 50% 1/1/08*	3. 15% 1/1/07					
	*LDN1990 adjusted to whole calendar years	4. 0% 1/1/10					
Group II Annex A (<u>avg 1995-1997</u> baseline)	1. 100% 1/2/02	1. 100% 1/1/02					
		2. 50% 1/1/05					
		3. 0% 1/1/10					
Group I Annex B (<u>avg 1998-2000</u> baseline)		1. 80% 1/1/03			**(No change)**		
		2. 15% 1/1/07					
		3. 0% 1/1/10					
Group II Annex B (<u>avg 1998-2000</u> baseline)		1. 15% 1/1/05					
		2. 0% 1/1/10					
Group III Annex B (<u>avg 1998-2000</u> baseline)		1. 100% 1/1/03					
		2. 70% 1/1/05					
		3. 30% 1/1/10					
		4. 0% 1/1/15					

ODS Group / Annex	Montreal Protocol (MP1987)	London Amendment (LDN1990)	Copenhagen Amendment (CPN1992)	Vienna Adjustment (VIE1995)	Montreal Amendment (MON1997)	Beijing Amendment (BEI1999)	Montreal Adjustment (MON2007)
Group I Annex C (avg 2009-2010 baseline - consumption)				1. 100% (2015 baseline) 1/1/16			1. 100% 1/1/13
				2. 0% 1/1/40			2. 90% 1/1/15
							3. 65% 1/1/20
							4. 32.5% 1/1/25
							5. 0% 1/1/30
Group I Annex C (avg 2009-2010 baseline - production)							1. 100% 1/1/13
							2. 90% 1/1/15
							3. 65% 1/1/20
							4. 32.5% 1/1/25
							5. 0% 1/1/30
Group II Annex C			0% 1/1/96			(No change)	
Group III Annex C						0% 1/1/02	(No change)
Group I Annex E (avg 1995-1998 baseline)			1. 100% 1/1/05	1. 100% 1/1/02			
					2. 80% 1/1/05	(No change)	
					3. 0% 1/1/15		

5.5.3 ODS emissions simulations

This simulation applied the *climate regime's* scheduled reductions in global GHG emissions relative to the 1990 baseline data, to *global ODS consumption* relative to the 1986 baseline. The reductions achieved in GHG emissions relative to 1990 were applied, as a proportionate change, to total ODS consumption figures in 1986.

The climate regime imposed 'quantified emission limitation and reduction commitments' on 'Annex B' (developed) parties[78] under the KP, as apportioned in Annex B to the KP. The KP did not impose any quantified emissions reductions on 'Non-Annex B' (developing) parties. Although the text of the 2012 *Doha Amendment* to the KP has not been analysed here, the 'quantified emission limitation and reduction commitments' applicable under that amendment have been used in developing the scenarios to better simulate that period following the KP's first 'commitment period' (2008-2012) and prior to the date of most of the first 'nationally determined contributions' (NDCs) under the PA (typically >2030). The PA did not maintain the distinction between 'Annex B' and 'Non-Annex B' parties, but it did distinguish between 'developed' and 'developing' parties, so for simplicity the distinction established by KP was maintained throughout the development of these scenarios. Accordingly, the scenario data are included in the 'Annex B Scenarios' and 'Non-Annex B Scenarios' Worksheets in the 'Scenarios_consolidated_final.xlsx' file,[79] in which 'AxB' and 'NAxB' are used as shorthand for the two classes of parties.

As with the ozone regime, these two distinct classes of party meant that the scenarios were developed separately for the AxB (developed) parties and the NAxB (developing) parties. The required reductions for AxB parties are summarised in Table 24.[80] No similarly summarised data is readily available for NAxB parties, so the alternative assumptions used to generate these scenarios are described in more detail below. Once the two separate sets of scenarios had been developed, like the ozone regime scenarios, they were then combined into overall, regime-wide scenarios. Once again, the general approach to scenario development is explained first, with certain other factors unique to a particular scenario then clarified below.

General approach

The GCP's time series of GHG emissions from 1960 to 2019 was imported to Excel. As was done for the A5/NA5 distinction under the ozone regime scenarios, a new column was

[78] Annex B to the KP is substantially the same as Annex I to the UNFCCC, but Annex I includes Belarus and Turkey.
[79] Available at this link: https://phaidra.univie.ac.at/o:1536416.
[80] Note that the 'EU' as listed in Table 24 does not reflect its current membership, as clarified in the footnotes to the table and in the general data manipulation described below.

added to the GHG emissions data series and the countries were labelled as AxB/NAxB parties by reference to Annex B to the KP. A shorter GHG emissions time series, from 1990 to 2019, for each of the two classes of parties were isolated in separate Worksheets labelled 'Annex B Scenarios' and 'Non-Annex B Scenarios' in the 'Scenarios_consolidated_final.xlsx' file.[81]

Once again, the first step was to develop a 'no regime' counterfactual scenario as a reference scenario. This assumed a future GHG emissions pathway similar to that modelled in 'representative concentration pathway' (RCP) 8.5 developed by Riahi et al. (2007; 2011; van Vuuren et al. 2011). The RCPs are multifactorial models, making various assumptions that seek to reflect dynamic and interacting phenomena, including land use change, climate interactions, technological development, and human population and GDP growth (van Vuuren et al. 2011). For present purposes, only the emissions growth assumptions were relevant. To that end, RCP8.5 assumes continued very high $CO_{2\text{-eq}}$ emissions until 2100, with annual GHG emissions beginning in 2000 at around 35 $GtCO_{2\text{-eq}}$ and increasing steadily over the course of the 21st century before plateauing at around 110 $GtCO_{2\text{-eq}}$ by 2100 (Riahi et al. 2011, 49). This results in projected mean cumulative emissions of 6180 $GtCO_{2\text{-eq}}$ in the period between 2012 and 2100 (IPCC 2013b, 27). Interpolating between 35 $GtCO_{2\text{-eq}}$ and 110 $GtCO_{2\text{-eq}}$ over the time step of 100 years results in an average annual increase of ~2.14% (non-compounding) and cumulative emissions between 2012 and 2100 of 6853 $GtCO_{2\text{-eq}}$. Although this total exceeds the stated mean, it still lies within the range cited by the IPCC for RCP8.5 (IPCC 2013b, 27). Meanwhile, since RCP8.5 only starts in 2000, linear interpolation was used to 'backdate' the time series to the common 1990 baseline figure used for all other scenarios. This series was taken to be the 'worst case', 'no regime' reference scenario for comparison with the other scenarios. Unlike the earlier scenarios, this serves as a single regime-wide scenario, which does not consist of separate sub-scenarios for each class of party.

Having isolated the 1990-2019 GHG emissions data in two separate classes, the next step was to develop a 'reality' or 'actual emissions' reference scenario. Accordingly, the annual totals for 1990-2019 were calculated (using '=SUM()' in Excel) and each time series was defined as 'Actual_AxB' and 'Actual_NAxB' (to distinguish these from the name 'Reality' used in the earlier scenarios).

Since the climate regime did not impose any quantifiable emissions reductions obligations on NAxB (developing country) parties until the PA, the scenario development process necessarily diverged at this point, as detailed below. However, for all scenarios, the aim

[81] Available at this link: https://phaidra.univie.ac.at/o:1536416.

remained to find a plausible basis to derive a time series of proportionate change relative to the 1990 baseline to allow for comparison between regimes and substances.

Approach to AxB (developed country) scenarios

The AxB data and the emissions reductions summarised in Table 24 were used to generate seven scenarios, as listed and described below. Similar to the ozone regime scenarios, each of the 27 countries (including the 'EU'[82]) included in Annex B to the KP was listed in a separate row, while annual GHG emissions were recorded in consecutive columns, representing each year from 1990 to 2070. The scenario series extend to 2070 as that was the latest target year in the NDCs considered under the PA framework (see description of 'Paris_1' and 'Paris_2' scenarios below). Thus, after the date of any relevant reduction year, most data were randomly extrapolated to 2070 using random number generation '=RANDOMBETWEEN()', with the lower bound set to 93% of the immediately preceding annual and the upper bound set to the applicable 'cap' imposed in the relevant reduction year. The lower bound was chosen because a year-on-year comparison of the 1960-2019 GHG emissions time series revealed that the largest year-on-year reduction was 7%. Constructed as such, the random number generation permits progressively greater reductions over time, without driving emissions to zero, and always within the relevant 'cap'. Meanwhile, due to the non-generation of decimal numbers, the emissions of relatively minor AxB emitters, Iceland, Liechtenstein and Monaco, were subjected to annual 7% reductions out to 2070, from the year following any relevant reduction year.

In generating these scenarios, the realities of international climate politics were largely ignored, given the complexities of including recent developments and unforeseeable futures. That is, the practical effect of the US' failure to ratify the KP, or Canada's ratification of, then subsequent withdrawal from the KP, was ignored. It was assumed that all AxB parties fully complied with the relevant reductions prescribed by the climate regime, regardless of ratification status. Similarly, in the context of the voluntary NDC pledges within the PA framework, it follows that it was also assumed that AxB parties would fully comply with whatever they had pledged in their NDCs. To assist in interpreting and standardising NDCs, which notoriously vary wildly by baseline, reduction year, metric[83] and their national legal status, the 'Climate Tracker' website was used. This service, provided by Climate Analytics and

[82] Consisting of its 12 Member States at the time the MP1987 entered into force.
[83] Note the general preference of developed countries to pledge absolute emissions reductions in a reduction year relative to a baseline year, with the general preference of developing countries to pledge relative emissions reductions (based on measures of 'emissions intensity' per unit GDP) in a reduction year by reference to a baseline year.

NewClimate Institute, seeks to quantify the climate mitigation targets, policies and actions of countries representing about 85% of global GHG emissions (Climate Analytics and NewClimate Institute 2022). Further details about these interpretations and associated assumptions are given in relation to the descriptions of the 'Paris_1' and 'Paris_2' scenarios below.

Note that, for consistency across datasets, the same definition of the 'European Union' (EU) used in the ODS data was also applied to the CO_2 data. This took the 12 members[84] of the 'European Community' as it existed at the time the MP1987 entered into force. After 'Brexit' on 31 January 2020, the UK ceased to be a member of the EU, with implications for how to account for future emissions reductions (refer 'Paris_2' scenario, below). Where the climate regime (e.g. the KP and Doha) set out shared emissions reductions to be achieved by the EU as a bloc, the same reduction was applied to the 12 countries of the 'EU' as defined above, and any other EU Member State listed in an Annex to the climate regime.

Meanwhile, despite being listed among the countries in Annex B to the KP, no data were available for Monaco. Thus, historical actual emissions data shown in a time series graph[85] prepared by UNEP in the lead up to COP7 of the UNFCCC was visually interpreted and the data entered for 1990-2000 (~0.1-0.14 $GtCO_2$). Given the paucity of other data and relative insignificance of this data anyway, this was then held steady at year 2000 levels (~0.14 $GtCO_2$) until the end of the time series in 2019.

1. ***'Actual_AxB'***

As above, this is the 'actual emissions' reference scenario, which takes the total annual GHG emissions data for AxB parties for every year from 1990 to 2019.

2. ***'KP_best'***

This scenario takes the real-world GHG emissions data from 1990-2007 and applies the AxB parties' 'quantified emissions reduction and limitation commitments' under the KP in 2008 (refer Table 24). This assumed full compliance by AxB parties in the *first* year of the KP's five year 'commitment period' and, as such, represents the 'best case scenario' within the KP context. After 2009, data is extrapolated as described in the general approach, above.

3. ***'KP_worst'***

By contrast to the previous scenario, this one takes the real-world GHG emissions data from 1990-2011 and then applies the AxB parties' 'quantified emissions reduction and limitation commitments' under the KP in 2012 (refer Table 24). This therefore assumes full

[84] Namely, Belgium, Denmark, France, Germany, Greece, Ireland, Italy, Luxembourg, The Netherlands, Portugal, Spain and the United Kingdom (UK).
[85] Available at: https://www.grida.no/resources/6590.

compliance by AxB parties in the *final* year of the KP's five year 'commitment period' and, as such, represents the 'worst case scenario' within the KP context.

As in 'KP_best', after 2013 a mix of random number generation (lower = 0.93*(year-1), upper = 2012 'cap') and annual 7% reductions (for Iceland, Liechtenstein and Monaco) are used until 2070.

4. ***'Doha_best'***

As noted earlier, the 2012 Doha Amendment to the KP was analysed for the limited purpose of extracting the 'quantified emissions reduction and limitation commitments' applicable in its 'commitment period' from 2013 to 2020. There was no real-world sense in simulating a 'best' and 'worst' case for Doha, since it only entered into force on 31 December 2020, but this was nevertheless simulated for the purposes of the exercise. In this case, the 'best case scenario' would have been if 'KP_best' had first been achieved and then the *additional* required reductions under Doha were achieved in 2013, the first year of its 2013-2020 'commitment period'.

Annex B of the KP was amended by Doha to include several additional countries,[86] while acknowledging that four countries,[87] plus the US,[88] that were previously listed under Annex B to the KP would not ratify Doha. Therefore, for the purposes of the scenario, the Doha reductions were simply applied in 2013 insofar as they remained relevant to countries still listed in Annex B and the additionally listed countries were ignored. Meanwhile, estimated reductions were calculated for Canada, Japan, New Zealand, Russia and the US for 2020, using the average net change in the emissions of all of the other AxB parties over this period (2013-2020). This average reduction was ~81% (refer Table 24).

Linear interpolation was used for the values in the intervening years (2009-2012) following 'KP_best' and before imposing the reductions required under Doha in 2013. After 2014, data is extrapolated to 2070 using the methods described in the general approach, above.

5. ***'Doha_worst'***

Like the 'KP_worst' before it, this scenario simply applied the required reductions under Doha in the last year of the relevant 'commitment period'. In this case, the 'worst case scenario' would have been if the 'KP_worst' had occurred first (only in 2012) and then Doha proved similarly slow to achieve the *additional* emissions reductions it required (in 2020). The required reductions were identical to those required under 'Doha_best', but simply delayed by seven years to the 2020 reduction year. Once again, linear interpolation was used for

[86] Including Belarus, Cyprus, Kazakhstan and Malta.
[87] Namely, Canada, Japan, New Zealand and the Russian Federation.
[88] Simply removed from the list by Doha.

the values in the intervening years (2013-2019) following 'KP_worst' and before the reductions required under Doha. After 2020, data is extrapolated to 2070 using the methods described in the general approach, above.

6. ***'Paris_1'***

The starting point for both scenarios under the PA framework was to fully populate the period from 1990 to 2019 with real-world data once again. No reductions under the KP or Doha were carried over. This was because of the wide variety in baselines stated in developed country parties' NDCs and because the PA both structurally and politically represents a clear 'break' with its predecessor agreements under the climate regime. Next, the relevant emissions reductions, based on AxB parties' pledged *first* NDCs,[89] as interpreted by 'Climate Tracker' and listed in *Table 24* (refer 'PA NDC1' column), were applied in the relevant target year, 2030 (and 2025, in the case of the USA). Where a country pledged an emissions reduction in a 'range' (e.g. Australia's 26-28% reduction from a 2005 emissions baseline by 2030), the upper end of that range was taken as the required reduction.

Once again, linear interpolation was used for the intervening years (2020-2029) and then the data were extended from 2031 to 2070 as described in the general approach above.

7. ***'Paris_2'***

This scenario simply updated the '*Paris_1*' scenario to account for the revised NDCs submitted by most developed states ahead of COP26 in November 2021 (refer 'PA NDC2' column in Table 24). The more ambitious pledges by those AxB parties that submitted such an updated NDC were shown in **bold black font** in the 2030 target year column of the 'Paris_2' scenario. At the time of writing, all AxB parties except for Australia, Liechtenstein, Monaco, the Russian Federation and Switzerland had made additional quantifiable pledges in the 2030 target year. Further, almost all AxB parties had pledged to achieve 'net zero' by 2050 (i.e., any GHG emissions in 2050 would be offset by enhanced 'sinks' or as yet unrealised removal technologies).

[89] Ignoring any preceding *Intended Nationally Determined Contributions*, to the extent that any AxB parties made such pledges, let alone whether they differed from their 'official' first NDC, made once the PA had entered into force.

Table 24: Summary of required/pledged reductions and baselines under climate regime – AxB parties only

Annex B parties	**KP (1990 baseline)**	**Doha (1990 baseline)**	**PA NDC1 (1990 baseline, unless otherwise indicated)**		**PA NDC2 (1990 baseline, unless otherwise indicated)**	
Target year(s):	2008-2012	2013-2020	2025	2030	2030	2050
Australia	1.08	0.995		0.72 (2005)	-	0
Austria	0.92	0.8		0.6	0.45	0
Bulgaria[#]	0.92	0.8		0.6	0.45	0
Canada	0.94	0.81*		0.7 (2005)	0.55 (2005)	-
Croatia[#]	0.95	0.8		0.6	0.45	0
Czech Republic[#]	0.92	0.8		0.6	0.45	0
Estonia[#]	0.92	0.8		0.6	0.45	0
EU^	0.92	0.8		0.6	0.45[&]	0
Finland	0.92	0.8		0.6	0.45	0
Hungary[#]	0.94	0.8		0.6	0.45	0
Iceland	1.1	0.8		0.6	0.45	0
Japan	0.94	0.81*		0.74 (2013)	0.54 (2013)	0
Latvia[#]	0.92	0.8		0.6	0.45	0
Liechtenstein	0.92	0.84		0.6	-	0
Lithuania[#]	0.92	0.8		0.6	0.45	0
Monaco	0.92	0.78		0.5	-	0
New Zealand	1	0.81*		0.7 (2005)	0.5	0
Norway	1.01	0.84		0.6	0.45	0
Poland[#]	0.94	0.8		0.6	0.45	0
Romania[#]	0.92	0.8		0.6	0.45	0
Russian Federation[#]	1	0.81*		0.7	-	-
Slovakia[#]	0.92	0.8		0.6	0.45	0
Slovenia[#]	0.92	0.8		0.6	0.45	0
Sweden	0.92	0.8		0.6	0.45	0
Switzerland	0.92	0.842		0.5	-	0
Ukraine[#]	1	0.76		0.6	0.35	-
United Kingdom					0.32	0
USA	0.93	0.81*	0.72 (2005)	0.72 (2010)	0.48 (2005)	0

[#] Indicates countries considered 'economies in transition' (i.e., those former countries of the Soviet Union transitioning from a communist to a market economy).
[^] Once again, the 'EU' here represents its historical membership of 12 States, at the time the MP1987 entered into force.
[*] Canada, Japan, NZ, Russia and US: inferred reductions under Doha based on average reductions for all other AxB parties.
[&] Note that the EU's PA NDC2 does not include the UK.

Approach to NAxB (developing country) scenarios

The NAxB parties were not subject to quantifiable emissions reductions under the climate regime, until the advent of the PA framework. For this reason, only five scenarios were developed for the NAxB parties, given the dearth of any relevant reference points to shape plausible GHG emissions trajectories.

1. ***'Actual_NAxB'***

As for the AxB parties, this is the 'actual emissions' reference scenario, which takes the total annual GHG emissions data for NAxB parties for every year from 1990 to 2019.

2. ***'AxB_Parties'*** and
3. ***'NAxB_Parties'***

Given the lack of relevant emissions-shaping reference points in the form of required reductions for NAxB parties under the pre-PA climate regime, the next logical reference point was the historical time series data. Two trends in the time series were relevant: the gradual trend up and then down in AxB parties' emissions from 1960 to 2019 and the clear upward trend in NAxB parties' emissions beginning around the year 2000 and continuing through to 2019. These two very different trends were taken as the upper and lower 'boundary conditions' for plausibly simulating NAxB parties' emissions during the period before the PA framework was introduced, for the reasons given in the following brief historical excurse.

Firstly, the AxB parties' emissions trajectory represents a broad cross-section of States, all of which are considered highly developed countries, but with mixed development paths. The start of the time series reflected the continued post-WWII 'Great Acceleration', albeit with less dramatic growth than immediately following the war. This continues somewhat steadily until 1989-1991, when emissions plateau. This slowing in emissions growth coincides with the collapse of the Soviet Union, which particularly affected the 'economies in transition' among the AxB parties. Thereafter, emissions remained more or less stable, before gradually declining from the mid to late 2000s. Such an emissions path seems reasonable to expect for some of the more developed NAxB parties nowadays, such as Brazil, China, Mexico, Saudi Arabia, South Africa and South Korea.

Secondly, the marked increase in emissions from about 2000 until 2019 in the time series of NAxB parties' GHG emissions represents a plausible upper limit for simulating emissions growth. The scope and timing of this surge coincides with China's remarkable recent development, which other less developed countries could be expected to emulate, particularly very populous countries like India, Indonesia and Nigeria.

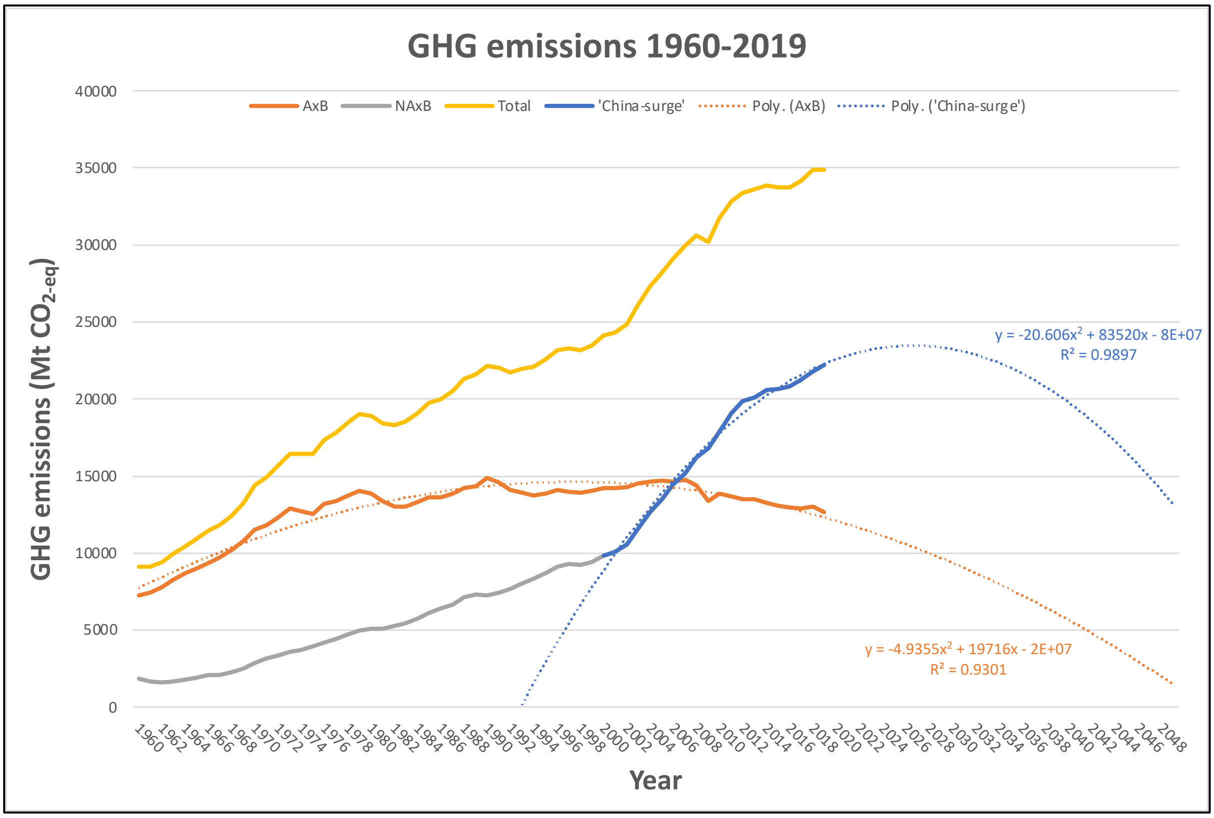
Thus, it stands to reason that the GHG emissions of NAxB parties as a whole would evolve somewhere in between these two very different trajectories, based on historical precedent. Therefore, polynomial lines of best fit were derived for each of these two sub-series of the total global GHG emissions time series, as shown in Table 25.

Table 25: Polynomial lines of best fit for sub-series of GHG emissions data, used in scenarios

Scenario	Polynomial equation of best fit	R^2 value
'AxB_Parties'	$y = -4.9355x^2 + 378.99x + 7347.5$ (1)	0.9301
'NAxB_Parties'	$y = -20.606x^2 + 2786.4x – 70722$ (2)	0.9897

The GHG emissions data and polynomial trajectories (extended by timestep = 30 years) are shown in *Figure 13* below (in the 'Scenarios_consolidated_final.xlsx' file). Of course, despite the high R^2 value, given the lack of datapoints for the 'China'-related surge in NAxB emissions after 2000 on which the polynomial line of best fit is based, as well as its long-term extrapolation, it must be noted that the 'NAxB_Parties' scenario is highly speculative. The lengthier AxB data series was source for greater confidence in the 'goodness' of the fit of that polynomial line of best fit, yet similar hesitations remain about the very long extrapolation.

Figure 13: GHG emissions 1960-2019 and two potentially relevant extrapolations



Despite these concerns, the line of best fit equations were then used to simulate emissions from 2020 onwards, using the following approach. First, the yearly timestep was converted to count data from year 1 to 111, representing 1960 to 2070. These count data were then used to solve the polynomial equation for each 'year', with x = 1 to 111. From timestep $x = 61$ (2020) onwards, the derivative of the equation at the immediately preceding timestep was used to calculate the next 'simulated' emissions value. This was extrapolated towards 2070, but was stopped once values turned negative (in 2053 for 'AxB Parties' and 2061 for 'NAxB Parties').

A further step was required at this point for the 'AxB Parties' scenario. Given the large (and increasing) difference in quantum (and direction) of NAxB and AxB parties' emissions by 2019, the 'AxB Parties' data had to be normalised to the 2019 level of total NAxB emissions. Thus, the difference between the real-world 2019 emissions for AxB and NAxB parties was calculated and this amount (~9519 $GtCO_2$) was added to all values after 2020 in the 'AxB Parties' scenario. As a result of this normalisation, the 'AxB_Parties' scenario could then be extended beyond its first negative year (in 2053), to 2069.

The time series were then assembled, using a composite of NAxB parties' real-world data (1990-2019) and projected values (>2020) derived from the polynomial equations. These series differ slightly in length: 1990-2069 for 'AxB_Parties' and 1990-2061 for 'NAxB Parties'.

4. ***'NAxB_NDC1'*** <u>and</u>
5. ***'NAxB_NDC2'***

The two scenarios developed under the PA framework of NDC pledges followed a similar process of development to the '*Paris_1*' and '*Paris_2*' scenarios for the AxB parties. However, to avoid the laborious task of finding, interpreting and standardising NDC pledges for about 150 NAxB parties, these scenarios focus on the 11 biggest NAxB emitters: Brazil, China, India, Indonesia, Iran,[90] Kazakhstan, South Korea, Mexico, Saudia Arabia, South Africa and Turkey. 'The Climate Tracker' was once again used to interpret the NDCs for these parties and the pledged emissions reductions are summarised in Table 26 below.

First, all emissions data from 1990-2019 were assembled for each of the 11 biggest emitters considered here. Next, the emissions reduction pledges were applied in the relevant target year(s). Where one of the 11 parties pledged a reduction within a range, or gave multiple reductions and baselines, then the reduction imposed in the target year was the average (i.e., of the range given or across the different baselines, respectively).

[90] Notwithstanding that Iran has signed, but is yet to ratify the PA.

Linear interpolation was used to fill the 'gap' after 2019 and any relevant target year(s). For those NAxB parties that did not pledge any 'net zero' target, the data were extended out to 2070 from the year following any target year using random number generation. The lower bound was 90% of the preceding year and the upper bound was the relevant target year 'cap'. As with the extension of AxB scenarios, the 90%lower bound reflected the maximum year-on-year reduction in the real-world GHG emission time series for NAxB parties (1960-2019).

Finally, a correction was applied to the total data, to account for the fact that the 11 largest emitters represented ~71% of all NAxB parties' emissions in 1990 and ~79% of all NAxB parties' emissions in 2019. Taking the average, a correction of $\sim\frac{1}{0.75}$ was applied to each annual total value in the scenarios 'NAxB_NDC1' and 'NAxB_NDC2' from 1990 to 2070.

Table 26: Summary of required/pledged reductions and baselines under climate regime – NAxB parties only.

NAxB parties	PA NDC1 (baselines as indicated)					PA NDC2 (1990 baseline, unless indicated)				
Target year:	**2025**	**2030**	**2050**	**2060**	**2070**	**2025**	**2030**	**2050**	**2060**	**2070**
Brazil	1.76 (1990) 1.05 (2010)	1.58 (1990) 1.06 (2010)				0.63 (2005)	0.57 (2005)	0		
China		1.33 – 1.56 (2010)		0			1.2-1.28 (2010)		0	
India		4.13-4.45 (1990) 1.46-1.61 (2010)			0		(no change)			0
Indonesia		5.35 (1990) 1.58 (2010)					(no change)		0	
Iran*		4.1 (1990)					(no change)			
Kazakhstan		0.83 (1990) 1.05 (2010)					(no change)			
South Korea		1.81 (1990)	0				0.6 (2018)	0		

NAxB parties	PA NDC1 (baselines as indicated)					PA NDC2 (1990 baseline, unless indicated)				
Target year:	2025	2030	2050	2060	2070	2025	2030	2050	2060	2070
		0.81 (2010) 0.756 (2017)								
Mexico		1.74 (1990) 1.18 (2010)					(no change)			
Saudi Arabia		4.16-5.62 (1990) 1.62-2.08 (2010) 1.35-1.72 (2015)					1.46-2.75 (1990) 0.81-1.24 (2019)		0	
South Africa		1.17-1.78 (1990) 0.74-1.12 (2010)					1.03-1.23 (1990)	0		
Turkey		3.56 (1990) 1.5 (2010)					(no change)	0 (2053)		

*Notwithstanding Iran's failure to ratify the PA, it has submitted an Intended Nationally Determined Contribution (INDC), on which its intended reductions here are based.

Application of scenarios to GHG emissions data

Having generated the scenarios for each class of party (seven AxB scenarios and five NAxB scenarios), they were then added together to form eight climate regime-wide scenarios, as shown in Table 27. The AxB and NAxB scenarios were combined using similar reasoning to that used in combining the AxB scenarios. That is, the 'best case' NAxB scenarios, being those modelled on developed country parties' 'flatter' emissions trajectory in the 'AxB_Parties' scenario, were added to each of the ***'_best'*** AxB scenarios. Conversely, the 'worst case'

NAxB scenario, being that modelled on developing country parties' 'surging' emissions trajectory in the 'NAxB_Parties' scenario, were combined with the '***_worst***' AxB scenarios. Given the very different structure and politics of the PA framework, these scenarios were not combined with those under the KP.

Table 27: Overall scenarios for both AxB and NAxB parties under the climate regime

	Scenario name (regime-wide)	**Constituent scenarios**	**Change >1990 (%)**	**Timestep (years)**	**Average annual change (%)**
1.	'No_Regime'	(single regime-wide scenario)	395%	80	4.94%
2.	'Actual'	=Actual_AxB+Actual_NAxB_Parties	158%	29	5.43%
3.	'KP_best'	=KP_best+AxB_Parties	-45%	79	-0.56%
4.	'KP_worst'	=KP_worst+NAxB_Parties	-43%	71	-0.61%
5.	'Doha_best'	=Doha_best+AxB_Parties	-51%	79	-0.65%
6.	'Doha_worst'	=Doha_worst+NAxB_Parties	-50%	71	-0.70%
7.	'Paris_1'	=Paris_1+NAxB_NDC1_CORR	-27%	80	-0.34%
8.	'Paris_2'	=Paris_2+NAxB_NDC2_CORR	-82%	80	-1.02%

For the purposes of the scenario 'swapping' exercise, as with the ozone regime scenarios, the next step was to derive a time series of year-on-year proportionate change for each regime-wide scenario. These proportionate series were then multiplied by the total ODS consumption figure for 1986 of 1,302,816 ODP tonnes and historical real-world ODS consumption was also provided as a reference 'scenario'.[91] Given the difference in baseline years noted earlier in relation to the ozone regime, the overall time series range shifted from 1990-2070 to 1986-2066. This represented the counterfactual 'world avoided', if the ozone regime had only imposed the less rigorous required reductions of the climate regime.

Interpretation of counterfactual ODS consumption data

To place the simulated ODS consumption results in their broader real-world context, the total cumulative consumption figures were calculated for each scenario time series. These were then compared with an historical ODS emissions dataset for the period 1961-2014, prepared by Our World in Data (Ritchie and Roser 2018b).[92]

[91] Once again, linear interpolation was used to bridge the 'gap' between the 1986 baseline and 1989 in the historical ODS consumption time series.
[92] https://ourworldindata.org/grapher/ozone-depleting-substance-emissions, which was itself based on data in figure Q0-1 in a previous WMO report (Hegglin et al. 2015, 7).

Three key assumptions were then made in order to convert the ODS consumption data, which had until now been used as a proxy for emissions, into estimated emissions data. These include assumptions about atmospheric lifetime, direction emissions and release factors, as detailed below. The estimation of ODS emissions proceeded as follows.

Although the original ODS consumption data were broken down by Annex / class of ODS, this differentiation was lost through the process of scenario development and by virtue of the need to derive overall proportionate change data. Nevertheless, the real-world ODS consumption data were compared to see how the relative share of total ODS consumption shifted between the different constituent classes of ODS over time. These data are shown as relative percentages, alongside the minima and maxima data, in rows 25 to 34 of the Worksheets labelled 'A5 Scenarios' and 'NA5 Scenarios'. Since the NA5 data included significant negative change, due to the effects of export data and ODS destruction technologies, these data were ignored and instead the percentages for the A5 data were used.

Having derived these percentage data, the first step was to take the average contribution of the individual Annex / class of ODS consumption figures as a percentage of overall ODS consumption, across the length of the time series. This showed that CFCs (Annex A/I) and HCFCs (Annex C/I) were the most dominant ODS in terms of relative consumption. Next, relevant ODS 'total lifetime' data were obtained from the most recent WMO Scientific Assessment of Ozone Depletion report (WMO et al. 2019, A.2-A.37). A substance's 'total lifetime' is the approximate amount of time that each ODS remains chemically active in the atmosphere, once emitted.[93] The applicable total lifetime of the most atmospherically abundant chemical species within each Annex group was taken to be representative of the total lifetime of all ODS consumed within that group. That is, the total lifetime figure for those ODS present in the highest atmospheric concentrations, according to Table A-1 in WMO (2019, A.2-A.37), was taken as the lifetime for any ultimate emissions from consumption within that Annex / class of ODS. Where more than one species was dominant, the total lifetimes were averaged. For example, the total lifetimes for CFCs and for Halons were averaged across the two most dominant species (CFC-11 and CFC-12, and Halon-1211 and Halon-1301, respectively). A 'weighted average total lifetime' was then calculated, using the overall relative consumption data and dominant species total lifetime data. These weighted average lifetimes were then summed to derive an overall 'total lifetime' for any ultimate emissions, as shown in Table 28 below.

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[93] 'Total lifetime' estimates account for both tropospheric and stratospheric loss, but only exceptionally does it include tropospheric Cl^- loss. Mesospheric loss is considered negligible, other than for very long-lived ODS (which do not dominate our time series here, so were ignored). Refer 'Footnote c' to Table A-1 in WMO (2019, A.38).

Table 28: Derivation of overall 'total lifetime' for emissions estimate

Annex Group / class of ODS		Avg. relative contribution to consumption 1986-2020 (%)	Total lifetime of dominant species (years)	Weighted avg. life-time (years)	Overall lifetime for all ODS (years)
A/I	Chlorofluorocarbons (CFCs)	36%	52 (CFC-11) 102 (CFC-12) **77** (avg)	28	**39**
A/II	Halons	8%	16 (H-1211) 72 (H-1301) **44** (avg)	3.4	
B/I	Other Fully Halogenated CFCs	0%			
B/II	Carbon Tetrachloride (CTC)	9%	**32**	2.9	
B/III	Methyl Chloroform (TCA)	1%	**5**	0.03	
C/I	Hydrochlorofluorocarbons (HCFCs)	43%	**12** (HCFC-22)	5.1	
C/II	Hydrobromofluorocarbons (HBFCs)	0%			
C/III	Bromochloromethane (BCM)	0%			
E/I	Methyl Bromide (MB)	3%	**0.8**	0.03	

Note that this 'total lifetime' is entirely theoretical, but it was developed by necessity because the finer resolution of the data, as originally differentiated by ODS / Annex Group, was lost in the scenario development process. The 'total lifetime' figure used here is largely a reflection of the shift from CFC-dominated consumption to HCFC-dominated consumption over the length of the real-world ODS consumption time series. In using this lifetime figure to convert the scenario ODS consumption figures into approximate emissions, this necessarily assumes that a similar shift in consumption would occur, from longer- to shorter-lived ODS, in each of the scenarios considered here.

The next step was to obtain indicative 'direct emissions' (DE) and 'release fraction' (RF) rates from the literature. RF rates reflect releases from 'banks' of ODS stored in refrigeration equipment, foams and other industrial applications. Lickley et al. (2020) recently investigated a range of DE and RF values for the three main CFCs (CFC-11, CFC-12 and CFC-113). This seemed particularly relevant here, given that the CFCs were one of the most dominant ODS in the consumption time series and that the scenario data totals are expressed in ODP tonnes, equivalent to CFC-11. Lickley et al. (2020) found DE factors ranging between 0.1-0.5 (CFC-11), 0.2-0.5 (CFC-12) and 0.3-0.7 (CFC-113) during the period from the mid-1980s to 2019. They found RF factors during the same period ranging from 0.05-0.1 (CFC-11), 0.07-0.2 (CFC-12) and 0.05-0.9 (CFC-113). For both DE and RF factors, there was more dynamism in the figures between 1986 and 2000, with steadier rates estimated from 2000 onwards. Accordingly, for the purposes of this thesis, the DE and RF factors shown in Table 29 below were applied to the ODS consumption data during the relevant periods to estimate ultimate ODS emissions.

Table 29: Direct emissions and release factors used to estimate ODS emissions from consumption data

Annex / class of ODS		**Period**	**DE**	**RF**
A/I	CFCs	1986-2000	**0.2-0.5**	**0.1-0.2**
		>2000	**0.1-0.3**	**0.05-0.1**

To apply all of the above assumptions in the context of this thesis, the eight scenario-based ODS consumption time series were copied and pasted into a fresh array of rows. The 'historical ODS' (i.e., real-world data for 1986-2020) were also repeated for added context. Total emissions for each of these nine time series were then determined as follows.

For every year of ODS consumption, a DE fraction was determined using random number generation (from 1986-2000, lower = 0.2, upper = 0.5; and from 2000 onwards, lower = 0.1, upper =0.3) and then extended across the length of each scenario time series.

Meanwhile, the RF was determined by random generation (from 1986-2000, lower = 0.1**bank*, upper = 0.2**bank*; and from 2000 onwards, lower = 0.05**bank*, upper =0.1**bank*). Here, '*bank*' represented the difference between the running total of ODS consumption, minus the running total of direct emissions <u>and</u>, after the first year of RF emissions, the total cumulative RF-based emissions. Thus, the size of the '*bank'* reduced over time, since the total

ODS consumption figures represented the theoretical maximum and there were annual losses due to direct emissions (DE) and previous bank releases (RF).

Finally, for those time series that exceeded 39 years in length, the overall 'total lifetime' calculated above was accounted for in year = t, by simply removing the total emissions from year = $t - 39$.

The total estimated emissions for each scenario time series were then calculated by summing each scenario's annual emissions fractions through DE, RF and (where relevant) total lifetime loss. The difference between the total ODS consumption 'stock' and these total emissive losses resulted in a theoretical 'remaining bank' for each scenario. The size of this remaining bank would determine the scale of the threat posed to the ozone layer, requiring careful monitoring, containment and/or destruction, and it was on this basis that the different scenarios were ultimately compared.

Table 30: Cumulative scenario totals for ODS consumption, total emissive losses and remaining 'bank'

Scenario name	ODS consumption (ODP t)	Total emissive losses (ODP t)	Remaining bank (ODP t)
'Historical ODS'	1.31E+07	1.24E+07	7.00E+05
'No Regime'	2.72E+08	1.53E+08	1.19E+08
'Actual'	4.93E+07	3.43E+07	1.49E+07
'KP_best'	1.25E+08	6.04E+07	6.50E+07
'KP_worst'	1.23E+08	7.05E+07	5.27E+07
'Doha_best'	1.19E+08	5.76E+07	6.15E+07
'Doha_worst'	1.19E+08	6.68E+07	5.21E+07
'Paris_1'	1.34E+08	6.72E+07	6.65E+07
'Paris_2'	1.07E+08	4.66E+07	6.03E+07

5.6 Interview with Professor Susan Solomon

Finally and in order to better inform the discussion of the results of this thesis, Professor Susan Solomon, the Lee and Geraldine Martin Professor of Environmental Studies at the Massachusetts Institute of Technology, graciously agreed to an interview via Zoom. The full transcript of that interview is available at the following link: https://phaidra.univie.ac.at/o:1536413. Edited extracts from that interview are included throughout this thesis. The interview audio recording is available at this link: https://phaidra.univie.ac.at/o:1536409.

6 Results & Discussion

This chapter combines the results from the different methods used in conducting this thesis. It begins with some descriptive statistics about the basic structure of the three implementing agreements, the MP, the KP and the PA, derived using textual analysis techniques. Then it introduces some general text-as-data results, including word count data, Jaccard similarity and hierarchical clustering results. These results are provided to give an overview and set the stage for the more detailed legal analysis that follows. Following the legal analysis, the implementing agreements' ratification rate data is introduced and discussed. Finally, the results from the counterfactual scenario development process are compared across the regimes, with these hypothetical results from each set of scenarios placed in their real-world context. For simplicity and consistency, in each case the results are first described and then discussed sequentially, rather than first describing and then discussing all results separately and subsequently.

6.1 Textual analysis results

A treaty or an international agreement often consists of two distinct structural components. First, a series of non-binding preambular paragraphs usually recite relevant aims, principles and motivations, and refer to significant events or phenomena at the start of an agreement. There then follows a series of substantive articles, which typically set out any binding obligations and procedural requirements. Thus, from the perspective of a party to an agreement, the preamble does not establish any rights or obligations, but the substantive articles may well do so (Rajamani 2016a, 343). For this reason, in the context of international negotiations, a distinction is often made between 'operative' (articular) and 'non-operative' (preambular) paragraphs (UNEP 2007, 69, 73, 77). Similarly, a treaty may or may not include certain technical or procedural information in an annex to the main agreement, in which case the annex will be given effect by a corresponding operative article.[94]

Having regard to this basic tripartite structure consisting of preamble – articles – annexes, the three implementing agreements were analysed using textual analysis techniques. The results show that the three agreements differed considerably, as summarised in Table 31.

[94] See, for example, MP2000 Articles 1(4) and 2A-2I and Annexes A to E; the KP Article 21 and Annexes A & B; the PA Article 23.

Table 31: Descriptive statistics for main implementing agreements of both regimes

	MP1987	***MP2000****	***KP***	***PA***
Number of preambular paragraphs	9	9	5	16
Preamble word count	241	241	68	458
Number of articles	20 (titled)	33 (titled)	28 (untitled)	29 (untitled)
Total number of words ('tokens')	4032	10814	8102	7032
Average number of words per article	202	328	289	242
Number of paragraphs in all articles	58	138	108	129
Average paragraphs per article	2.9	4.5	4.0	4.4
Total number of paragraphs	67	147	113	145
Words per paragraph (preamble + articles)	60	74	72	48
Number of annexes+	1 (A)	5 (A to E)	2 (A & B)	0

**Note that, for brevity here, the MP1987 was compared with the MP2000, as a proxy for the four[95] MP Amendments considered elsewhere. Given that the MP2000 also incorporates the text of a number of 'Adjustments', the text of which has not been analysed as part of this thesis, the MP2000 statistics are somewhat inflated relative to the plain text of the MP1987 and the four Amendments.*

+Note that the text in the annexes was not included in any of the textual or legal analysis.

A number of relevant observations flow from the above. Firstly, the KP had the shortest and least detailed preamble, whereas the PA had by far the longest, in terms of both number of preambular paragraphs (or 'recitals') and total preamble word count.

All agreements had roughly the same number of articles, although the MP1987 expanded from 20 to 33 articles through the successive Amendments up until the MP2000. It

[95] Being the LDN1990, CPN1992, MON1997 and BEI1999 (or, when referred to collectively, 'the Amendments').

was also apparent from a simple visual comparison of the different regimes that the articles in the MP had titles, whereas the articles in the KP and the PA were untitled. This was despite the provisions of both regime framework conventions (the VCPOL and the UNFCCC) having a title for each article.[96] This was significant as the titles in a treaty may be useful in its interpretation (*Vienna Convention on the Law of Treaties 1969* (VCLT), Art 31(1)-(2); Villiger 2009, 427). The decision to include titles in the UNFCCC[97] was a politically contentious one and for this reason the Chairman for the negotiations of the KP deliberately left all articles untitled in the negotiation drafts (Depledge 2000, 13). The absence of titles in the KP and the PA therefore provides another preliminary indication of the more intense controversy surrounding the climate regime and points to broader contextual factors that will be discussed in more detail later.

The total word counts differed wildly across the three implementing agreements. The MP1987 was about half as long as the KP or the PA, but the MP2000 was much longer than either the KP or the PA. The average number of words used per article[98] reflects a similar shift, with the MP1987 more economical with words in each article than the KP or PA, but the MP2000 was noticeably more verbose per article. Similarly, the Amendments added many more paragraphs up until the MP2000, which contained more than double the number of paragraphs compared to the MP1987, and more than either the KP or the PA. Likewise, the MP1987 contained noticeably fewer average paragraphs per article than the KP or the PA. However, by the year 2000 the MP2000 had a similar but slightly higher average number of paragraphs per article than the KP and the PA. Meanwhile, when the total word count was averaged across all (preamble and operative) paragraphs, the MP2000 and the KP had a similar average number of words per paragraph, and both had noticeably more average words per paragraph than the PA.

Once again, this all points to general trends that will be discussed in more detail below. First, the MP1987 tended to be succinct and technically drafted, whereas the KP and the PA were visibly lengthier and their provisions more prolix, but the more detailed MP2000 later bridged this grammatical gap between the two regimes. Importantly, the text of the MP2000 consolidated revisions to the MP1987 contained in several adjustments[99] and the four Amendments, particularly the two most substantial ones the LDN1990 and the CPN1992. Second,

[96] See various other contemporary MEAs with titled articles, including: the Alpine Convention Protocols; the Cartagena Protocol; the Long-range Transboundary Pollution protocols; and the Environmental Protection Protocol to the Antarctic Treaty.
[97] See footnote to Article 1, entitled 'Definitions'.
[98] Not including the preambular paragraphs or 'recitals'.
[99] The text of which has not been studied here.

the differing lengths and levels of detail between the regimes must be kept in mind in considering the text-as-data and legal analysis results. Without (yet) knowing the content of these words, paragraphs and articles, it suffices for now to infer from the above that the ozone regime tended to demonstrate more 'precision' than the climate regime. This greater 'precision' is indicated by the presence of titles for every one of its articles, the addition of more words across multiple metrics over time (refer Table 31) and by making greater use of technical annexes than the climate regime. Of course, these are neither firm nor particularly well-founded conclusions at this stage, but these descriptive statistics set the scene for the results that follow below.

6.2 Text-as-data results

The results from the text-as-data analysis of the two regimes are summarised below, before being further discussed and placed into broader context in the more detailed legal analysis.

6.2.1 Overall word counts

Figure 14: 'Word cloud' for 'corpus' of all implementing agreements

The most frequently used words in the eight-text 'corpus'[100] from across the two regimes were visualised using the data mining software Orange to create the 'word cloud' in

[100] The eight texts: the MP1987, the LDN1990, the CPN1992, the MON1997, the BEI1999, the MP2000, the KP and the PA.

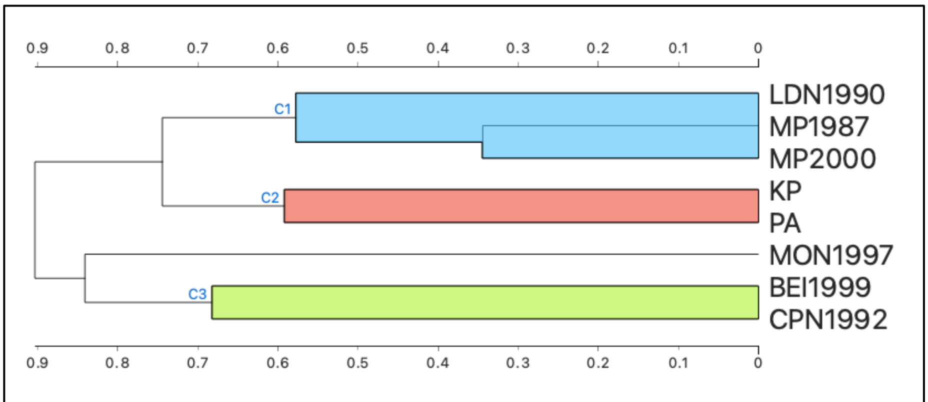
Figure 14. The greater the size of the word in the word cloud and the closer it is positioned to the centre, the higher the frequency of occurrence of that word in the corpus. Thus, 'shall' was clearly the most frequently used word across the corpus, followed by 'substance', 'level', 'calculated', 'production', 'controlled', 'consumption', 'exceed', 'group', 'ensure' etc. Note that the word cloud does not include certain 'stopwords' (e.g., 'the', 'a', 'and') and frequently used, but analytically uninteresting words (e.g., 'convention', 'parties', 'meeting', 'agreement'), which were removed in text pre-processing.

6.2.2 Jaccard distances

The trends emerging from the preliminary descriptive statistics were reinforced by the Jaccard distance data. Figure 15 is a composite of the Jaccard distance matrix and hierarchical clustering of the corpus based on that matrix. Recall that a Jaccard distance closer to 0 reflects a higher degree of similarity between documents, as visualised in the hierarchical clustering diagram. The Jaccard distance data show, somewhat unsurprisingly, that the MP1987 and MP2000 were the two most similar agreements in the corpus ($J_{(MP1987,MP2000)} = 0.344$). The next most similar agreements were the LDN1990 and the MP2000 ($J_{(LDN1990,MP2000)} = 0.494$), which reflects the more substantial contribution of the LDN1990 towards the MP2000 among the four Amendments analysed.

Note also that the KP and the PA ($J_{(KP,PA)} = 0.591$) were the next most similar agreements within the corpus, albeit without as clear a 'lineage' of similarity as between the

Figure 15: Jaccard distance matrix and hierarchical clustering



	BEI1999	CPN1992	KP	LDN1990	MON1997	MP1987	MP2000	PA
BEI1999		0.681	0.959	0.875	0.817	0.908	0.914	0.968
CPN1992	0.681		0.883	0.727	0.863	0.778	0.752	0.912
KP	0.959	0.883		0.766	0.949	0.689	0.650	0.591
LDN1990	0.875	0.727	0.766		0.891	0.659	0.494	0.812
MON1997	0.817	0.863	0.949	0.891		0.930	0.900	0.965
MP1987	0.908	0.778	0.689	0.659	0.930		0.344	0.734
MP2000	0.914	0.752	0.650	0.494	0.900	0.344		0.719
PA	0.968	0.912	0.591	0.812	0.965	0.734	0.719	

MP1987 and MP2000. In fact, the KP is almost as similar to the MP1987 ($J_{(KP,MP1987)}$ = 0.689) and the MP2000 ($J_{(KP,MP2000)}$ = 0.650), as it is to the PA; while the PA is even less similar to the MP1987 $J_{(PA,MP1987)}$ = 0.734) and MP2000 ($J_{(PA,MP2000)}$ = 0.719).

Within the ozone regime, the MP1987 and the LDN1990 were most similar ($J_{(MP1987,LDN1990)}$ = 0.659), closely followed by the CPN1992 and the BEI1999 ($J_{(CPN1992,BEI1999)}$ = 0.681).

Finally, the MON1997 was the most dissimilar to all others in the corpus, while the PA and the BEI1999 were the most dissimilar of any two agreements $J_{(PA,BEI1999)}$ = 0.968).

6.2.3 Use of verbs across corpus

The verb used in drafting a provision of a treaty substantially, but not decisively, determines the nature of that provision, particularly whether it is considered 'binding' (Bodansky 2016, 145; Rajamani 2016a, 343). In considering whether a treaty provision is 'binding', the nature of enquiry is whether the particular provision entails an obligation (UNEP 2007, 15) and if that obligation is imposed on a State party, since relevant international law only recognises States as having the legal capacity to conclude a treaty (VCLT 1969, Arts 2(1)(a), 6).

By reference to the previously defined hierarchy of verbs, the corresponding word count results from the Orange software are summarised in Table 32.

Table 32: Verb count results

	MP 1987	***LDN 1990***	***CPN 1992***	***MON 1997***	***BEI 1999***	***MP1987 + Amendments***	***MP 2000***	***KP***	***PA***
Can	1					1	2	1	4
Encourage	1					1	1		
May	21	19	3	2	2	47	45	31	20
Shall	69	75	32	12	13	201	191	158	117
Should	8					8	7	1	25
Strive						0		2	1
Undertake	4	1				3	1		3
Will	3	1	4		1	9	15	1	6

The column headed 'MP1987 + Amendments' represented the cumulative total for the MP1987 and the four Amendments. This was included for comparison with the MP2000 results to show the subtle effects of article amendment and replacement over time, as well as the effect of the various adjustments consolidated in the MP2000.[101]

The verb count data showed that 'shall' predominated across all agreements in the corpus, followed by 'may' and 'should'. The other verbs were only used sporadically across the agreements, but this did not necessarily diminish their significance, as will be seen in the context of the use of 'undertake', below. Similarly, the mere use of a certain verb, such as the typically mandatory 'shall', was not significant of itself. It did not mean that an obligation that was binding on the parties automatically flowed from the presence of that verb. If it were that simple, the text with the most instances of 'shall' could merely be declared the most 'binding'. In reality, as above, the verb used in a provision strongly indicates its character, but that cannot be empirically decisive in every case. At this point, contextual factors come to the fore, requiring further analysis not just of the verb, but the of the position of the clause within the agreement (e.g., preamble or article), the subjects of the obligation (e.g., each party, a class of party, all parties, or none, if drafted passively), the content of the provision, the precision of the provision and whether any qualifying language or phrases were used (Werksman 2010; Rajamani 2016a, 343; Bodansky 2016, 145). Such careful contextualisation was the primary task in the legal analysis below. That analysis focussed on certain instances of use of the verbs in the hierarchy and compared relevant provisions in key thematic areas common to both regimes.

In summary, the preliminary data above suggested that the structure and language used in the ozone and climate regimes were distinct, albeit with some degree of similarity. The legal analysis aims to bridge the evidentiary gap between these preliminary trends and results indicated from the descriptive statistics and text-as-data analysis, in pursuit of the aims and hypotheses of this thesis.

6.3 Legal analysis

As discussed in Chapter 5, this thesis identifies and applies the following hierarchy of verbs that appear in the regimes under study (in descending order of 'bindingness'): *undertake, shall, should, encourage, may, will, can* and *strive*.

The results of the legal analysis below are grouped by overarching thematic areas that are, as far as was possible to discern, characterised by reference to identifiably similar

[101] Again, the text of which is beyond the scope of this thesis and so has not been analysed here.

concepts across the regimes. Conversely, and finally, certain ‘wildcard’ terms unique to a particular agreement are briefly discussed in the context of divergence and differentiation between the regimes. With reference to the comparative ‘anatomy’ of the regimes set out in Table 3 (Chapter 3), the legal analysis focusses on the following topics common to all agreements and essential to the regime design:

6.3.1 Purpose of implementing agreements and defined atmospheric pollutants;
6.3.2 Reference baselines
6.3.3 Regime control mechanisms relating to the relevant atmospheric pollutants;
6.3.4 Regulation of trade in atmospheric pollutants;
6.3.5 Transfer of technologies to reduce production of atmospheric pollutants;
6.3.6 Financial transfers for the required technological and social transformations;
6.3.7 Monitoring and review;
6.3.8 Non-compliance; and
6.3.9 Miscellaneous.

6.3.1 Purpose of implementing agreements

As established by Article 31 of the VCLT, the purpose of a treaty is essential to the interpretative task. The stated purpose of each of the three implementing agreements differed considerably in scope, timing and specificity.

The MP and Amendments

The MP did not state its intended purpose in any substantive article. In the absence of such a clear statement, recall that preambular paragraphs can be used to infer the object and purpose of an agreement, although they do not operate to confer rights or obligations (Rajamani 2016a, 343). Here, preambular paragraph 6 (PP6) gave a clear indication of the MP’s purpose:

> ‘Determined *to protect the ozone layer by taking precautionary measures to control equitably total global emissions of substances that deplete it, with the ultimate objective of their elimination on the basis of developments in scientific knowledge, taking into account technical and economic considerations’*.
>
> (emphasis *in original*)

Note that PP6 of the MP uses the verbs '*protect*' and '*control*', with the explicit goal of the MP (its '*ultimate objective*') being the '*elimination*' of total global ODS emissions.[102] PP6 also refers to several principles that were relevant when compared against similar language in the climate regime: '*precautionary measures*', the equitable control of emissions ('*control equitably*') and '*scientific… technical and economic*' considerations.

The Kyoto Protocol

Like the MP, the KP did not contain any express objective in a substantive article,[103] but several of its preambular paragraphs invoked relevant provisions of the UNFCCC and recall that the UNFCCC's objective extends to '*any related legal instruments*' made under it.[104] Thus, PP2 of the KP recited that the parties were in pursuit of the '*ultimate objective*' in UNFCCC Article 2. Further, PP4 said the parties were '*guided by*' the principles in UNFCCC Article 3. Those principles include the '*precautionary principle*', '*common but differentiated responsibilities*' and '*respective capabilities*', '*low cost, sustainable development*' within a '*supporting and open international economic system*' and the '*special situation of developing countries*'. These echo and expand on the MP principles.

The Paris Agreement

In contrast, the PA's ostensible purpose was expressed in a substantive article ('*This Agreement… aims*'),[105] which stated the PA's landmark global average temperature goals. Those dual goals were to hold '*the increase in the global average temperature to well below 2°C above pre-industrial levels*', while '*pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels*'.[106] These goals were intended to enhance the '*implementation of the Convention, including its objective*'.[107] Note that the goals did not explicitly link the prospect of 2°C of warming with the concept of '*dangerous*' climate change in the UNFCCC (Ghaleigh 2021, 76),[108] but it did shed further light on that vague concept, as the PA

[102] Another meaning might be the elimination of ODS (per se), but having regard to '*scientific… technical and economic*' factors and given that ODS-destroying technologies exist, this militates in favour of a less extreme interpretation.
[103] The practical purpose of the KP was the Annex B (AxB) parties' required 5% GHG emissions reduction (from 1990 levels) in the 2008-2012 commitment period – refer Art 3, but since it wholly ignores the Non-Annex B parties, it is difficult to attribute this as the objective of the agreement as a whole.
[104] UNFCCC Art 2. See also Art 4(2)(b), which refers to the '*aim*' for developed country parties to return to 1990 emissions levels, but this was expressed in the context of an obligation to '*communicate progress*' and in any event UNFCCC Art 4 is not picked up and given effect by any reference in the KP or PA here.
[105] PA Art 2. See also Art 3: '…with the view to achieving the purpose of this Agreement as set out in Article 2'.
[106] PA Art 2(1)(a).
[107] PA Art 2(1).
[108] *Cf*: the (dubious) claim that the PA's temperature goals 'supplant' the UNFCCC's 'nebulous' goal (Colburn 2019, 192–93).

recognised that the temperature goals '*would significantly reduce the risks and impacts of climate change*'.[109]

In addition to the global temperature goals in Article 2(1)(a), the PA placed equal emphasis on increasing adaptation, climate resilience and low GHG emissions development, without threatening food production,[110] and making finance flows consistent with low GHG and climate-resilient development pathways.[111]

The PA also contained several PPs relevant to its purpose. PP3 said the PA was made '*in pursuit of*' the objective of the UNFCCC, but did not cite Article 2.[112] PP3 also referred to '*being guided by*' the principles of the UNFCCC,[113] including the '*principle of equity*', '*common but differentiated responsibilities*' and '*respective capabilities*', in light of '*different national circumstances*'. These principles were reinforced by substantive Article 2(2) of the PA, which largely repeated PP3, albeit downgrading the reference to '*equity'* from a '*principle'* to a requirement to simply '*reflect equity*'. The PA was also unique among the three agreements, and indeed treaties more generally, for its combination of binding, non-binding, observational and exhortatory (encouraging) statements within the ostensibly operative provisions of its text (Rajamani 2016a).

Summary

To summarise all of the above, picking an appropriate science-based target is an exercise fraught with ethical and value judgements (Knutti et al. 2016). The MP had the surprisingly direct ultimate objective to eliminate ODS emissions, consistent with scientific evidence of stratospheric ozone depletion. Of the three agreements, this was the most ambitious objective in its scope, although it was silent as to timing ('*ultimate*') and was located in the preamble, which severely limited its utility. By contrast, the KP merely recited the aims and principles of the UNFCCC, which was a very deliberate negotiating decision to minimise political risk (Depledge 2000, 100–101). Although the emissions reduction obligations the KP imposed on AxB parties in Article 3 could be taken to be its most obvious purpose in practical terms, such a construction would otherwise leave NAxB parties rather 'aimless'. Meanwhile, after the dangerous ambiguity of the UNFCCC objective, the PA's temperature goals represented a 'quantifiable and verifiable global target' (Colburn 2019, 193). Such temperature-

[109] PA Art 2(1)(a).
[110] Ibid Art 2(1)(b).
[111] Ibid Art 2(1)(c).
[112] In fact, the only explicit mention of UNFCCC Art 2 throughout the PA was made in the context of the '*enhanced transparency framework*' in PA Art 13(5). Even then, the purpose of the framework was weakly expressed as providing a '*clear understanding of climate change action in the light of the objective*' in Art 2.
[113] Unlike the KP, without expressly referring to Article 3.

based GHG emissions targets had a long gestation since at least the 1990s, represented a 'least-bad' option in a moral and ethical minefield for natural scientists and enabled the development of the easy to grasp concept of a 'carbon budget' (Knutti et al. 2016; Schleussner et al. 2016).

Although not strictly necessary to the main interpretative task at hand, note the other considerations and principles that were referred to alongside each agreement's objectives. The language in the ozone regime referred to a narrower range of mainly scientific and technical considerations, whereas the climate regime expanded their scope and emphasised social and economic development factors alongside scientific issues. The blending of the language of obligation with the language of ambition in operative paragraphs, which is the hallmark of the PA, is also apparent from the inclusion of Article 2(2).

Defined atmospheric pollutants

The architecture of any legal regime requires subject matter. Here, the MP listed over 76 '*controlled substances*' (i.e., ODS) with '*ozone-depleting potential*' (ODP) in Annexes A through E.[114] In addition, many isomers of the controlled ODS were captured under the ozone regime. By contrast, the KP listed just six GHGs in its Annex A. The PA adopted[115] the same definitions as the UNFCCC and referred repeatedly to '*greenhouse gases*',[116] but unlike the KP, it did not include an annex of GHGs. Regardless, decades of State practice in reporting national inventories of emissions of the six GHGs listed under Annex A to the KP suggest that this is now an accepted part of the climate regime (Van Calster and Reins 2021, 64).

In short, the MP regulated a wider range of atmospheric pollutants emitted in smaller volumes, while the KP and the PA regulated a narrower range emitted in greater volumes.

6.3.2 Reference baselines

An essential component of both the ozone and climate regimes was the requirement for each party to prepare and provide reports on ODS- and GHG-generating activities. Both the VCPOL and the UNFCCC required parties to support international research and systematic observation,[117] and to cooperate and exchange information across various legal, scientific and technical fields.[118] Both conventions also required the parties to provide regular reports on

[114] Since the *Kigali Amendment* in 2016, there is now also an Annex F, but neither the Kigali Amendment nor the text of the Annexes were considered here.
[115] PA Art 1.
[116] Defined in UNFCCC Art 1(5).
[117] VCPOL Art 3; UNFCCC Art 5.
[118] VCPOL Art 4 and Annex II; UNFCCC Art 4(1)(g).

these activities and this information to the respective regime secretariats.[119] However, the details and timing of these reports were left to the implementing agreements[120] and relevant decisions of the meetings of the parties.[121] The provision of this information was fundamental to each regime because it established clear ODS/GHG reference baselines for required reductions and to track progress towards the fulfilment of the regimes' objectives. Relevantly, given the importance of this information to the regimes, the reporting requirements across all three implementing agreements are phrased in the language of obligation ('*shall*') and directed at 'each party' individually,[122] with subtle yet important differences in drafting.

The MP and Amendments

The MP contained a range of baselines, depending on the ODS and the development level of the parties. Non-Article 5 (NA5, developed country) parties were subject to single year baselines, while those parties operating under Article 5 (A5, developing countries) were subject to fixed multiyear average baselines. The baselines for the ODS listed in Annex A (1986 [NA5 parties] / avg. 1995-1997 [A5 parties]) were earlier than those for the ODS listed in Annex B (1989 / avg. 1998-2000). The baselines grew progressively later for the ODS listed in Annex C (1989 / avg. 2009-2010) and Annex E (1991 / avg. 1995-1998). This reflected the progressive development and addition of further ODS to the ozone regime over time, such as the use of hydrochlorofluorocarbons (HCFCs) as an early substitute for CFCs, before their ozone-depleting effects were discovered and further substitutes were developed.

The MP imposed baselines for both ODS 'production'[123] and 'consumption'.[124] The baseline was described as a '*calculated level of production'* and '*…consumption*'. The '*calculated level*' phrase typically appeared four times for each control measure; once to refer to the party's transient level of consumption and then again to refer to the fixed baseline level. This wording was then repeated in the subsequent sentence, but applicable to production. Meanwhile, the definitions of '*production'* and '*consumption'* in Article 1 set out simply how to account for these quantities, including any imports and exports of controlled ODS. The MP then required each party to report statistical data on controlled ODS to the Ozone Secretariat

[119] VCPOL Art 5; UNFCCC Art 12(1)(a).
[120] MP Art 7 ('shall provide… statistical data'); KP Art 7(3) ('shall submit the information required'); PA Art 13(7) ('shall regularly provide the following information').
[121] See, for example, paragraph 90 of Decision 1/CP.21 made under the PA.
[122] MP, KP and PA, above n 17.
[123] MP Art 1(5): 'the amount of controlled substances produced, minus the amount destroyed by technologies to be approved by the Parties'.
[124] MP Art 1(6): 'production plus imports minus exports of controlled substances'.

annually.[125] This included relevant baseline year data,[126] as well as annual volumes produced, used as feedstock, destroyed and imported/exported.[127]

The Kyoto Protocol

The KP adopted 1990 as its baseline reference year for GHG emissions,[128] with some exceptions.[129] The KP required only those parties listed in Annex I to the UNFCCC (developed countries) to '*provide… data*' to the Subsidiary Body for Scientific and Technological Advice to establish their 1990 '*carbon stocks*' and to estimate subsequent changes in those stocks,[130] with much of the detail, including more precise accounting methods, to be determined by a decision of the COP serving as the meeting of the parties to the KP (CMP).[131] Any such decision by the CMP would only apply in the second and any subsequent '*commitment periods*'.[132] However, the KP also required ('*shall*') Annex I parties to have in place by 2007 at the latest, a national system for estimating GHG sources and sinks, by reference to the IPCC and its methodologies. [133]

Article 3(3) of the KP defined verifiable changes in these '*carbon stocks*', consisting of net GHG '*emissions by sources and removals by sinks*',[134] as the basis for Annex I parties to meet their commitments under the KP. Thus, in effect the KP linked the GHG inventory reports already required under the UNFCCC with the commitments made by Annex I parties under Article 3 of the KP and required that these parties provide the necessary '*supplementary information*' to demonstrate '*compliance'* with their commitments under the KP.[135] These reports were required annually.[136]

The Paris Agreement

The PA did not specify any overall baseline reference year.[137] It required each party to '*regularly'* provide information '*necessary to track progress'* made towards their '*nationally*

[125] See MP2000 Art 7.
[126] MP2000 Art 7(1) and (2).
[127] MP2000 Art 7(3).
[128] KP Art 3.
[129] See KP Art 3(5), (8). Decision 9/CP.2 at COP2 granted an alternative baseline to Bulgaria, Hungary, Poland and Romania (Depledge 2000, para. 235).
[130] KP Art 3(4).
[131] Ibid Arts 3(4), 7(4). See also 'COP' in Glossary of Terms.
[132] Ibid.
[133] Ibid Arts 3(4), 5(2) and (3).
[134] Ibid 3(3). UNFCCC Art 1(4),(8),(9) define '*emissions'*, '*sink'* and '*source'*, respectively.
[135] KP Art 7(3).
[136] Ibid.
[137] Note the combined effect of PA Art 21(2), para 104 of Decision 1/CP.21 and Annex I to FCCC/CP/2015/10. The 2015 baseline GHG emissions figures have a 'special meaning' (VCLT Art 31(4)) and this baseline only applies for the purposes of the PA's EIF provision in Art 21.

determined contribution' under Article 4,[138] but this was not explicitly related to the overall temperature goals. It largely continued the system of national GHG inventory reports established by the UNFCCC and the KP, including a requirement that they be based on '*good practice methodologies*' accepted by the IPCC, but did not require them annually.[139]

In summary, the MP and the KP provided for clear baselines, whereas the PA did not. The MP demonstrated a consistent differentiated approach to baselines, based on class of ODS and class of party (A5/NA5). The KP established an overall 1990 baseline for Annex I parties, but then permitted certain exceptions for 'economies in transition'[140] and the optional use of 1995 baselines for three of the six GHGs listed in Annex A.[141] Since no GHG emissions reduction commitments were imposed on Non-Annex I parties, no such reporting requirements were imposed on them by the KP. By contrast, since the PA applied to all parties, it did not set an overall baseline and required only 'regular', rather than annual reports.

6.3.3 Regime Control mechanisms

Having considered the agreements' overarching purpose, the atmospheric pollutants they target and their baselines (where relevant), this section considers the key operative paragraphs of each agreement: their control mechanisms. Consistent with the trends apparent in the earlier results, the key operative paragraphs of each agreement differed wildly in their drafting.

The MP and Amendments

The MP and its Amendments introduced a comprehensive suite of control measures, following a consistent formulation for every 'control measure'. Using clear titles, every article in this part of the MP was linked with a correspondingly titled annex, which listed the controlled ODS within that class, as follows:[142]

1. Article 2A (Annex A Group I, CFCs);
2. Article 2B (Annex A Group II, Halons);
3. Article 2C (Annex B Group I, Other fully halogenated CFCs);
4. Article 2D (Annex B Group II, Carbon tetrachloride);
5. Article 2E (Annex B Group III, Methyl chloroform);
6. Article 2F (Annex C Group I, HCFCs);

[138] PA Art 13(7).
[139] See PA Art 13(7): '*Each party shall regularly provide*'. *Cf*: KP Art 7(1), (3).
[140] KP Art 3(5). Mainly countries of the former USSR or Yugoslavia.
[141] Ibid 3(8).
[142] All references to Articles/Annexes of the MP2000.

7. Article 2G (Annex C Group II, Hydrobromofluorocarbons);
8. Article 2H (Annex E, Methyl bromide); and
9. Article 2I (Annex C Group III, Bromochloromethane).

The operative paragraphs within each article were sequential; the first one imposed the first required reduction in consumption/production of a given ODS by reference to the baseline level, with subsequent operative paragraphs then imposing the further required reductions (if applicable), in separate paragraphs. By reference to the hierarchy of verbs, the MP persistently used the construction '*shall ensure*' together with the negative '*does not exceed*' relative to the baseline. In all cases, '*shall'* was used as a modal verb, indicating that compliance was required with the action that was the subject of the subsequent verb (i.e., ensuring that minimum required reductions in ODS production and consumption were not exceeded). The drafting structure was as follows:

> ***Each party shall ensure*** *that for* [the first year of any required reduction and every year thereafter] *its calculated level of* ***consumption*** *of the controlled substance in* ***Annex*** [A to E] ***does not exceed****, annually, its calculated level of* ***consumption*** *in* [baseline year]. ***Each Party*** *producing the substance* ***shall****, for the same period,* ***ensure*** *that its calculated level of* ***production*** *of the substance* ***does not exceed****, annually, its calculated level of* ***production*** *in* [baseline year].
>
> **(emphasis added)**

The usual pattern was to use '*shall ensure*' twice: once for placing a required reduction on ODS consumption and once for placing the same reduction on ODS production.[143] Note that each pair of obligations applies to each party individually and that the limit is phrased in terms of the negative '*does not exceed*', which was then linked to the baseline year. This basic drafting pattern was followed consistently in Articles 2A to 2I across all Amendments, as further ODS were identified, included in additional Annexes and brought under the 'control measures'. Since each of the nine Articles above dealt with a separate ODS and there was a pair of required reductions to both consumption and a production for each one, there were at least 18 such reduction obligations imposed on each party. However, each controlled ODS was subject to a different reduction schedule, so each Article imposed a different number of reduction steps. Every step in a reduction schedule gave rise to a further pair of reduction obligations. For example, the five-step reduction schedule in Article 2H contained 10 pairs of

[143] There were exceptions to this, such as MP2000 Art 2I, which imposed one single reduction (to zero) in both consumption and production.

reduction obligations for each party, while the single-step reduction schedule in Article 2I imposed a single obligation to reduce both consumption and production of Bromochloromethane to zero. Nevertheless, in general, the more required reductions for a given ODS, the more repetition of this drafting structure and hence the more binding language was used.

Through amendments, or similar 'adjustments', agreed by the Meetings of the Parties, some of the ODS reduction schedules were brought forward. With the exception of the London Amendment, which permitted an increase in consumption/production of up to 150% of 1986 levels for an 18-month period in 1991 to 1992, all amendments and adjustments to 'control measures' were progressive; they did not permit backsliding.

There were several important modifications to this general drafting structure. One important exception related to ODS *production*: parties operating under Article 5 (developing country) parties were allowed to exceed the relevant baseline year ODS production level by 10-15%, if this was necessary to meet their '*basic domestic needs*' (an undefined term). The very first mention of this exception in Article 2A(1) of the MP2000 states that any such minor increase '***shall be permitted only*** *so as to satisfy the* **basic domestic needs** *of the Parties operating under Article 5 and for the purposes of industrial rationalization*[144] *between Parties*'. Despite introducing several further basic domestic needs exceptions, this was the one time that the construction '*shall be permitted only*' was used, with all subsequent references to '*basic domestic needs*' shifting to a different construction using '*may'*.[145] The use of 'shall' in this way was somewhat permissive and the use of the qualifier 'only' indicates that it was probably intended to be a strictly limited exception.[146] Ironically, however, the '*basic domestic needs*' exception eventually proliferated to the point that it became subject to its own series of subsidiary required reductions,[147] in which the construction '*shall ensure*' was used once again. But since the '*basic domestic needs*' exception was only open to developing country parties operating under Article 5, these additional obligations applied only to that class of party, whereas the main required reductions discussed above applied to every party equally.

Another significant and deliberate structural modification to this general drafting structure was the differentiation between the same two classes of parties, A5 and NA5 parties, as was discussed in the context of the relevant baselines. Recall that A5 parties were usually subject to fixed multiyear average baselines. Article 5(1) of the MP entitled the A5 parties to

144 '*Industrial rationalization*' was defined in Article 1 as transfers of calculated production levels between parties on economic grounds. It was used five times in the MP1987 (in Arts 2(1)-(5)), but after the LDN1990 only one reference to it remained in Article 2A(1).
145 Using the more permissive '*may exceed*'.
146 Similarly limited exceptions applied for '*essential'* uses (see, for example, MP2000 Art 2B(2)) and in '*quarantine and pre-shipment applications*' (see, for example, MP2000 Art 2H(6)).
147 See, for example, MP2000 Art 2H(5*bis*) and (5*ter*).

delay their compliance with the control measures in Articles 2A to 2E for up to 10 years, in order for them to meet their '*basic domestic needs*'. This must be briefly distinguished from the earlier '*basic domestic needs*' exception. When used in the context of that exception, the phrase entitled A5 parties to increase their ODS *production* above baseline levels by between 10-15%. In Article 5, the whole suite of control measures required under Articles 2A to 2E were simply delayed for 10 years. Put differently, once the control measures would take effect for the A5 parties after 10 years, the '*basic domestic needs*' exception for production would continue to operate for A5 parties.[148] Thus, the same phrase provided the basis for two very different exceptions to the control measures in 2A to 2E.

A combination of relevant factors meant that NA5 parties were subject to larger absolute cuts in ODS consumption than A5 parties. First, ODS production and consumption activities were concentrated in NA5 party States. Second, the earlier, single year baselines for NA5 parties tended to result in a larger maximum ODS production/consumption 'cap' than the later, multiyear baselines for A5 parties. However, by agreeing in advance to such an arrangement, the NA5 parties effectively 'bet' that they would be able to assist the A5 parties, through trade, technology and financial transfers, to minimise the future multiyear baselines. This could therefore be interpreted as having also introduced a structural incentive for them to do so.

The Kyoto Protocol

The KP was remarkable for directing almost all of its obligations, and certainly the only quantified emissions reductions, at Annex I parties alone. Article 10 was the only substantive article directed at 'All Parties';[149] almost all other articles required action by Annex I parties only. This analysis focuses on the Annex I parties' obligations under Article 3, which sets out the required reductions in GHG emissions as follows:

> ***The Parties included in Annex I shall, individually or jointly, ensure*** *that their* ***aggregate*** *anthropogenic carbon dioxide equivalent* ***emissions*** *of the* ***greenhouse gases listed in Annex A do not exceed*** *their* ***assigned amounts****, calculated pursuant to their quantified emission limitation and reduction commitments inscribed in Annex B and in accordance with the provisions of this Article,* ***with a view to reducing*** *their overall*

[148] Ibid and see discussion in text. This explains the need for the additional subsidiary series of 'basic domestic needs' reduction schedules.
[149] Other than those provisions directed at 'all parties' acting as the 'Conference of the Parties', in which context the provisions impose certain procedural obligations on the COP as a body, so those references are ignored for present purposes.

emissions of such gases ***by at least 5 per cent below 1990 levels*** *in the* ***commitment period 2008 to 2012****.*

(emphasis added)

The terms in **bold** were then analysed sequentially as follows.

- ***'The Parties included in Annex I'***

As noted earlier, the KP generally and Article 3 here was directed solely at those parties listed in Annex I of the UNFCCC.[150] Note that it refers to the parties collectively, which gives this drafting slightly more latitude than if it had said 'each party' in Annex I (Rajamani 2016a).

Article 3 goes on to mention Annex B in the context of these parties' required reductions, but Annex I to the UNFCCC and the list of countries in Annex B are not the same. Annex B omits Belarus and Turkey, who were only listed in Annex I after later becoming parties to the UNFCCC (with Turkey requesting it be deleted from the list), without assuming any corresponding obligations under the KP and its Annex B (Depledge 2000, paras 455, 482).

All of the following terms should be read together, as they relate to one another in important ways:

- ***'shall… ensure'***
- ***'individually or jointly'***
- ***'aggregate… emissions'***
- ***'greenhouse gases listed in Annex A'***
- ***'do not exceed'***
- ***'with a view to reducing'***
- ***'by at least 5 per cent below 1990 levels'***

By contrast to the extensive use of this construction in the MP, the KP only used the phrase '*shall ensure*' twice.[151] Similar to the MP, the KP used the formulation '*shall ensure'* with the negative '*do not exceed*' to create what was clearly intended to be a mandatory obligation (Depledge 2000, 31–32), consistent with the political fallout it caused (Sunstein 2007, 20). However, the use of '*individually or jointly*' departed from the MP formula. This subclause served to make Article 3(1) more permissive, by allowing Annex I parties to achieve

[150] As defined in KP Art 1(7).

[151] See KP Art 12(8), where it was used to impose an obligation on the CMP to ensure that certain administrative funds were used for particular purposes. This provision is copied almost verbatim in PA Art 6(6). As above, since these constitute procedural obligations and were directed at the CMA as a *body*, rather than as individual parties, those provisions were ignored.

their commitments by collective action. This was included after sustained lobbying by the EU and despite other delegations' protests (Depledge 2000, paras 143–146).

The term '*aggregate… emissions*' was a necessary corollary of allowing the Annex I parties to achieve their commitments through joint action. Similar to the MP, by referring to the six GHGs in Annex A, Article 3(1) gave effect to the corresponding list of defined atmospheric pollutants. However, the Annex I parties were free to take action on any of the six GHGs and no gas-by-gas reductions were proposed in the KP, in contrast to the MP.

Meanwhile, the use of the qualifier '*with a view to reducing*' marked a further departure from the MP drafting. This phrase operated here to effectively add the 'collective target' of at least a 5% overall reduction below 1990 levels (Depledge 2000, paras 216–221), to what was otherwise an obligation for the Annex I parties to achieve their assigned amounts in Annex B.

- ***'assigned amounts'***

Once again, this phrase must be read together with the phrases *'quantified emission limitation and reduction commitments inscribed in Annex B'* as well as *'and in accordance with the provisions of this Article'*. This is because the phrase '*assigned amounts*' referred to both the '*quantified emission limitation and reduction commitments*' (QELRCs) specified in Annex B and, for those 'economies in transition' to a market economy following the collapse of the USSR, an alternative basis for determining their QELRCs. The QELRCs specified in Annex B were determined by national declaration or Chairman's prerogative during the negotiation of the KP at COP3 (Depledge 2000, paras 201–215). Meanwhile, the alternative basis (and certain procedural requirements) was set out in Article 3(7) and this was to be read together with Article 3(6),[152] as well as Article 4(6) of the UNFCCC, for those States marked in the list in Annex B with an asterisk (Depledge 2000, paras 235–240). Thus, there were two alternative bases to determine the scope of the QELRC under Article 3(1). Hence, both bases were referred to collectively as '*assigned amounts*'. Note that some QELRCs allowed States to *increase* their GHG emissions relative to the 1990 baseline,[153] which explained why the phrase QELRCs included the term '*limitation*'.

- ***'commitment period 2008 to 2012'***

Finally, the multiyear '*commitment period*' was another clear departure from the MP formula of fixed, single reduction years. Notwithstanding this more flexible approach, it was

[152] Which was included as a 'reassurance' provision to certain transition States, granting them '*a certain degree of flexibility*' in implementing the KP, but crucially such flexibility only applied to commitments '*other than those under this Article'*.
[153] E.g., Australia, Iceland and Norway.

still clearly intended to be legally binding, as reinforced by the very deliberate use of the word 'commitment' (Depledge 2000, para. 454; Ghaleigh and Verkuijl 2021, para. 3.19).

- **Other general commitments – Article 10**

Although the vast majority of the KP's provisions were directed at Annex I developed parties, Article 10 set out general obligations for '*all parties*'. However, buried in the exceedingly long 'chapeau' or introductory paragraph to Article 10 were the words '*without introducing any new commitments for Parties not included in Annex I*', but rather '*reaffirming existing commitments under Article 4, paragraph 1, of the Convention*'. Article 10 then proceeded to set out seven separate 'obligations', which largely restated existing obligations under the UNFCCC. It was beyond the scope of this thesis to compare the wording of this provision word-by-word with the corresponding provisions of the UNFCCC to determine any inconsistencies, but this indicates some of the inherent challenges of interpreting, let alone litigating, on the basis of such vague international environmental laws on climate change (Sands 2016). To the extent that the KP set out any other substantive obligations applicable to non-Annex I parties, they were extremely limited, as detailed further herein. For example, all other references to '*all Parties*' were as passive recipients of information from the UNFCCC secretariat[154] or the Secretary-General of the UN, acting as Depositary for the KP.[155]

The Paris Agreement

The PA took an approach to its control mechanisms that was radically different to either the MP or the KP. The architecture that it established started with Article 3:

> *As **nationally determined contributions** to the **global response** to climate change, **all Parties are to undertake and communicate ambitious efforts** as defined in Articles 4, 7, 9, 10, 11 and 13 **with the view to achieving** the **purpose of this Agreement** as set out in Article 2. The **efforts** of **all Parties will** represent **a progression** over time, while recognizing the need to support developing country Parties for the effective implementation of this Agreement.*
>
> **(emphasis added)**

The inverted construction of Article 3 was the first remarkable feature here. By emphasising '*nationally determined contributions*' (NDCs), it clearly signalled their non-binding nature. The crucial word here was '*contribution'*, which was deliberately chosen to avoid

[154] KP Art 8(3).
[155] Ibid Arts 20(3), 21(4),(5).

using ‘commitment’ as was used in the legally binding KP (Ghaleigh and Verkuijl 2021, para. 3.19). Further, a ‘*nationally determined*’ approach was seen as a ‘bottom-up’ inversion of the ‘top-down’ imposition of obligations by an international negotiation process.[156] Yet directing the clause at the subject ‘*all parties*’ was less prescriptive than ‘each party’, and somewhat at odds with this emphasis otherwise on the national circumstances of the individual parties. In addition, the choice of verb (‘*are to*’), noun (‘*efforts*’) and qualifier (‘*with the view to*’) were further indications of a non-binding intention (Ghaleigh and Verkuijl 2021, para. 3.24).

Regardless, it would be a mistake to write this provision off because it was non-binding or vague. The NDC framework lay at the heart of the PA and it was this mechanism that overcame years of international gridlock on climate change (Ghaleigh and Verkuijl 2021, para. 3.28). Moreover, through subtle linguistic references, Article 3 linked to a number of recurrent concepts in the PA. First, take the term ‘*global response*’, which hinted at the global average temperature goals, followed by the explicit reference to Article 2 at the end of the first sentence. The expected action by the parties (to ‘*undertake and communicate*’) echoed subsequent substantive requirements for NDCs. These should be read together with ‘*ambitious efforts*’, said to be ‘defined’ by the six other articles cited.[157] Further, there was a clear expectation[158] (‘*will*’) that these efforts would increase in rigour in the years ahead (‘*represent a progression over time*’) (Mayer 2021, 117).

Taken together, these subtle references represented what has been termed a ‘series of interlocking devices’ used throughout the PA, which were intended to ensure rigour and potentially lead to incremental improvement over time, in the absence of overtly legally binding language (Ghaleigh and Verkuijl 2021, para. 3.24). The effect of these interlocking devices here can be summarised as follows:

1. ‘*Each party*’ must prepare, communicate and maintain successive NDCs that it intends to achieve.[159]
2. ‘*Parties’* must take domestic mitigation measures which aim to achieve their NDCs.[160]

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[156] Albeit a process that consists of *national* delegations and is notoriously prone to political paralysis in its exacting pursuit of consensus-based decision-making (Kemp 2015). See also Ghaleigh’s (2021, para. 2.30) criticism of such ‘fuzzy’ and inaccurate descriptions of the inclusive, nationally-determined process that led to the Kyoto targets.

[157] Each of Articles 4, 7, 9, 10, 11 and 13 particularised further details to be provided in the parties’ NDCs, yet in contrast to the MP and the KP, none of those articles required an absolute GHG emissions reduction or any particular reduction year.

[158] On another view, the strong expectation of ‘*progression’* in successive NDCs in Article 3 arguably represents a ‘substantive obligation’ (Rajamani 2017, 139–40). If so, then it would only represent an ‘obligation of conduct’, as distinct from an ‘obligation of outcome’ (Ghaleigh and Verkuijl 2021, 103). Such an obligation is a civil law concept that is similar to the English common law requirement in certain contexts to ‘exercise reasonable care’ and it is not ‘weak’ simply because it goes to conduct (Mayer 2021, 126).

[159] Art 4(2).

[160] Art 4(2).

3. ‘*Each party’s successive*’ NDC ‘*will represent a progression*’ beyond the last.[161]
4. ‘*All parties*’ must provide necessary information for clarity, transparency and understanding of their NDCs.[162]
5. ‘*Each party*’ must communicate an NDC every five years.[163]
6. ‘*Parties’* must account for their NDCs in terms of ‘*anthropogenic emissions and removals*’ and must avoid double-counting.[164]
7. ‘*Each party*’ must prepare adaptation plans and actions, and may choose to include that as part of its NDC.[165]
8. ‘*Each party*’ must provide the information necessary to track progress in implementing and achieving its NDC.[166]

When considered as such, in light of the whole agreement, Article 3 appeared to serve as a mini ‘framework agreement’ for the development of NDCs, in a similar way to the VCPOL and UNFCCC in establishing the overarching regime frameworks. Importantly, this ‘interlocking’ architecture of the PA introduced a number of substantive procedural obligations, as listed in points 1-2 and 4-8 above. Note the variations in referring to a subject party or parties and recall that individual obligations tend to be more prescriptive than collective ones, even in relation to these relatively banal obligations.

In summary and in stark contrast to the equivalent MP and KP provisions, Article 3 of the PA was inherently vague and open to subjective interpretation. It did not impose objective criteria to assess the ‘ambition’ and ‘progression’ of NDCs, nor did it require that a party’s NDC demonstrate consistency with the overall temperature goal. Like their nationally determined nature, the degree of ‘progression’ between successive NDCs appeared to be open to self-determination by the parties (Rajamani 2016b, 501). Given this distinct lack of detail, it is little wonder that the parties have been given such a ‘free hand’ to draw up their NDCs, which vary greatly in methodology, detail and ambition (Ghaleigh and Verkuijl 2021, 101).

6.3.4 Regulation of trade

Emissions of both ODS and GHGs were closely related to trade and human economic activity, yet the three implementing agreements dealt with trade matters very differently.

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161 Art 4(3).
162 Art 4(8). Note that the ‘*necessary information*’ is arguably subject to future amendment by a decision of the CMA.
163 Art 4(9). Note that the timing of NDCs is arguably subject to future amendment by a decision of the CMA.
164 Art 4(13). Subject to any ‘*guidance*’ that may be adopted by the CMA.
165 Art 7(9), (11).
166 Art 13(7)(b).

The MP and Amendments

As an additional 'control measure' in Article 4, the MP introduced an import and an export ban on each 'controlled substance' listed in an Annex. This mirrored the structure of the articles requiring reductions in ODS consumption and production: each paragraph used mandatory language ('*shall ban*') to prohibit first the import and then the export of any of the controlled ODS to or from States that were not a party to the MP. Imports and exports were the subject of separate paragraphs, but for every ODS, a restriction on imports had a corresponding restriction on exports.[167] Further, the restrictions were introduced in six separate paragraphs, with one each for the ODS listed in Annex A, Annex B, Annex C Group II, Annex E, Annex C Group I, and Annex C Group III. This jumbled sequence was because, like the rest of the MP, these restrictions were introduced progressively by the LDN1990, CPN1992, MON1997 and BEI1999 Amendments. Thus, the effect of the trade restrictions was to impose at least 12 obligations on each party; six restricting imports and six restricting exports of controlled ODS.

Note that at least six further uses of the phrase '*shall ban*' were made in Article 4(3)-(4*ter*) of the MP2000. Each of these paragraphs was a contingent obligation. For a substantive obligation to arise, the parties first had to consider the feasibility of further bans or restrictions on importing products *containing*, or even *produced with* (but not containing), controlled substances in Annexes A to C. If the parties had considered such restrictions were feasible, then they would also have to elaborate a list of such products in an appropriate Annex.[168] Even then, some parties might object to that annex. Thus, these further obligations to ban ODS would only arise if it was considered feasible, if an annex was then duly elaborated, and then no parties objected to that annex. In reality, only one list of products containing the controlled ODS in Annex A was ever elaborated via this process, as included in Annex D.[169] Thus, these were at best interpreted as contingent obligations.

Finally, the later MON1997 introduced two new articles governing trade in ODS. If a party had been unable to cease production of ODS for whatever reason, Article 4A(1) prohibited ('*shall ban*') the export of '*used, recycled and reclaimed quantities*' of any ODS after its applicable '*phase-out date*' (i.e., reduction to zero), '*other than for the purpose of its destruction'*. Yet Article 4A(2) substantially undermined the intended effect of Article 4A(1), because it '*shall apply without prejudice*' to the operation relevant dispute resolution and non-

[167] Refer MP2000 Art 4(1)-(1*sex*) and (2)-(2*sex*)
[168] See MP2000 Annex D.
[169] See MP2000 Art 4(3). Adopted at the Third MOP in Nairobi, 21 June 1991

compliance procedures.[170] The effect of this meant that there was no threat of enforcement of the obligation in Article 4A(1), but the parties were still bound by virtue of their good faith duty to observe their treaty commitments, *pacta sunt servanda* (VCLT 1969, Art 26).

MON1997 also introduced Article 4B, which required ('*shall*') parties to establish and implement a system of licensing the import and export of '*new, used, recycled and reclaimed*' ODS in Annexes A, B, C and E. '*Each party*' was to establish such a licensing system by 1 January 2000, although A5 parties were permitted to delay such a licensing system for ODS in Annexes C and E (which were still used more prevalently) until later.[171] '*Each party*' also had to report to the Ozone Secretariat on the establishment and operation of its licensing system.[172]

The Kyoto Protocol

In contrast, neither the KP nor the PA introduces any restrictions on trade. In fact, one of the 'principles' in Article 3(5) of the UNFCCC states that:

> '*The Parties should cooperate to promote a supportive* ***and open international economic system*** *that would lead to sustainable economic growth and development in all Parties, particularly developing country Parties, thus enabling them better to address the problems of climate change.* ***Measures taken to combat climate change****, including unilateral ones,* ***should not constitute*** *a means of arbitrary or unjustifiable discrimination or* ***a disguised restriction on international trade***'.
>
> (**emphasis added**)

Given this wider context, it was no surprise that the KP and the PA avoided any such strong trade restrictions. However, both provide for voluntary trading schemes, as briefly outlined below.

The KP established a Clean Development Mechanism (CDM).[173] This was intended to achieve the 'win-win' of assisting developing countries with their aspirations for sustainable development, while assisting Annex I developed countries to achieve their emissions reduction commitments.[174] Developing countries had the strong expectation ('*will*') that they would benefit from '*project activities*' in their countries, which could be used as the basis for

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170 See VCPOL Art 11 and MP2000 Art 8, as supplemented by relevant decisions of the MOP.
171 See MP2000 Art 4B(1)-(2): for Annex C ODS, A5 parties could delay until 1 January 2005; for Annex E ODS, until 1 January 2002.
172 MP2000 Art 4B(3).
173 KP Art 12(1).
174 Ibid 12(2).

tradeable '*certified emission reductions*'. Annex I developed country parties could ('*may*') use such reductions towards demonstrating compliance with their QELRCs under Article 3.[175] *If* parties entered into such a scheme, then the KP imposed some mandatory procedural obligations.[176] Importantly, these obligations were drafted without a subject, which generated 'expectations of the regime and its institutions', rather than an obligation on the parties per se (Rajamani 2016a, 343). This included the requirement that both parties' participation in any such '*project activity*' was voluntary,[177] that the climate mitigation benefits were real[178] and that any emissions reductions were '*additional*' (i.e., were not simply business as usual or that would have occurred in the absence of the '*project activity*').[179]

The Paris Agreement

The PA was less prescriptive than the KP about any '*voluntary*'[180] cooperation that parties may choose to enter into in implementing their NDCs, albeit with similarities to the KP's CDM scheme. Like the KP, the PA established a 'mechanism',[181] which aspired ('*shall aim*') to allow one party to '*host'* certain beneficial '*mitigation activities resulting in emissions reductions*' that could be used by another party towards fulfilment of their NDC.[182] However, unlike the KP, the PA did not require proof of 'additionality'; the mechanism was simply expected to '*deliver an overall mitigation in global emissions*'.[183] Moreover, *if* parties entered into such a cooperation arrangement, then the PA imposed obligations ('*shall*') on the parties to the arrangement. These were 'obligations of conduct' to '*promote sustainable development and ensure environmental integrity and transparency*', including by applying '*robust accounting to ensure… the avoidance of double counting*',[184] and to be consistent with any '*guidance*'[185] from the COP serving as the meeting of the parties to the PA (CMA).[186] Like the KP's CDM, there were also procedural obligations directed at no particular subject,[187] or at the CMA.[188] Finally, like the use of '*certified emissions reductions*' under the CDM

[175] See KP Arts 3(12), 12(3)(b), (10).
[176] See KP Art 12(4)-(8).
[177] KP Art 12(5)(a).
[178] Ibid 12(5)(b).
[179] Ibid 12(5)(c).
[180] See PA Arts 6(1)-(4).
[181] Ibid Art 6(4).
[182] Ibid Art 6(4)(c).
[183] Ibid Art 6(4)(d).
[184] See also Art 6(5), which prohibits ('*shall not*') double-counting of 'mitigation activities' by multiple parties towards their separate NDCs.
[185] Any 'guidance' provided by the CMA would be non-binding. *Cf*: in certain circumstances, subject always to the particular drafting used, a decision of the COP *may* be binding (Bodansky 2016, 148)
[186] PA Art 6(2). See also 'COP' in Glossary of Terms.
[187] Ibid Art 6(4)-(5).
[188] Ibid Art 6(4), (6)-(7).

towards a party's QELRC under the KP, the '*internationally transferred mitigation outcomes*'[189] under Article 6 of the PA could be used to achieve NDCs, but had to be ('*shall*') voluntary and '*authorized*' by the participating parties.[190] This final obligation was not directed at any particular subject, which arguably generated 'expectations of the regime and its institutions', rather than an obligation on the parties per se (Rajamani 2016a, 343).

Summary

In summary, the MP banned imports and exports of ODS to and from non-Parties to the ozone regime. This was later expanded to apply to imports and exports of ever more specific quantities of ODS, including their use in products and feedstocks, and used, recycled or reclaimed quantities. By contrast and constrained by UNFCCC Article 3(5), neither the KP nor PA sought to limit or control GHG emissions directly or indirectly through trade restrictions. Rather, both the KP and PA established enabling, voluntary trading schemes. Like the MP's approach to direct as well as intermediates sources of ODS, note that there have been attempts to differentiate between different sources of GHG emissions, namely 'Scope 1', 'Scope 2' and 'Scope 3' emissions (increasing in their indirectness) (WBCSD and WRI 2004). However, this is simply a GHG accounting framework widely adopted by accounting professionals and this framework is not sanctioned by the international climate protection regime.

6.3.5 Technology transfer

The ozone and climate regimes included provisions for the transfer of emission reduction technologies from developed to developing country parties.

The MP and Amendments

The MP2000 required ('*shall*') '*each party*' to take '*every practical step*' to ensure that the best available ODS substitutes and related technologies were '*expeditiously*' transferred to A5 (developing) parties.[191] It further required that any such transfers occur under '*fair and most favourable conditions*'.[192] This reflects language used in the prevailing system of international trade[193] and reinforces the ozone regime's active use of trade restrictions among its control measures. However, in the context of technology transfers in the MP1987, there was originally even more rigorous language, as detailed below.

[189] Cf: 'certified emissions reductions' under the KP.
[190] PA Art 6(3).
[191] MP Art 10A(a).
[192] MP Art 10A(b).
[193] See, for example, General Agreement on Tariffs and Trade 1947 Art I.

Articles 5(2) and (3) of the MP1987 required as follows:

2. The Parties ***undertake to facilitate*** *access to environmentally safe alternative substances and technology for Parties that are developing countries and assist them to make expeditious use of such alternatives.*
3. The Parties ***undertake to facilitate*** *bilaterally or multilaterally the provision of subsidies, aid, credits, guarantees or insurance programmes to Parties that are developing countries for the use of alternative technology and for substitute products.*

(*emphasis added*)

Note that the provisions were directed to all parties collectively and used in combination with the verb '*to facilitate*'. Both of these drafting devices serve to add some distance between the content of the clauses (technological and financial transfers) and any particular party or class thereof. However, the fact that '*developing countries*' were mentioned suggests by omission that these paragraphs were directed more at 'developed country' parties, since they were the parties with the available technologies and the greater financial resources.

Regardless, the common commitment shown by the combination of '*the parties*' and '*undertake*' was even more interesting here. These two instances of 'undertake' were unique among the three implementing agreements analysed. Recall that the VCLT requires that a treaty be interpreted '*in good faith in accordance with the ordinary meaning to be given to the terms of the treaty in their context and in the light of its object and purpose*' (VCLT 1969, Art 31(1)). Further, '*A special meaning shall be given to a term if it is established that the parties so intended*' (VCLT 1969, Art 31(4)).

Here, the absence of any modal verb meant that '*undertake'* was the operative verb[194] and serves to modulate the subsequent verb, '*to facilitate*'. Understood in this way, the word was not used in the more common, popular sense, but rather in the alternative sense of 'to bind oneself contractually' or 'to promise' (Garner 1995, 898),[195] with solemn implications. In an international context, the solemnity of the use of the verb to 'undertake' is clear from the other, much more grave contexts in which it is typically used, such as nuclear non-proliferation.[196]

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[194] *Cf*: use of undertake as a transitive verb (with a direct object) together with a modal verb, e.g. 'will undertake the transfer of technology', where 'undertake' has a very different meaning; 'to take upon oneself, try earnestly' (Garner 1995, 898).
[195] This is the modern English equivalent of the Latin *assumpsit* (root: *assumere*) (Britannica 2018), as in a person 'undertook' or 'promised', and related to the existing concept of the *assumption* of an obligation (Garner 1995, 84, 898). A related common law legal concept is the giving of an 'undertaking', usually to a court, which is a very solemn promise to give a bond that has no collateral security; it is personally enforceable against the promisor (Garner 1995, 898).
[196] See, for example, *Treaty on the Non-Proliferation of Nuclear Weapons 1968* Arts I, II, III(1)-(2), IV(2), V and VI.

Importantly, by virtue of the construction of the sentence as outlined above, this was not necessarily a 'special meaning'. Moreover, even if it was, in the context of an international legal agreement, drafted with substantial input from legally trained national representatives, it can be assumed to have been used deliberately. Proof of such an intention here would be relatively easily established. First, by having regard to the broader context of the MP, made as it was under the overarching framework of the VCPOL. Interestingly, 'undertake' was also used repeatedly in the same solemn, binding sense in Article 3(1), (2) and (3) of the VCPOL.[197]

Further and in any event, there is evidence from the contemporary surrounding circumstances that access to technology to avoid the construction of obsolete CFC production assets and to 'leapfrog' CFC production loomed as a pivotal issue for developed and developing countries alike (Benedick 1998, chap. 12). It follows from all of the above that such a strong reassurance was intended to be included. All of this suggests that through the use of the verb 'undertake', all parties had solemn 'obligations of conduct' to facilitate access to technologies and financing for developing countries under the MP1987.

This was removed and somewhat watered down to a requirement ('*shall*') to '*take every practical step*' as inserted in Article 10A by the LDN1990. Thus, what were originally quite rigorous general obligations in Articles 5(2) and (3) of the MP1987 became very different obligations in Articles 10 (discussed below) and 10A of the MP2000. At the same time as it removed the above two references to 'undertake', the LDN1990 also inserted the following in Article 4(5):

> '***Each Party undertakes to the fullest practicable extent to discourage*** *the export to any State not party to this Protocol of technology for producing and for utilizing controlled substances.*'
>
> (***emphasis added***)

This was accompanied by the immediately following sub-paragraph 4(6):

> ***Each Party shall refrain*** *from providing* ***new subsidies, aid, credits, guarantees or insurance programmes for the export*** *to States not party to this Protocol of products, equipment, plants or technology that would facilitate the production of controlled substances in Annexes A, B, C and E.*

[197] Those obligations relate to scientific cooperation, in the context of grave contemporary concerns and scientific uncertainty about the extent of stratospheric ozone depletion and the corresponding direct risk to human and environmental health.

Unlike in Articles 5(2) of the MP1987, note that these obligations were directed at (preventing) the transfer of technologies that would *produce* ODS, rather than technologies that would avoid or reduce them. Both were directed at each party individually, rather than all parties collectively. The insertion of sub-paragraph 4(5) also used 'undertake' in its stricter, legal sense and then immediately qualified the extent of that obligation through the use of the phrase '*to the fullest practicable extent*', as well as the requirement to merely '*discourage*' (but not 'ban', 'refrain from' or 'prevent') exports of ODS technologies. Despite these qualifiers, the fact that it was directed at each party individually and used the solemn legal meaning of the verb 'to undertake' suggested that this was another solemn 'obligation of conduct' in relation to technology transfer. Meanwhile, the use of '*shall refrain*' in sub-paragraph 4(6) was another unique phrase across all three implementing agreements, similar in effect and force to '*shall ensure*', but it required each party to abstain from acting, rather than requiring positive action.

The Kyoto Protocol

By comparison, the KP required ('*shall*') '*all parties*' to '*cooperate'* on '*effective modalities for*' and '*take all practicable steps to promote*' the transfer of technologies, '*in particular to developing countries*'.[198] The KP also referred to both the public and the private sectors' roles in technology transfer.[199] However, only the '*developed country Parties and other developed Parties included in Annex II*'[200] were required ('*shall*') to provide financing necessary for technology transfer,[201] with the details of a funding mechanism delegated to the CMP.[202] Article 11 also included an unnumbered 'note' following sub-paragraph (2)(b), which imposed a procedural obligation or 'expectation of the regime and its institutions' (Rajamani 2016a, 343) that these commitments would be implemented taking into account the need for '*adequacy and predictability*' in the '*flow of funds*' and the '*importance of burden sharing*' among developed country parties.[203] Despite Article 11(2)(b) making it clear that only the developed country parties were obliged to provide financial resources, the absence of any subject from this 'note' was therefore conspicuous.

[198] KP Art 10(c).
[199] Ibid.
[200] Annex II to the UNFCCC listed 23 countries, plus the 'European Economic Community'. This list excludes the former USSR countries and other 'economies in transition'.
[201] KP Art 11(2)(b).
[202] KP Art 3(14) 'funding, insurance and transfer of technology'.
[203] This substantially replicates the final sentence of UNFCCC Art 4(3).

The KP also included an unnecessary reference to permit ('*may*') developed country parties to provide and developing countries to receive other bilateral, regional or multilateral funding,[204] which was already well within their sovereign rights as States.

The Paris Agreement

The PA referred repeatedly to '*technology transfer*', although most of these references were included in provisions drafted in the language of ambition rather than obligation.[205] Some of this visionary language was given effect by expanding the mandate of the UNFCCC's 'Technology Mechanism' to also service the PA, as well as the '*technology framework*' established by Article 10(4). However, little detail nor concrete obligations were imposed. Article 10(2) of the PA required parties to '*strengthen'* cooperation on technology development and transfer. This was reinforced somewhat by a requirement that developing country parties '*shall*' be provided with financial support for such cooperation in Article 10(6), but that 'obligation' was not imposed on any subject. Article 10(6) also referred to the transfer of technology with the common intention of finding a '*balance between support for mitigation and adaptation*'. This was consistent with the PA's greater focus on adaptation than the more mitigation focussed KP.

Elsewhere, developed countries had to report on the extent of any technology transfer support provided to developing countries,[206] while developing countries were strongly recommended ('*should*') to report on their technological needs,[207] with this information to be taken into account as part of the 'global stocktake'.[208]

Summary

The MP clearly contained more rigorous provisions on technology transfer, including originally solemn promissory and later strongly mandatory language on this issue. Moreover, the MP compelled both positive action to transfer certain environmentally beneficial technologies, while at the same time compelling parties to abstain as far as practicable from transferring environmentally harmful technologies. The KP set out some obligations and other details relevant to technology transfer, but left the substantive details to subsequent decisions of the CMP. The PA said very little about technology transfer beyond restatements of the existing aims of the climate regime, other than to confirm that developing countries would be provided

[204] KP Art 11(3).
[205] PA PP6 and Arts 6(8), 10(1) and 10(4).
[206] PA Art 13(9). Note also that '*other Parties that provide support*' were recommended ('*should*') report similarly.
[207] Ibid Art 13(10).
[208] Ibid Art 10(6). See also 'Monitoring, review' section, below.

financial resources. However, in contrast to Article 10A of the MP and Article 11(2)(b) of the KP, the PA was most remarkable in requiring that '*Support… shall be provided to developing country Parties…*',[209] without explicitly requiring that such support be provided by developed countries. This has led some commentators to conclude that: '*The prescriptiveness and precision of wording in Article 10 is such that no party can be held to any specific action.*' (de Coninck and Sagar 2017, 266)

6.3.6 Finance

The ozone and climate regimes made provision for financing to achieve various relevant regime goals, but took very different approaches, particularly as to who would provide the financing and how it would be assessed.

'*…you're going to have to work out a regime that fairly compensates those people for loss and damage and makes good on the promises that were made in Paris about financial transfers. One of the real problems and I don't know how to solve this, I think at this point it's not solvable, and it's kind of sad actually. You know the good thing about Montreal was that the financial arrangement was that the developed countries would pay the developing countries the difference in cost between doing whatever they were going to do with CFCs and doing it with the alternatives. Not the total cost, but the extra cost, if there was any.*'

- Professor Susan Solomon, 27 July 2021

The Montreal Protocol

As introduced by the LDN1990, Article 10 of the MP required the parties to establish a financial mechanism,[210] which was to include a Multilateral Fund (MLF).[211] The MLF was to be financed by '*Parties not operating under paragraph 1 of Article 5*'[212] (i.e., developed country parties) and could only be disbursed with the consent of the '*beneficiary party*'[213] (i.e., developing country parties). The MLF was funded by developed country parties on the basis of the United Nations scale of assessments (or 'membership fees').[214] This was significant, as funding has never been agreed on a similar basis under the climate regime. As at 30 October 2020, the MLF had earnt USD $4.25 billion and disbursed USD $3.93 billion (UNEP

[209] Ibid.
[210] MP2000 Art 10(1). MP1987 Art 10 established a simple system of 'technical assistance'
[211] Ibid 10(2).
[212] Ibid Art 10(6).
[213] Ibid Art 10(8).
[214] Ibid 10(6).

2021). The MLF's functions included covering certain '*agreed incremental costs*'[215] incurred by developing country parties and to provide financial and technical cooperation and capacity-building activities to those countries.[216]

In the context of the Multilateral Fund (MLF), there was a mix of binding language ('*shall*')[217] and carefully drafted contingent obligations, using '*may'*.[218] The reason for the differentiation was simple. Even as it sought to encourage bilateral or regional cooperation,[219] the MLF also had to avoid a situation where an NA5 developed country party might seek to avoid paying its assessed contributions by pointing to its bilateral or regional cooperation initiatives instead. Thus, Article 10(6) allowed for such alternative funding to be considered ('*may*') as a contribution in-kind to the MLF, with certain strict conditions. First, it had to be '*up to a certain percentage and consistent with any criteria*' specified by the MOP. Further, it would be recognised *'provided that*' and '*as a minimum*' such cooperation was:

1. '*strictly*' related to compliance with the MP;
2. provided '*additional*' resources; and
3. met agreed *'incremental*' costs.[220]

These strict qualifiers therefore operated to significantly curtail what would otherwise be a permissive ('*may*') provision. Finally, note that the MP's financial mechanism (and MLF) was '*without prejudice*' to any future funding arrangements that '*may be developed*' for other environmental issues.[221] In other words, this meant that the MP funding arrangements did not 'set a precedent' for the funding of legal and policy responses to other environmental issues.

The Kyoto Protocol

The KP imposed obligations to provide financial assistance on developed country parties only.[222] This included a requirement ('*shall*') for developed country parties[223] to provide new and additional financial resources for the '*agreed full costs*' incurred by developing country parties in implementing the UNFCCC's requirement[224] to establish national GHG inventories.[225] Article 11(2)(b) of the KP also required developed country parties to meet the

[215] With an indicative list of categories of incremental costs to be agreed on by the MOP, pursuant to MP2000 Art 10(1).
[216] MP2000 Art 10(3).
[217] Ibid Art 10(1)-(9).
[218] Ibid Art 10(6).
[219] See MP2000 Art 10(2), (3)(b)(iv).
[220] Ibid 10(6)(a)-(c).
[221] Ibid 10(10).
[222] See above n 98. Note, once again, the '*developed country parties listed in Annex II*' (to the UNFCCC).
[223] KP Art 11(2).
[224] UNFCCC Art 4(1)(a).
[225] See KP Art 11(2)(a) and 10(a).

'*agreed full incremental costs*' of developing countries in meeting various other commitments, including: mitigation and adaptation planning, technology transfer, capacity-building, scientific and technical cooperation, education and training, and reporting on national implementation.[226] Note the reference to '*incremental'* costs. [227] Like the KP's reference to '*additionality*' in the context of the CDM,[228] this meant that the costs must be in addition to business-as-usual actions, with some demonstrable GHG mitigation or adaptation benefit (UNEP 2007, 49).[229]

Otherwise, the language on financial assistance in the KP substantially replicated related provisions of the UNFCCC.[230] The KP's references above to '*agreed'* costs were particularly apposite. The KP set out that these were to be agreed between a developing country party and the international entity operating the financial mechanism.[231] The KP further provided that any contributions from developed country parties were to be paid through the UNFCCC's financial mechanism.[232] However, unlike the MP, the KP did not stipulate how the developed country parties' financial contributions were to be assessed. Rather, pursuant to Article 11 of the UNFCCC, these matters were delegated to decisions of the CMP[233] and were to be agreed with the entity entrusted with operation of the UNFCCC's financial mechanism.[234]

The Paris Agreement

The PA provisions on financial assistance required ('*shall'*) that developed country parties provide financial resources to developing country parties.[235] However, similarly to the KP, this did not impose any new obligation on developed country parties and instead simply repeated the existing obligations[236] and mechanism[237] under the UNFCCC. Further, the PA gave only the feeble recommendation that developed country parties '*should'* continue to '*take the lead*' in mobilising '*climate finance*'[238] from a wide variety of sources and that this

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[226] See KP Art 11(2)(b); compare commitments in UNFCCC Art 4(1) and KP Art 10.
[227] The MP also referred to '*agreed'* incremental costs, but it further provided that the meeting of the Parties was to decide on an indicative list of incremental costs (see Article 10(1)). Both are examples of an 'agreement to agree' details later, but once again the MP was more specific in at least including agreed parameters for that future agreement, in contrast to the silence of the KP.
[228] See KP Art 12(5)(c) and above n 77.
[229] See also UNEP and UNFCCC (2001).
[230] See, for example, UNFCCC Arts 4(3) and 11(5) and compare KP Arts 11(2) and 11(3), respectively
[231] KP Art 11(2)(b). Note that reference to '*a*' (singular) developing country party suggests that this was intended to be agreed on a case-by-case basis.
[232] KP Art 11(2).
[233] See UNFCCC Art 11(1), (3), (4).
[234] Being the Global Environment Facility, pursuant to COP decisions 12/CP.2 and 12/CP.3.
[235] PA Art 9(1).
[236] Ibid.
[237] PA Art 9(8).
[238] Not defined in the PA, nor any other international agreement – see Mehling (2021, para. 9.03) for suggested definitions.

should be a '*progression'* beyond previous efforts.[239] Moreover, the '*scaled-up financial resources*' were intended ('*should aim*') to reach a '*balance between adaptation and mitigation*'.[240] Such weak language provided a very stark contrast to the equivalent provisions in the MP and even the KP. At the very least, the PA required ('*shall*') developed country parties to provide '*transparent and consistent information*' biennially about support provided to developing country parties, in accordance with procedural requirements to be agreed by the CMA.[241]

Finally, though much has been made of the USD$100 billion 'Green Climate Fund' agreed at COP21 in Paris, there is no reference to this amount, nor that entity in the text of the PA. Rather, the details were relegated to the decision document of the COP, which was of limited legal effect (Ghaleigh 2021, para. 2.21; Bodansky 2016, 148).

Summary

All three implementing agreements had at least one thing in common: they each allowed for additional voluntary funding from developed countries via bilateral, regional or other multilateral means.[242] Yet the funding provisions were critically different in material ways.

First and foremost, the MP established not only a financial mechanism, which included the MLF, but it also provided that developed country parties were to pay for it *and* the basis on which they were to pay. Both the KP and the PA confirmed, with less emphatic language, that developed country parties were to pay financial assistance under those agreements too. However, neither agreement set out the basis on which this assistance was to be paid. Both also utilised the existing UNFCCC financial mechanism, yet introduced potential confusion in their reliance on COP decisions to differing extents as to further financing details. In this respect, the MP's inclusion of a clause to the explicit effect that the MLF was not to be seen as a precedent for international funding mechanisms therefore proved prescient, given the continued negotiations on these fundamental financial matters under the climate regime.[243]

Further, where the MP referred to '*agreed incremental costs*', it also set out parameters to guide the MOP in further striving to agree on this inherently contentious issue. By contrast, the KP referred to a confusing mix of existing arrangements under UNFCCC provisions and

[239] PA Art 9(3).
[240] Ibid Art 9(4). Note the emphasis on adaptation, as elsewhere in the PA.
[241] Ibid Art 9(7). Other parties were '*encouraged to do so*'.
[242] See MP Art 10(2), noting also the criteria in Article 10(6)(a)-(b); KP Art 11(3), and; PA Art 6. None of which were necessary, given States' sovereign rights to do this anyway.
[243] To say nothing of the tortuously slow negotiations towards compensation for 'loss and damage', which was at least mentioned in PA Art 8. Since no such provisions were included in the MP or the KP, they were not analysed more closely here, but Article 8 does not impose any new obligations for parties either.

provided no such guidance for narrowing down the scope of issues. Meanwhile, the PA did not mention the issue of costs and their quantification, but it did at least establish an obligation for developed country parties to report every two years about financial support provided to developing countries.

6.3.7 Monitoring and review

Ongoing monitoring and review of progress towards pollutant reduction goals and, if necessary, adjustments to the regulatory framework were important parts of both regimes. This was all the more essential in the context of the dynamic atmospheric science phenomena here.

The Montreal Protocol

The 'control measures' in the MP were subject to review every four years on the basis of available '*scientific, environmental, technical and economic*' information, to be conducted by panels of experts qualified in those fields.[244] Following such a review, the parties to the MP were empowered ('*may decide'*) to adjust the ozone-depleting potentials of listed ODS and adjust or further reduce the ODS production/consumption reduction schedules, including the '*scope, amount and timing*' of any such adjustments or reductions.[245] Any proposed changes had to be notified to the parties,[246] who had to make every effort to agree to the change by consensus, or a two-thirds majority of both NA5 (developed country) and A5 (developing country) parties.[247] Any such changes were binding on all parties and entered into force within six months of being notified to the parties.[248]

Another potential outcome of any review of the 'control measures' was that the parties were empowered ('*may decide'*) to add or remove controlled ODS to the annexes to the MP, together with the '*mechanism, scope and timing*' of any applicable control measures.[249] If the parties decided to add or remove controlled ODS, then any change to the MP had to be by way of an amendment to the Protocol.[250]

As for the annual reports on ODS production and consumption data,[251] the MP did not provide for any regular review. However, somewhat concerningly, there has been some history of unexplained revisions in national reports to the Ozone Secretariat (McCulloch 2005).

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[244] MP2000 Art 6.
[245] Ibid Art 2(9)(a).
[246] Ibid Art 2(9)(b).
[247] Ibid Art 2(9)(c).
[248] Ibid Art 2(9)(d).
[249] Ibid Art 2(10).
[250] Ibid Art 10. See also VCPOL Art 9.
[251] Ibid Art 7.

The Kyoto Protocol

The KP required ('*shall*') the CMP[252] to '*regularly review and, as appropriate, revise*' methods used for calculating emissions and global warming potentials of GHGs.[253]

Further, national GHG inventories submitted by each party every year were subject to a '*thorough and comprehensive*'[254] annual expert review.[255] These expert review teams would then report to the CMP and the Ozone Secretariat would identify any issues of implementation requiring the CMP's attention at its next meeting.[256] On receipt of this report, the CMP had a broad power ('*shall*') to take decisions on '*any matter required for the implementation*'.[257]

More broadly, the KP empowered the CMP to '*periodically review*' the KP in light of the '*best available scientific information and assessments on climate change and its impacts, as well as relevant technical, social and economic information*'.[258] Any such review should be coordinated with relevant reviews of the UNFCCC[259] and had to take place '*at regular intervals and in a timely manner*'.[260] After any such review, the CMP '*shall take appropriate action*'.[261]

Finally, the CMP had to regularly review the implementation of the KP and had broad power to make decisions, within its mandate, that would promote its more effective implementation.[262] The CMP had various important functions, including assessing the cumulative '*environmental, economic and social*' effects of implementing action by the parties and the extent of progress towards the ultimate objective of the UNFCCC.[263] It had to also periodically examine the parties' obligations under the KP, taking into account related reviews under the UNFCCC, progress in implementation, developments in '*scientific and technological knowledge*' and the ultimate objective of the UNFCCC.[264] It also had a number of important oversight functions,[265] various powers on implementation including to make recommendations,[266] to establish subsidiary bodies[267] and to carry out certain functions,[268] while also

252 Serving as the meeting of the parties to the KP, as opposed to the COP to the UNFCCC – refer KP Art 13.
253 KP Art 5(2) and (3).
254 Ibid Art 8(3).
255 Ibid Art 8(1).
256 Ibid Art 8(3).
257 Ibid Art 8(6).
258 Ibid Art 9(1).
259 Ibid.
260 Ibid Art 9(2).
261 Ibid Art 9(1).
262 Ibid Art 13(4).
263 Ibid Art 13(4)(a).
264 Ibid Art 13(4)(b).
265 Ibid Art 13(4)(c)-(e).
266 Ibid Art 13(4)(f).
267 Ibid Art 13(4)(h).
268 Ibid Art 13(4)(j).

playing a role in leveraging greater financial resources[269] and promoting international cooperation.[270]

The Paris Agreement

The PA established an '*enhanced transparency framework*',[271] which required ('*shall*') each party to '*regularly*' communicate information about its national GHG inventories[272] and progress towards its NDC.[273] Each party was strongly recommended ('*should*') to also include information about climate change impacts and adaptation.[274] Each developed party was required ('*shall*') to provide information on financial, technology transfer and capacity-building support that it had undertaken,[275] while each developing party was strongly recommended ('*should*') to provide information about its needs in relation to each of those topics.[276] The reports on GHG inventories and developed countries' reports[277] on financial, technology transfer and capacity-building support were to be subject to '*technical expert review*'.[278] Such a review may '*identify areas of improvement*' and '*review the consistency of the information*' provided by parties against agreed procedures and guidelines.[279] Further, as part of such a review, each party was required ('*shall*') to participate in a '*facilitative, multilateral consideration of progress*' on financing and towards its NDC.[280]

The PA required the CMA[281] to conduct a '*global stocktake*' in 2023 and every five years thereafter.[282] The purpose was to take stock of collective implementation and overall progress towards achieving '*the purpose of this Agreement and its long-term goals*'.[283] It was to be conducted in a '*comprehensive and facilitative'* manner, '*in light of equity and the best available science*'.[284] The outcome of any global stocktake was intended to better inform parties in updating and enhancing their nationally determined contributions and promoting international cooperation.[285] Accordingly, the stocktake represented another 'interlocking device', that linked back to much of the preceding structure of the PA. First, it was to take into account

[269] Ibid Art 13(4)(g).
[270] Ibid Art 13(4)(i).
[271] PA Art 13(1).
[272] Ibid Art 13(7)(a).
[273] Ibid Art 13(7)(b).
[274] Ibid Art 13(8).
[275] Ibid Art 13(9)
[276] Ibid Art 13(10).
[277] But <u>not</u> developing countries' reports – see PA Art 13(11).
[278] PA Art 13(11).
[279] Ibid Art 13(12).
[280] Ibid.
[281] Serving as the meeting of the parties to the PA.
[282] PA Art 14(2).
[283] Ibid 14(1).
[284] Ibid.
[285] Ibid 14(3).

the information provided as part of the transparency framework, as outlined above.[286] Further, it was to recognise developing countries' adaptation efforts, review and enhance adaptation action, and review overall progress towards the '*global goal on adaptation*'.[287] The global stocktake had to also consider relevant information about climate finance provided by developed country parties[288] and available information on technology development and transfer for developing country parties.[289]

Finally, the PA also required ('*shall*') the CMA to keep implementation of the PA under regular review and make decisions to promote its effective implementation.[290] This included establishing any subsidiary bodies and exercising any other functions as may be required.[291]

Summary

The monitoring and review provisions under the three agreements were similar in requiring review over multiple years and at different scales. Notably, the MP and the KP provided for specific scientific, environmental, technical and economic considerations. By contrast and consistent with the ambiguity of its other provisions, the PA introduced '*equity*' as a relevant factor, while it also reformulated the more technical language of the MP and the KP to provide simply that the '*best available science*' be taken into account.

In the absence of more clearly binding provisions, the PA placed great emphasis on the 'transparency framework' and 'global stocktake' in promoting a normative role for the PA. By contrast, the monitoring and review provisions of the MP and the KP were directed at the more mundane institutional tasks typically expected of such provisions.

Just as the MP was never intended to be a 'set and forget' framework, but rather an adaptive regime for avoiding further ozone depletion, so too it 'might take 30 Kyotos over the next century' in order to bring GHG emissions under control (Malakoff 1997). Through its transparency framework and global stocktake 'interlocking' with the other devices, the PA aims similarly via its very different design.

6.3.8 Non-compliance

The non-compliance provisions of any regime are inherently controversial due to the prospect of punishment. This is reflected in a conspicuous lack of detail across both regimes.

[286] Ibid Art 13(5) and (6), which state that the purpose of the framework is in part to '*inform the global stocktake under Article 14'*.
[287] Ibid 7(14). See also the 'global goal' in PA Art 7(1).
[288] Ibid 9(6).
[289] Ibid 10(6).
[290] Ibid 16(4).
[291] Ibid.

The Montreal Protocol

The MP did not contain any substantive non-compliance provisions, with those procedures and mechanisms delegated to the first MOP.[292]

The Kyoto Protocol

Similarly, the KP did not contain any non-compliance procedure, with the first CMP[293] required (‘*shall*’) to approve an ‘*appropriate and effective*’ mechanism, including an ‘*indicative list of consequences*’ reflecting the cause, type, degree and frequency of any non-compliance.[294] Any mechanism with binding consequences was to be adopted by way of amendment to the KP.[295] The KP also included narrow circumstances in which a party would be taken to be non-compliant, with limits placed on that party’s further participation in the regime.[296]

The Paris Agreement

By contrast, the PA established a mechanism to ‘*facilitate implementation and promote compliance*’ with the Agreement.[297] Further, this mechanism was to consist of an expert-based, facilitative committee, which had to function in a ‘*transparent, non-adversarial and non-punitive*’ manner and pay particular attention to respective national capacities and circumstances.[298] However, the committee’s modalities and procedures were also delegated to the first CMA.[299]

Summary

On non-compliance, the PA contained more detail and at least a basic structure when compared to either the MP or the KP. Like the other agreements, the PA left much of the detail to be determined by the CMA, but together with the transparency framework and the global stocktake, the compliance mechanism was the third arm of a ‘rigorous system of oversight’ (Rajamani 2016b, 502). Interestingly, the KP at least set parameters within which the

[292] MP Art 8.
[293] Serving as the meeting of the parties to the KP.
[294] KP Art 18.
[295] Ibid.
[296] See KP Art 6(1)(c) and (4). In the former situation, a failure to meet the minimum requirements in Articles 5 and 7 (i.e., to establish a national GHG inventory system and provide annual national GHG inventory reports, respectively) will disqualify a party from claiming any ‘*emission reduction units*’. In the latter situation, if any question of implementation is raised during the process of expert review, the affected party will temporarily be disqualified from claiming any ‘emission reduction units’ against its quantified emission limitation and reduction commitments, though it may continue to trade in such units, for so long as the question remains unresolved.
[297] PA Art 15(1).
[298] PA Art 15(2).
[299] Serving as the meeting of the parties to the PA; PA Art 15(3).

CMP was to elaborate such a mechanism, which represented a role reversal from these two agreements on the issue of agreed costs. Ironically, for all of its more rigorous language in the earlier provisions, the MP said the least on compliance in the text of the agreement.

The regimes have since developed a more detailed compliance architecture through relevant decisions of the meetings of the parties. Moreover, Savaşan's (2019) detailed case analysis of the practice and procedure of the relevant compliance mechanisms under both the MP and the KP suggests that the PA's 'facilitative' and 'non-punitive' focus simply reflects the dominant approach under both established mechanisms in practice. Further, if strong cooperation and coordination between the parties can be assured within the system, then the non-binding status may be irrelevant (Savaşan 2019, 281–85). This is consistent with the broader scholarship on legal regimes and the relevance of other factors besides 'bindingness' in promoting compliance (Raustiala 2005, 589, 611–13; R. Stavins et al. 2014, 1020; Bodansky 2016, 149). Yet it remains to be seen whether the PA will prove vindicated in focussing on such factors rather than a strictly binding framework.

6.4 Legal analysis results in context

The relative lack of binding language in the climate regime could be attributed to several factors. However, before considering these factors in more detail, the landmark status of the PA must be acknowledged. Unlike the KP, which only imposed obligations on the Annex B developed country parties, the PA is significant for being the manifestation of a common global intention by both developed and developing country parties to reduce GHG emissions in pursuit of its global average temperature goals.

As Raustiala (2005, 589) notes, the absence of more elaborate obligations, or an effective enforcement mechanism, should not detract from this fact and such a 'soft law' instrument can influence State behaviour in myriad ways. Although the more binding an obligation is, the more credibly it is likely to be received, it is not through law alone that states change their behaviour (Raustiala 2005, 589–90). In other words, international law is one independent variable, which may operate to differing degrees on State behaviour, the dependent variable (Raustiala 2005, 590). This is consistent with the findings from sustained attempts to empirically assess the 'effectiveness' of international legal regimes over recent decades (Sprinz and Helm 1999).

In the model advocated by Raustiala (2005), the MP and the KP represent (very different) 'deep contracts', while the PA represents a 'shallow contract'. Further indications of the agreements' differing degrees of 'depth' come from the ratification rate data (in 6.5, below).

The PA blends the two approaches in the prevailing dichotomy of international law: legally binding treaties and political statements or pledges. As the foregoing analysis has attempted to show, the PA functions in several places like a 'framework agreement' for a subsidiary set of political pledges, particularly in relation to the NDCs.

6.5 Ratification data

In order for a treaty to take effect and be legally enforceable between State parties in international law, each State party must indicate its consent to be bound by the treaty (VCLT 1969, Arts 11-15). The VCLT provides for multiple modes of indicating such consent, including '*ratification*', '*acceptance*', '*approval*' and '*accession*', all of which refer to '*the international act so named whereby a State establishes on the international plane its consent to be bound by a treaty*' (VCLT 1969, Art 2(1)(b)). To use the language of the climate regime, the VCLT therefore reflects and equally respects States' different '*national circumstances*' in terms of the manner and form in which each gives legal effect to its intention to be bound by a treaty entered into by that State. A treaty usually specifies the threshold number of State ratifications required before it can enter into force (EIF), or take international legal effect (VCLT 1969, Arts 16, 24).

The ratification data were collated for each agreement under study here and the results are summarised in Figure 16.[300]

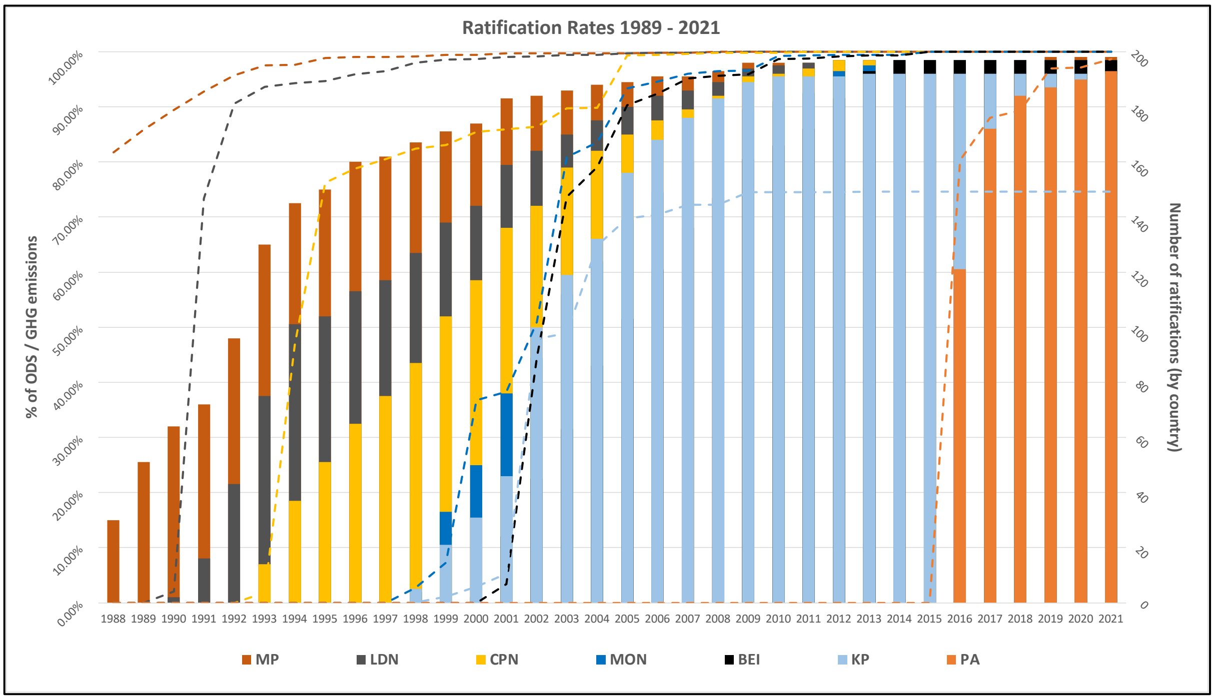
The ratification rates for both regimes, both in terms of the number of parties and the representative share of total global ODS consumption, or GHG emissions (as relevant), varied significantly. There were just 30 ratifications of the MP1987 in the first year that it opened for signature in 1988, yet these parties represented ~82% of total global ODS consumption (1986 baseline). This was more than sufficient for the MP1987 to enter into force on 1 January 1988.[301] In 1992, five years after the date of the agreement, the MP had been ratified by 96 countries, representing ~96% of 1986 ODS consumption. The ratification rates five years after the date of the Amendments, in terms of the number of parties and percentage of 1986 ODS consumption, were similarly comprehensive for the LDN1990 (104 parties; ~95% global ODS consumption in 1995), the CPN1992 (75; ~81% in 1997), the MON1997 (89; ~51% in 2002) and the BEI1999 (86; ~79% in 2004). However, the 'international community' of UN Member States has also expanded significantly since the date of the MP1987, from 155 States

[300] A corresponding data table is included in the file 'Consolidated Ratification Data.xlsx' at this link: https://phaidra.univie.ac.at/o:1536414.

[301] Refer MP1987 Art 16(1), which required at least 11 State parties to have formally deposited instruments of ratification representing at least two-thirds of 1986 estimated global ODS consumption. A further condition precedent to EIF for the MP1987 was that the VCPOL necessarily had to have also entered into force (which it did on 22 September 1988).

before 1990 to 193 today, which represents an increase of 125%. This reflects the fall of the Soviet Union and continued decolonisation in the Pacific, but even when accounting for this dynamic membership, the MP1987 had a slower ratification rate than the PA.

Figure 16: Ratification rates by number of parties (columns) and representative proportion of global ODS consumption/GHG emissions (dotted lines)



The MP1987 and all of the Amendments[302] have since been universally ratified by all 193 UN Member States, as well as non-Member States the Cook Islands, the EU, Holy See, and Niue. In addition, the Palestinian Authority ratified the MP in 2019, but it has not ratified any of the Amendments. Taken together, this accounts for the MP's current 198 parties, covering 100% of global ODS consumption (1986 baseline). As amended by the four Amendments considered here, the MP has been ratified by 197 parties and covers 99.97% of global ODS consumption (1986 baseline).

Conversely, in 1998, the year that the KP opened for signature, there were only 5 ratifications and this only represented ~0.02% of global GHG emissions (1990 baseline). After five years, the number of countries that had ratified the KP increased significantly to 100, while the corresponding proportion of global GHG emissions plateaued at ~48%. However, this was below the required 'double-majority' of at least 55 parties to the UNFCCC, incorporating such parties listed in Annex I to the UNFCCC as to exceed a corresponding proportionate global GHG emission level of at least 55% (1990 baseline). It was not until 2004, after

[302] That are considered here, not including the 2016 Kigali Amendment.

the Russian Federation and other Annex I parties ratified the KP, that this emissions-based threshold was reached, which allowed the KP to enter into force on 16 February 2005. Further ratifications have continued since 2005 and the KP currently has 192 parties, representing ~75% of global GHG emissions (1990 baseline). However, the fraction of corresponding GHG emissions has plateaued (and is likely to remain) at this level because one of the biggest cumulative GHG emitter, the USA (~23% of 1990 GHG emissions), never ratified the KP.

Finally, the PA was ratified by 121 countries in 2016, the same year that it entered into force, which collectively represented ~80% of total global GHG emissions (2015 baseline[303]). After five years, this increased to 190 ratifications and ~97% of global GHG emissions. The PA has now been ratified 193 times, representing ~99% of 2015 global GHG emissions.

Interestingly, a group of 59 'early adopter' countries[304] ratified the MP, the KP and the PA within the first five years of all three agreements and represented about 50%[305] of proportionate consumption/emissions in each case. This group of countries is geographically diverse and although it is dominated by European States (including the 'EU'[306]), it also includes Argentina, Brazil, Chile, China, India, Japan, South Africa and South Korea. Note that the NDCs submitted by several of these high-emitting NAxB (developing country) parties were analysed more closely as representative proxies for the wider group of NAxB parties in the context of the climate regime scenarios detailed later in this Chapter.

In summary, the PA had the fastest ratification rate in terms of both the number of ratifying parties and their proportionate global GHG emissions, while the KP had the slowest ratification rates and least representative corresponding proportion of global emissions, albeit reflecting the non-participation of a single party (the USA) with an outsized proportionate emissions footprint. Meanwhile, the MP1987 was somewhat slower to be ratified by a large number of parties, although those parties that had ratified early made up a disproportionately large proportion of overall ODS consumption. This probably reflects the concentration of the ODS industries in a handful of countries. Delicate negotiations were required to get these ODS producing States (and powerful industry representatives) to agree to introduce ODS control measures, particularly among those with oppositely oriented negotiating positions such as the USA and the EU (Benedick 1998; Sunstein 2007).

[303] See PA Art 21(2), para 104 of Decision 1/CP.21 and Annex I to FCCC/CP/2015/10. This 'baseline' only applies for the purposes of the EIF provision in Art 21(1) and does not purport to be an overall baseline for parties' pledged reductions in their NDCs under the PA.
[304] Refer 'List of 'early adopter' countries' in the file 'Consolidated Ratification Data.xlsx' at this link: https://phaidra.univie.ac.at/o:1536414.
[305] ~50% (1986 ODS consumption), ~44% (1990 GHG emissions) and ~51% (2015 GHG emissions) of corresponding consumption/emissions, respectively, under the relevant regimes
[306] As defined, for the purposes of the data used in this thesis, to include the 12 EU Member States as at the date of EIF of the MP1987.

More broadly, the different patterns of ratification here reflect international legal theory and the dichotomy between shallower pledges grounded in 'soft' law versus deeper contracts based in 'hard' law (Raustiala 2005; Young 2011). The former tend to have high levels of participation, but that often comes at the cost of substantive content, binding character and normative effect. Conversely, the latter give rise to a presumption of more substantive content and binding or normative effect (Colburn 2019, 183–84). There are exceptions to these two extremes, such as the Helsinki Accords, which were non-binding political pledges, yet widely considered effective in promoting normative compliance through transparency and review (Raustiala 2005, 611–13; Bodansky 2016, 149).

Applying this theoretical approach in the context of the ratification data here, the PA seemed the quintessential shallow 'pledge' with widespread, rapid participation, while the MP1987 and the KP were stricter, deeper 'contracts', with more cautious State participation (Raustiala 2005; Colburn 2019). The MP1987 and the KP's added depth may account for States' general reluctance to agree and hence slower rates of ratification, although this was spectacularly overcome in the case of the MP's universal ratification. In the case of the KP, the slower ratification rate reflects its failure to impose binding emissions reductions on NAxB developing parties and infamous US domestic political divides on that issue (Sunstein 2007; Bodansky 2016, 149; Ghaleigh and Verkuijl 2021, 104–8).

In the context of a 'harder', 'deeper' agreement, the need for widespread ratification seems essential to public confidence in a regime and hence to its success (Bodansky 2016, 149). Yet MP-style universal ratification of such agreements is exceedingly rare and, in light of recent challenges to the post-WWII arrangements of international law and institutions, this seems increasingly unlikely. Moreover, ratification is of limited significance to non-lawyers. In the context of already notoriously difficult to enforce international law, the recent proliferation of increasingly vague, non-binding or non-justiciable[307] international agreements such as the PA must be acknowledged, yet the courts and the law are finding a way (Sands 2016). As Colburn (2019) notes, the decentralised 'We Are Still In!' response by US State and municipal governments to the Trump Administration's withdrawal from the PA, not to mention increasingly significant and active non-State actors on the international level (Ghaleigh and Verkuijl 2021, 108), provide further cause for optimism. All of this suggests that the 'clumsy' solution of the PA is muddling through (Verweij et al. 2006). It is therefore important not to focus too much on the means (i.e., ratification) rather than the ends of a regime. In any event, the PA already enjoys much higher ratification rates and international political goodwill than

[307] Giving rise to no recognised legal action or claim.

the KP ever did (Rajamani 2016b). In the face of apparently immovable domestic political obstacles, such as in the US on climate change, and their extraordinarily distorting international effects (Ghaleigh and Verkuijl 2021, 104–8), Rajamani (2016b) and Colburn (2019) argue forcefully that the world should 'give Paris a chance'.

To that end, the ratification data were analysed from another angle in order to contribute to ongoing assessments of progress towards the implementation of the PA and in light of the first 'global stocktake' scheduled for 2023. The regime ratification rates were compared to determine the average amount of time between the dates of agreements and their respective dates of entry into force (EIF), as shown in Table 34 below. This is particularly relevant in the context of the future development of the PA and its intended timetable of rolling five year updates to the NDCs.

Assume that the length of time between the dates of agreements is an indicator of the complexity and controversy of the preceding negotiations. Table 33 below summarises the differing lengths of final plenary negotiations on each of the three implementing agreements considered here. Recall that there has been a 125% increase in sovereign equivalent UN Member States since the MP1987 was agreed, which would be expected to have caused an increase in the number of participants and hence length of conference time if it were to be re-negotiated today. Meanwhile, the spectacular size and diversity of participants in modern international climate negotiations is well-known (Kemp 2015), as reflected in Table 33.

Table 33: 'Negotiation time' across the three main implementing agreements

	MP1987	***KP***	***PA***
Length of final plenary conference*	3 days (14-16 Sept 1987)	11 days (1-11 Dec 1997)	13 days (30 Nov-12 Dec 2015)
Participating parties	Negotiations: 55 States + EU (EEC) Observers: 6 States + 29 organisations	Negotiations: 155 Parties Observers: 6 States + 278 organisations	Negotiations: 196 Parties Observers: 2 States + 1236 organisations

Note: formal conference negotiations for the MP were much shorter and involved far fewer delegates than for the KP and PA. Yet, in reality, all 3 agreements followed protracted negotiations over years (Benedick 1998; Depledge 2000; Gillespie 2006; Van Calster and Reins 2021).

Meanwhile, further assume that the interval between EIF dates reflects the complexity and controversy of negotiations (since the EIF date must necessarily follow the agreement date, plus an average 'lag' time after the date of the agreement and before its EIF to reflect each State's national circumstances and treaty-making procedures and traditions). Also assume that EIF dates indicate the regime's substantive 'dynamism'; the shorter the EIF dates, the more the regime is reacting to dynamic circumstances and bringing more of the subject matter of the agreement under legal control. Finally, assume that the time between the date of an agreement and its EIF indicates States' attitudes towards the negotiated text; it is one thing to agree to the text of an agreement during negotiations, but a separate act of ratification is required for the agreement to take effect. For this reason, the difference between the date of an agreement and its EIF date is an indication of political will and the perceived political risk of ratifying it.

Taking all of these assumptions together, the relevant ratification data for the two regimes and main implementing agreements are summarised in Table 34. On average, the ozone regime demonstrated a much shorter interval between the dates of its relevant legal instruments than the climate regime (2.9 years vs 7.9 years, respectively). Further, the average interval between EIF dates was shorter under the ozone regime than under the climate regime (2.7 years vs 8.9 years). Finally, the average amount of time between the date of an agreement (DoA) and its EIF, or the 'lag' time described above, was about half as long for the ozone regime (2.2 years) as it was for the climate regime (4.5 years). This holds despite including data for the Kigali and Doha Amendments for the limited purpose of this exercise, which serve to lengthen the average interval for the ozone regime[308] and shorten the interval for the climate regime.[309]

All of the above has significance for the future implementation of the PA regime. The PA establishes a 'bottom-up', 'nationally determined' approach to NDCs, which does not mandate any particular form or legal effect to be given to a State's NDC. Rather, the PA establishes a system of political pledges, which are intended to be updated every five years and with each iteration intended to represent a 'progression' over time. However, without defining some standard manner and form (and baseline[310]) for NDCs, the PA as currently drafted stands in stark contrast to its predecessor, the KP, and the ozone regime. NDCs are not treaties, but could perhaps have the status of a unilateral declaration (Van Calster and

[308] Due to the 17 years between BEI1999 and Kigali.
[309] Due to the inclusion of Doha as a 'step' between the KP and the PA.
[310] By Decision 6/CMA.3, the CMA 'encouraged' all parties to communicate an NDC in 2025 with an end date of 2035, in 2030 an NDC with an end date of 2040, and '*so forth every five years thereafter*'.

Reins 2021, 125). The NDC approach thereby avoids lengthy international negotiations in pursuit of consensus, which is assumedly a significant source of historical delays between regime agreements.

Table 34: 'Frequency' of agreements and entry into force dates across both regimes

	Date of agreement (DoA)	Time between agreements (days)	Date of entry into force (EIF)	Time between EIF dates (days)	Time between DoA and EIF (days)
VCPOL	22-Mar-85	-	22-Sep-88	-	1280
MP1987	16-Sep-87	908	1-Jan-89	101	473
LDN1990	29-Jun-90	1017	10-Aug-92	1317	773
CPN1992	25-Nov-92	880	14-Jun-94	673	566
MON1997	17-Sep-97	1757	10-Nov-99	1975	784
BEI1999	3-Dec-99	807	25-Feb-02	838	815
Kigali[+]	15-Oct-16	6161	1-Jan-19	6154	808
UNFCCC	9-May-92	-	21-Mar-94	-	681
KP	11-Dec-97	2042	16-Feb-05	3985	2624
Doha[+]	8-Dec-12	5476	31-Dec-20	1518[*]	2945
PA	12-Dec-15	1099	4-Nov-16	4279[*]	328
Ozone regime (avg)		**1074** ***(2.9 years)***		**981** ***(2.7 years)***	**786** ***(2.2 years)***
Climate regime (avg)		**2872** ***(7.9 years)***		**3261** ***(8.9 years)***	**1645** ***(4.5 years)***

[+] Included for fuller context

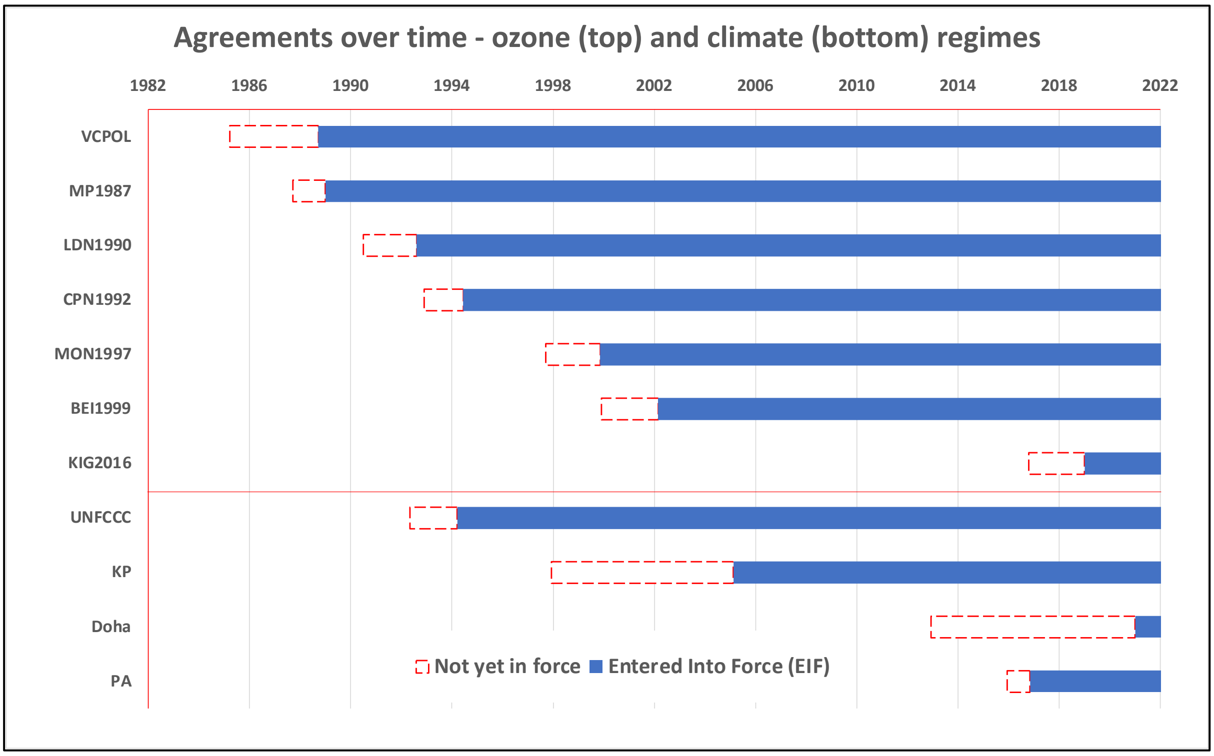
[*] Sequential difference in dates taken to avoid negative result.

Even if a State complies with the envisaged five year timeframe, there is no standardised manner for giving effect to a State's NDC, as opposed to the recognised means of ratification for treaties. Some States may pursue national or regional policies, others may adopt a stricter legislative approach, while others may merely announce a target, aim or goal. By contrast, the MP (with Amendments) and KP had the status of treaties, which permit some flexibility in manner and form of ratification, yet share the common minimum requirement of ratification.

The average 'lag' time prior to EIF is visualised for the historical development of both regimes in Figure 17 below. Recall that States have historically been twice as fast to put ozone regime treaties into effect than climate regime treaties (2.2 vs 4.5 years, respectively). Recall also that there is evidence from the historical development of both regimes that domestic (i.e., US climate politics) and regional (i.e., defensive EU positions on ODS producers) political considerations have led to significant delays in regime development and progression.

Having regard to all of the above and in anticipating how the five year NDC cycles under the PA may unfold in decades ahead, the time between the DoA and its EIF may assume increased relevance. This is because the average 'lag' time for climate regime agreements to be put into effect is 4.5 years, which is the majority of the intended five year cycle for NDCs. It is also similar to the length of common political cycles (e.g., 3-5 year terms of office in most liberal democracies). Without a common means of putting NDCs into effect, there is therefore a high risk of the NDCs regime descending into a 'moving feast' not only of shifting emissions baselines, but also shifting and unimplemented pledges. Against the background of the climate regime's 8-9 years between agreements and an average 'lag' time of 4.5 years in putting each agreement into effect, the intended five year cycle for NDCs therefore appears to be ambitious. And this history of significant delay makes a mockery of the UN Secretary-General's recent call for States to shift to annual pledges until the 1.5°C goal is achieved (Sengupta 2021). Of course, in devolving the responsibility for developing NDCs to individual States (or regional organisations, like the EU) and avoiding protracted international negotiations on a binding text, the NDC cycle would be expected to be quicker, although it remains to be seen just how much faster it will be and how State practice will develop around implementation of NDCs.

Figure 17: Visual comparison between DoA and EIF dates across both regimes



6.6 Hypothetical alternative emission reduction scenarios

6.6.1 Simulated GHG emissions, applying ozone regime reductions

In further exploration of the differences between the ozone and climate regimes, the emissions reductions schedules under each regime, as both agreed and actually achieved, were inverted between the regimes and the results were compared as described below.

Figure 18 shows the range of GHG emission scenarios that might have occurred, had the ozone regime's schedule of reductions in ODS consumption levels been agreed and implemented since 1990 in the context of global GHG emissions. It includes the 'No Climate Regime' worst case scenario based on RCP8.5. Figure 19 shows the same scenarios, but with the 'No Climate Regime' removed. In both figures, the time series data for each scenario are plotted as faint dashed lines, with 10-year moving averages shown more prominently to reduce the effects of random number generation and better distinguish the finer differences between the later Amendments (from the CPN1992 to the BEI1999). Some of the key statistics from the scenarios are summarised in Table 35.

Table 35: Summary of overall changes in the hypothetical GHG emissions scenarios

	Net change (%)	***Timespan (years)***	***Average annual change (%)***	***Min. (MtCO2)***	***Max. ($MtCO_2$)***	***Aggregate emissions ($MtCO_2$)***
Historical GHGs	158%	60	3%	9091	34877	1308411
No Climate Regime	300%	52	6%	22135	66500	2461490
Reality ODS	-100%	33	-3%	158	28247	692845
MP1987	-13%	52	0%	14967	29928	1685696
LDN1990	-82%	52	-2%	2437	30642	918107
CPN1992	-93%	52	-2%	861	29223	776154
VIE1995	-100%	52	-2%	57	29223	749667
MON1997	-100%	52	-2%	2	29587	741410
BEI1999	-100%	52	-2%	0	29587	741386
MON2007	-100%	42	-2%	0	29587	724255

Figure 18: Hypothetical GHG emissions scenarios, including 'No Climate Regime' worst case scenario

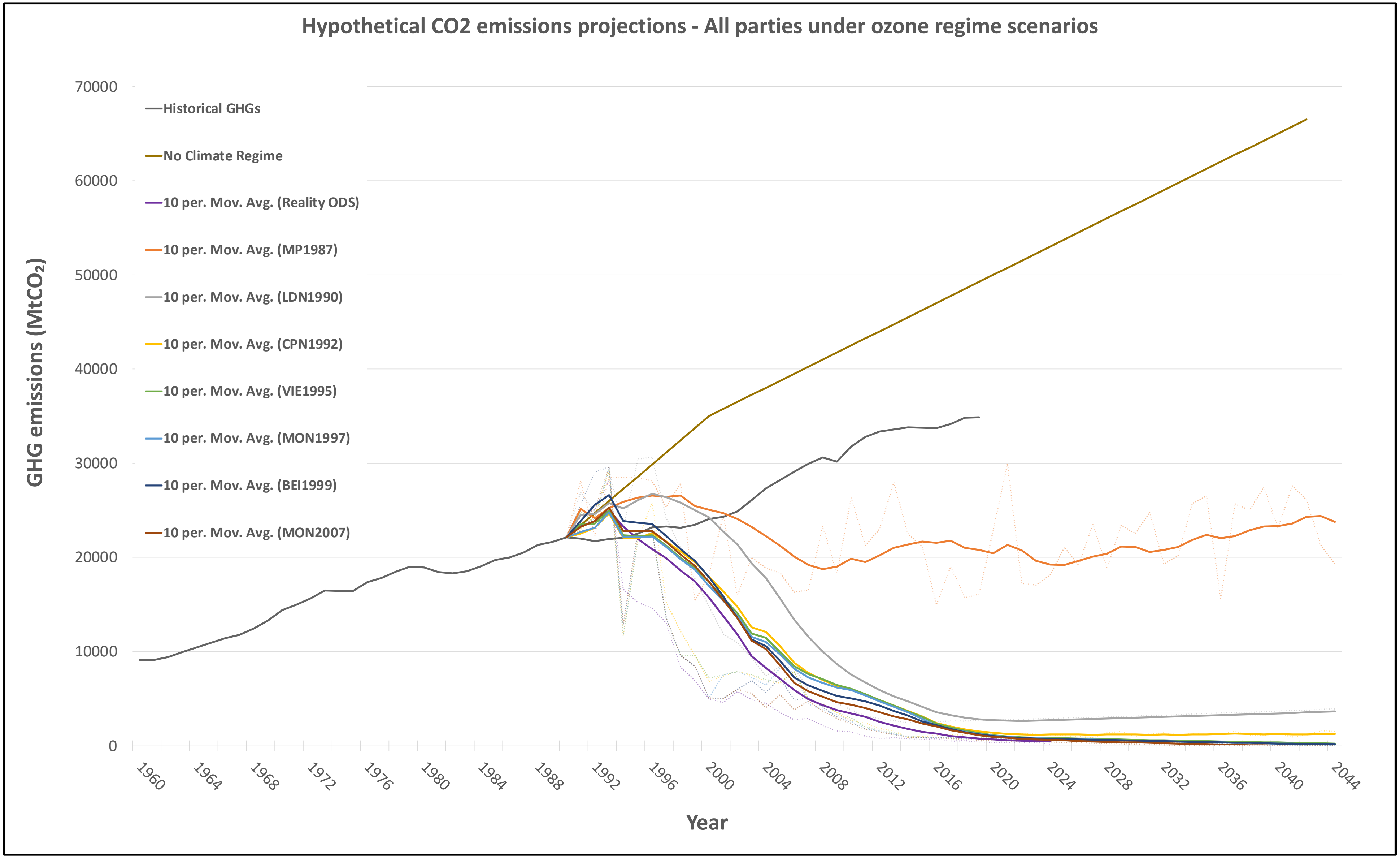
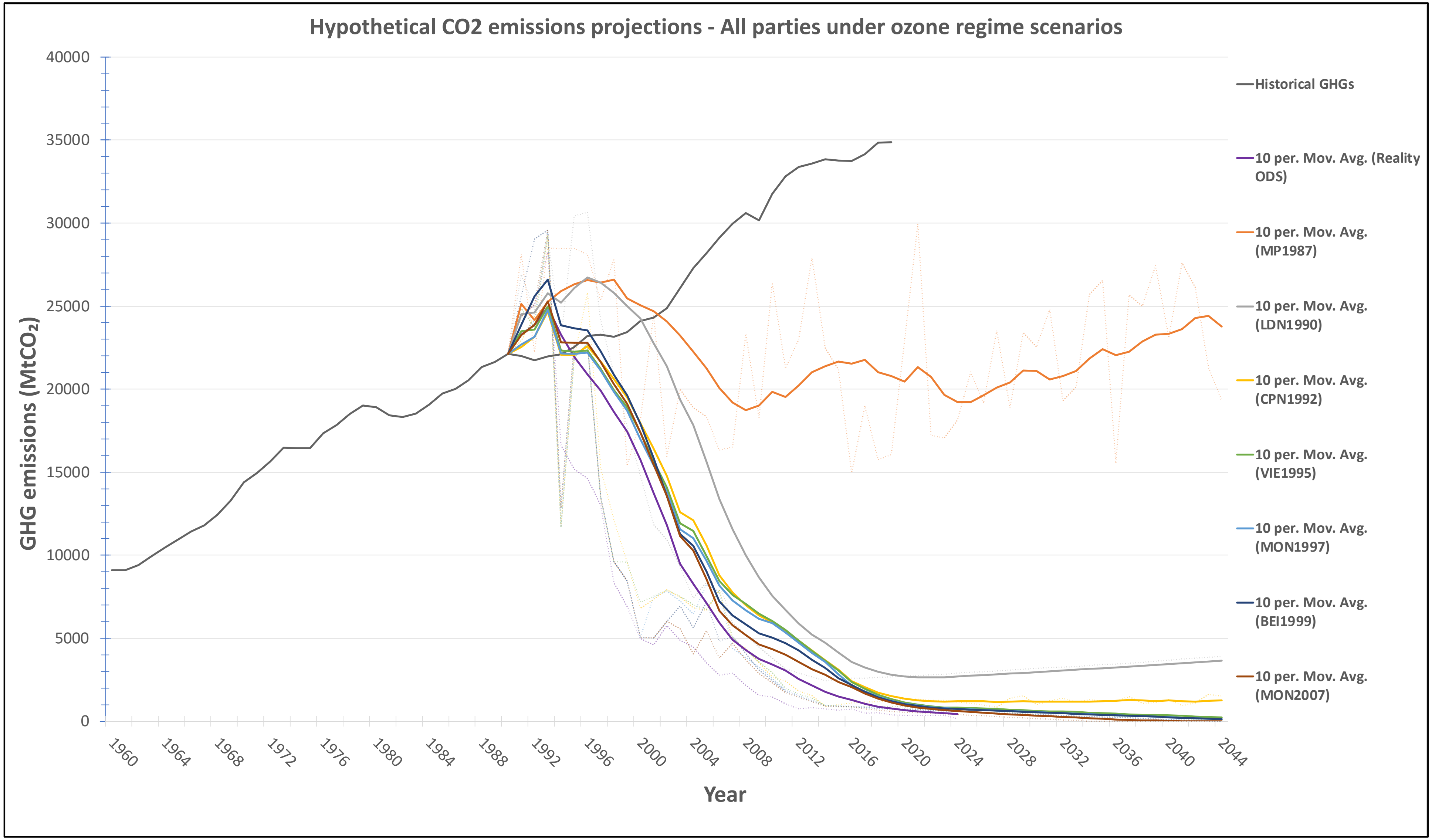


Figure 19: Hypothetical development of GHG emissions, following ozone regime scenarios



The purple line labelled ‘Reality ODS’ shows how GHG emissions would have been reduced since 1990, had the actual real-world reductions in ODS consumption been achieved in the same proportions, but for GHGs. Meanwhile, the dark grey line labelled ‘Historical GHGs’ shows how GHG emissions have actually developed between 1960 and 2019. The ‘No Climate Regime’, ‘Reality ODS’ line and the ‘Historical GHGs’ line are therefore provided to put the hypothetical scenarios based on the ozone regime into relevant, broader context.

Under the most optimistic ozone regime-based scenario plotted in brown and labelled ‘MON2007’, by analogy to the fully implemented schedule of reductions under the MP as amended and adjusted up until the MON2007 adjustment, GHG emissions would have been permitted to surge by up to ~133% in the short-term (3 years). However, after 6 years, GHG emissions would have fallen back to approximately 1990 levels, before a series of rapid reductions would have been imposed until 2005. Thereafter, reductions would have continued at a slower rate until about 2020, when the rate of reduction would have slowed further again. Emission reductions would then be expected to continue reducing gradually, reaching ‘net zero’ by 2034.

The scenarios marked ‘BEI1999’, ‘MON1997’, ‘VIE1995’ and ‘CPN1992’ (in decreasing order of severity of emission reductions) would unfold in substantially the same manner as ‘MON2007’. The main difference between these four scenarios came between 2005-2015, based on their respective reductions in consumption of the more marginal ODS. Besides ‘MON2007’, the only other scenario to reach zero was ‘BEI1999’ (albeit 10 years later, in 2044).

The scenario marked ‘LDN1990’ mirrored the same shape of the main cluster of more ambitious scenarios, but with more permissive GHG emissions after 1994 and only returned to 1990s levels in about 2001. After 2010, emissions reductions tend to slow until about 2018, and then plateau before trending slightly upwards. Note that the LDN1990 scenario reflects the suite of new binding emissions reduction obligations introduced by the LDN1990 to the ozone regime. By comparison, the MP1987 also imposed substantial cuts on ODS consumption (of CFCs), as reflected here, but by comparison to the relatively marginal reductions achieved by the other Amendments, the LDN1990 was clearly the most consequential.

Finally, the scenario marked ‘MP1987’ simulated the most ‘realistic’ trend in GHG emissions, relative to the ‘Historical GHGs’ (real) emissions reference scenario. The ‘MP1987’ scenario consisted of GHG emissions freezes and modest cuts, and unlike the other scenarios it did not permit the early ‘surge’ of up to 150% in emissions. The MP1987 scenario returned to 1990 baseline GHG emission levels by ~2004, yet without the further phased reductions in the other scenarios, GHG emissions remained stubbornly high out to 2044. Note that both the MP1987 and the LDN1990 10-year moving average trendlines show a slight 'increase' after 2020. This reflects the dual effects of the 10-year moving average line and the bounds of the random number generation. The number generation permitted random annual fluctuations in data, provided that absolute emissions figures always remained within the last emissions reduction 'cap' imposed by the regime. Thus, while the 10-year moving average may show a trend upwards in certain combinations of random data, the absolute emissions levels always remained within the relevant annual 'cap'.

In summary, the MP scenarios considered here, if they had been applied to GHG emissions since 1990, would have achieved substantial GHG emissions reductions and the world would be well on its way to achieving 'net zero' by the 2030s or 2040s. Instead, the dark grey line labelled 'Historical GHGs' shows the scale of the world's challenge (as at 2019) to reduce GHG emissions and how steeply emissions still need to be cut from the levels at the end of 2019, prior to the COVID-19 pandemic.

6.6.2 Ozone regime scenarios in real-world context

To assess the scale of this challenge against a real-world benchmark and to put the visible effectiveness of the ozone regime shown in Figure 18 and Figure 19 in more tangible terms, the cumulative GHG emissions from each of the scenarios were calculated across the length of each time series. These cumulative totals were then compared with the Global Carbon Project's 'remaining carbon budgets'[311] effective from 2022 (Friedlingstein et al. 2022), which were 'backdated' to 1990 to be applied here, as detailed in Chapter 6.

The concept of a 'remaining carbon budget' is closely linked to the concept of the 'transient climate response to cumulative carbon emissions' (TCRE). As the name suggests, the TCRE is the average transient temperature increase in response to increasing global GHG emissions, implied from the approximately proportional relationship between GHG emissions and global average temperature (Rogelj et al. 2019). It is to be distinguished from the concept of the equilibrium climate response, which has a much longer-term focus and accounts for changes in radiative forcing as a result of various climate system feedback processes (IPCC 2021b, 11). The TCRE continues to be the subject of intense scientific investigation. In the most recent IPCC 6th Assessment Report, the best estimate for the Earth's TCRE was

[311] See IPCC (2021a, Appendix VII: Glossary) and IPCC (2021b, 28–29).

narrowed to a *likely*[312] range of 1 to 2.3°C of global average temperature increase for every 1000 PgC emitted (IPCC 2021b, 28), where 1 PgC = 1 GtC = 3.664 $GtCO_{2\text{-eq}}$.

As at the end of 2021, the 'consumed carbon budget' was estimated by Friedlingstein et al. (2022) to be 2475 $GtCO_{2\text{-eq}}$. Thus, from 2022 onwards, the corresponding 'remaining carbon budgets', representing a 50% likelihood of limiting the global average temperature increase to 1.5°C, 1.7°C and 2.0°C above the pre-industrial average, were estimated to be 420 $GtCO_{2\text{-eq}}$ (1.5°C), 770 $GtCO_{2\text{-eq}}$ (1.7°C) and 1270 $GtCO_{2\text{-eq}}$ (2.0°C), respectively.[313] The cumulative scenario emissions results are shown in Table 36, where they are also compared with the GCP's calculated remaining 'budgets' that would be consistent with 1.5°C, 1.7 °C and 2.0 °C of TCRE.

Table 36: Cumulative emissions by scenario and comparison with remaining carbon budgets

	***Cumulative emissions (> 1990)* ($GtCO_{2\text{-eq}}$)**	***1.5°C budget (>1990)* ($GtCO_{2\text{-eq}}$)**	***1.7°C budget (1990)* ($GtCO_{2\text{-eq}}$)**	***2.0°C budget (>1990)* ($GtCO_{2\text{-eq}}$)**
Remaining carbon budgets		1328	1678	2178
Historical GHGs	908	420	770	1270
No Climate Regime	2461	-1133	-783	-283
Reality	693	635	985	1485
MP1987	1686	-358	-8	492
LDN1990	918	410	760	1260
CPN1992	776	552	902	1402
VIE1995	750	579	929	1429
MON1997	741	587	937	1437
BEI1999	741	587	937	1437
MON2007	724	604	954	1454

The comparison with the remaining carbon budgets revealed that almost all scenarios based on the ozone regime schedules of required reductions would be consistent with the

[312] The IPCC reports all of its findings by reference to its degree of confidence, which ranges across five levels: very low, low, medium, high and very high. It often also reports its assessment of the 'likelihood' of an outcome or result. Here, *likely* means >66%.

[313] Note that these subsidiary remaining carbon budgets are smaller than those estimated by the IPCC, for the same 50% confidence level, viz.: 500 $GtCO_2$ (1.5°C), 850 $GtCO_2$ (1.7°C) and 1350 $GtCO_2$ (2.0°C), respectively (IPCC 2021b, 38). However, since all GHG emissions data used here was also from the GCP, for consistency, those budgets were preferred.

GCP's remaining carbon budgets. The only scenarios inconsistent with these budgets were the 'No Climate Regime' (which would significantly exceed all three budgets) and the 'MP1987' (which would exceed the 1.5°C budget and just exceed the 1.7°C budget, but not yet the 2.0°C budget by the end of the series in 2044). By the end of all of the other ozone regime-based scenarios, there would be at least as much $CO_{2\text{-eq}}$ remaining in the budget as there currently is in the world's remaining 1.5°C budget (420 $GtCO_{2\text{-eq}}$).

In conclusion, the ozone regime-based scenarios suggest that if GHG emissions reductions of the same proportion as the reductions in ODS consumption under the ozone regime had been achieved since the 1990 baseline, then the world would have avoided more transient warming than it has (and will). Moreover, notwithstanding continued GHG emissions for between 33 and 52 years, the majority of the scenarios would leave a larger remaining carbon budget after that period, than the world currently has remaining after cumulative real-world emissions to date. In that context, recent analysis concluded that, if all conditional and unconditional pledges in existing NDCs under the PA were achieved, then the world could limit TCRE to within the 2.0°C global average temperature goal in the PA (Meinshausen et al. 2022). However, even the 'best case scenario' on NDC implementation assumed by Meinshausen et al. (2022) would only just achieve this goal. The results based on the scenarios here would have provided much more 'breathing room', but both sets of results stand as timely reminders of the importance of acting early to cut emissions and that it is still not too late to change course on reducing global GHG emissions. The last word here goes to Professor Susan Solomon:

'The 2030 pledges in many ways are more important than the 2050 pledges. 2050 is largely aspirational. ***2030 sends a clearer signal to industries****…*

We don't know what's going to be possible by 2050, but we do probably have a pretty good idea what can be possible by 2030. It's already 2020, so you can look 10 years down the line and when you get to that point 10 years down the line, you'll be able to look the next 10. So ***if we had started earlier, maybe we could have done more earlier we maybe could be further along than we are now, but as I say that the technology and costs have gotten to the point where things are practical and a lot is going to happen****, a lot is already happening…*

… ***today's small emitters will be tomorrow's big emitters and everybody has to be part of this****…'*

6.6.3 Simulated ODS consumption, applying climate regime reductions

This section describes the results for the reverse of the situation in 6.6.1, above. Here, counterfactual hypothetical reductions in ODS consumption were simulated, based on observed and agreed reductions in GHG emissions under the climate regime.

Figure 20 shows the range of ODS consumption scenarios that might have occurred, had the climate regime's schedule of reductions been applied to ODS consumption figures since 1986. It includes a 'No Ozone Regime' reference scenario, based on similar assumptions to those used in Velders et al. (2007). Figure 21 plots the same ODS consumption scenario data, but with the 'No Ozone Regime' reference scenario removed. The datapoints for each scenario are plotted as dashed lines, with more prominent 10-year moving averages shown to reduce the effects of random number generation between defined minimum reduction thresholds. The use of the 10-year moving average trendlines results in a corresponding common 10-year shift forward (relative to 1986) for all climate regime-based scenarios.

The overall changes and key statistics across all climate regime-based scenarios are summarised in Table 37.

Table 37: Summary of overall changes in the hypothetical ODS consumption scenarios

	Net change (%)	***Timespan (years)***	***Average annual change (%)***	***Min (ODP t)***	***Max (ODP t)***	***Cumulative ODS consumption (ODP t)***
Historical ODS	-99%	34	-2.92%	9328	1662589	1.31E+07
No Ozone Regime	1185%	52	23%	1302816	15441774	3.25E+08
Actual GHGs	158%	29	5.43%	1279584	2052835	4.93E+07
KP_best	-43%	79	-0.55%	737726	2080457	1.25E+08
KP_worst	-41%	71	-0.58%	766717	2169816	1.23E+08
Doha_best	-53%	79	-0.66%	618596	2004508	1.19E+08
Doha_worst	-49%	71	-0.70%	658065	2054799	1.19E+08
Paris_1	-25%	80	-0.32%	938981	2335431	1.34E+08
Paris_2	-88%	80	-1.10%	156010	2155860	1.07E+08

Figure 20: Hypothetical ODS consumption scenarios including 'no ozone regime' worst case scenario

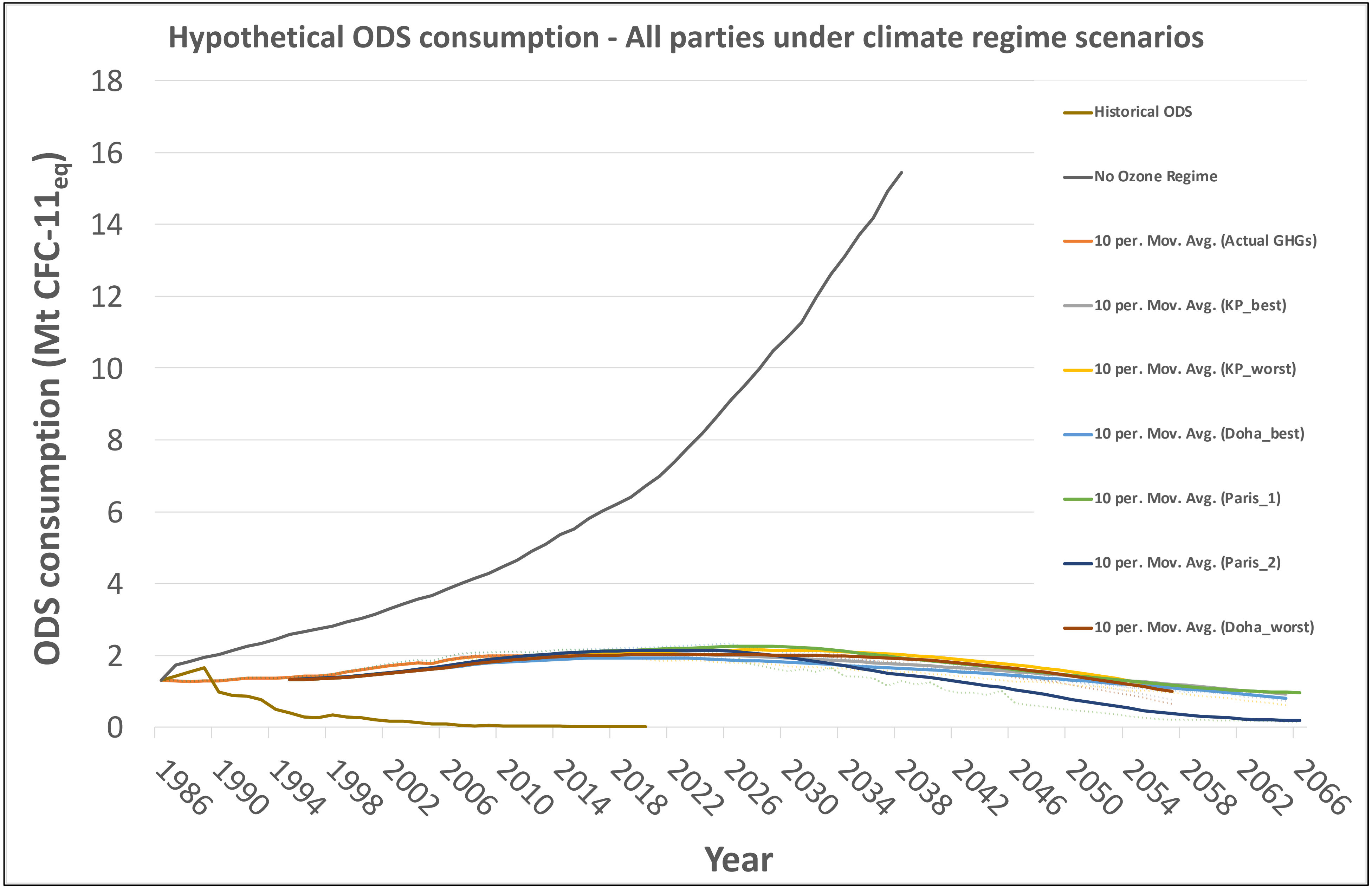
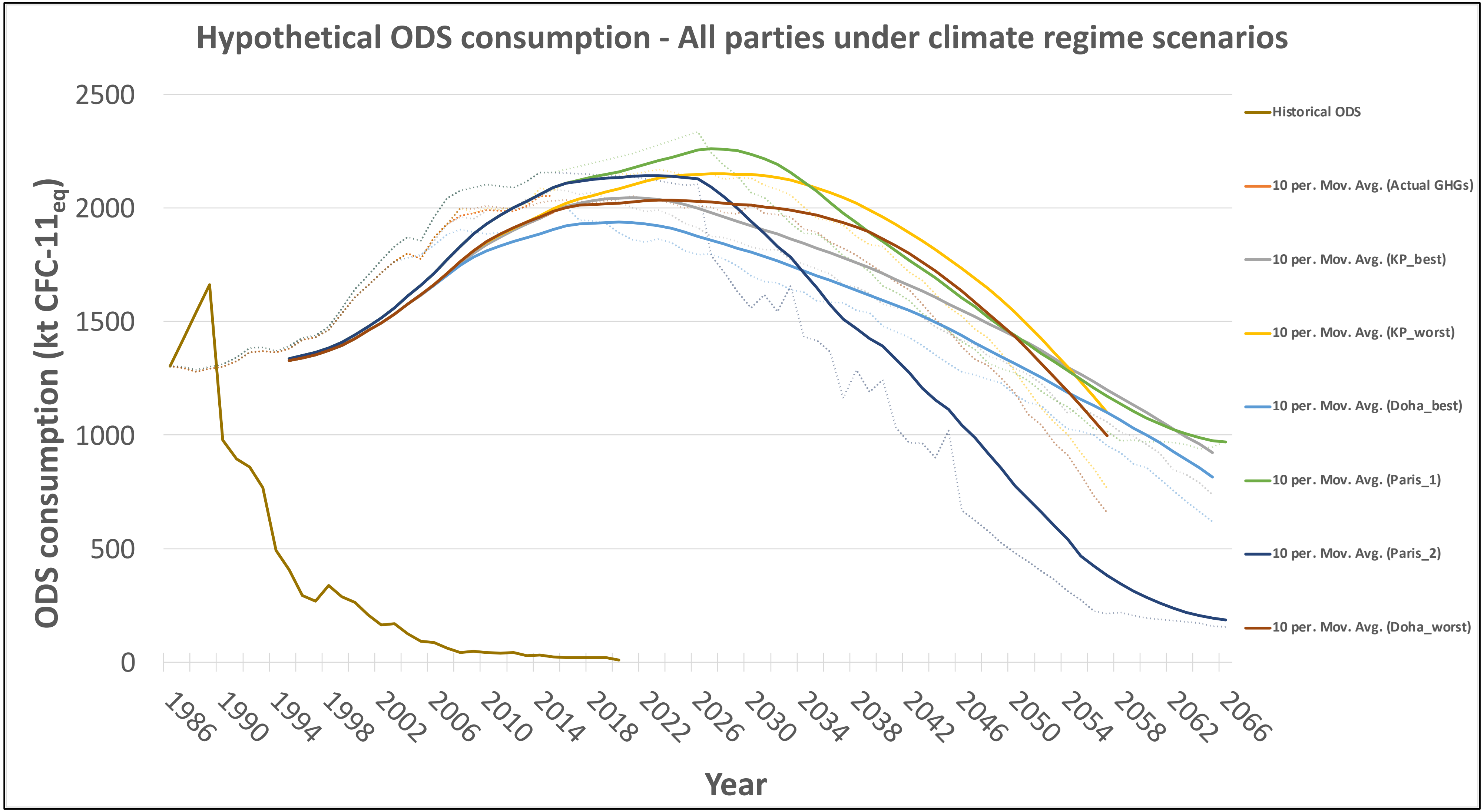


Figure 21: Hypothetical development of ODS consumption levels, following climate regime scenarios



Like the 'Historical GHGs' scenario considered in the ozone regime-based scenarios in 6.6.1, the orange line labelled 'Actual GHGs' shows how ODS consumption levels would have been reduced since 1986, had the actual real reductions in GHG consumption been achieved in the same proportions, but for ODS. Meanwhile, the brown line labelled 'Historical ODS' shows how ODS consumption levels actually developed between 1986 and 2020. Thus, the 'No Ozone Regime', 'Actual GHGs' line and the 'Historical ODS' line once again placed the hypothetical scenarios based on the climate regime into some broader context.

The most significant climate regime-based scenario, in terms of projected substantive ODS consumption reductions, was the dark blue 'Paris_2' scenario. That scenario assumed compliance with first and second (if applicable) NDCs, including any pledged net zero goals, by developed country parties to the PA[314] and the 11 highest emitting developing country parties. However, even under this 'best case scenario' and when compared with the much steeper reductions shown by the 'Historical ODS' line, the projected continued growth in ODS consumption levels and significantly slower reductions would have been cause for additional concerns about the implications for the ozone layer. In particular, ODS consumption would have only returned to 1986 levels in the mid-2030s. (Even more concerningly, for the other scenarios, ODS consumption would not return to 1986 levels until the mid-2040s or 2050s.)

The next most significant scenario in terms of absolute reductions in ODS consumption levels was the 'Paris_1' scenario. This scenario assumed that certain developed country parties to the PA[315] would meet, and that the 11 highest emitting developing country parties would also achieve, their first NDCs. Unsurprisingly, this less onerous reduction pathway, relative to 'Paris_2', would lead to an even worse outcome for ODS consumption and further raise concerns about the potential implications for stratospheric ozone levels.

Note the sharp inflection point in both PA-based scenarios from the mid-2020s. This largely reflects the first NDC pledge by the largest historical GHG emitter, the US, to cut its GHG emissions by 26-28% of 2005 levels in 2025. The subsequent sharp decrease from 2030 onwards reflects the NDC pledges of other developed countries with significant GHG emissions baselines also committing to reductions by 2030, and the effect of a linear decrease towards most major developed countries' goals to achieve 'net zero' by 2050.

Meanwhile, there was a range of potential outcomes in the other ODS consumption scenarios. Under the 'Doha_best' and 'KP_best' scenarios, full compliance with Doha by 2013

[314] Namely, those developed countries that are listed in Annex B of the KP and that are also parties to the PA.
[315] As for 'Paris_2', those parties listed in Annex B of the KP that are also parties to the PA.

and with the KP by 2008 was assumed for AxB (developed country) parties, while NAxB (developing country) parties were assumed to achieve reduction rates similar to those actually achieved by AxB parties between 1990-2019. This was reflected in the polynomial equation line of best fit through the real 1960-2019 GHG emissions time series for AxB parties. This projection was then extended on the assumption of sustained reductions thereafter within the (negative) range of the real 1960-2019 GHG emissions time series. This aspect of this scenario substantially ignores the reality of a growing trend in the 11 highest NAxB parties' emissions and the KP's 'common, but differentiated responsibilities' principle in assuming a 'best case scenario' for emissions from developing country parties, which suggests that it is unrealistic. Regardless, even in such an idealised situation, the absolute cuts in total global ODS consumption would be insufficient to avoid much higher levels of ODS consumption and correspondingly heightened concerns about a tremendous reduction in stratospheric ozone levels.

Two further and similarly formulated ODS consumption scenarios arose under the KP, 'Doha_worst' and 'KP_worst'. These '_worst' scenarios assumed full compliance by AxB parties with the required reductions under Doha and the KP, but only by the latest year of the relevant 'commitment period' (2020 for Doha and 2012 for the KP). Meanwhile, both scenarios assumed that NAxB parties' GHG emissions would continue to rise and then start falling, in line with the polynomial equation line of best fit through the real 2000-2019 GHG emissions data for NAxB parties, which was substantially driven by China's emissions during that period. In the result, as with all the other hypothetical ODS consumption scenarios above, both the 'Doha_worst' and 'KP_worst' scenarios would lead to substantially higher ODS consumption levels than was observed in the real world. This would be expected to lead to increased concern about what such higher cumulative ODS consumption could mean for stratospheric ozone levels over the long term.

Note the substantially similar trajectories in 'Doha_best' and 'KP_best', and 'Doha_worst' and 'KP_worst'. This largely turned on the underlying assumptions as to NAxB parties' emissions and the AxB parties' required reductions under the KP and Doha. Thus, the 'Doha_best' had substantially the same trajectory as 'KP_best', given the common assumption in both scenarios as to the 11 highest emitting NAxB parties' emissions following the polynomial 'line of best fit' based on AxB parties' historical emissions (1960-2019). Meanwhile, the near-constant vertical displacement between these two otherwise substantially similar scenarios was a function of the linear interpolation between the required reductions in the AxB parties' emissions under those scenarios. Likewise, the substantial similarity between the trajectories of the 'Doha_worst' and 'KP_worst' scenarios was substantially due to the common assumption as to NA5 parties' emissions. That is, following a similar 'surge' to that observed in China's emissions since 2000, this assumed (highly speculatively) that, having increased so rapidly, these emissions would soon peak and then start reducing at a similarly rapid rate, as represented by the relevant polynomial line of best fit. Once again, the vertical displacement between the similar 'Doha_worst' and 'KP_worst' curves was a function of the linear interpolation between AxB parties' required emissions reductions.

In summary, the climate regime-based scenarios considered here, if they had been applied to ODS consumption since 1986, would have resulted in substantially more ODS consumption, at levels above historical highs, well into the 21st century. Further, the observed recovery of the ozone layer in recent decades has been dependent on continued decreasing emissions in ODS and it is assumed that the only substantial remaining emissions sources for most successfully phased-out ODS are existing 'banks' of such substances (WMO et al. 2019, chap. 1; Lickley et al. 2020; Montzka et al. 2021). As a result of such large ODS consumption increases, banks would be expected to increase accordingly, with dire implications for ultimate emissions in the absence of any enhanced regulatory or destructive technological interventions.

6.6.4 Climate regime scenarios in real-world context

There are various different real-world comparisons that can be made with the scenario results described above.

Note that a typical way to report results of such a counterfactual scenario exercise is to model and calculate the expected 'equivalent effective stratospheric chlorine' (EESC). This is a commonly used metric in studies quantitatively assessing the effectiveness of the ozone regime (Newman et al. 2007; Morgenstern et al. 2008; Newman et al. 2009; WMO et al. 2019). However, the calculation of EESC depends on much more sophisticated modelling, including consideration of the particular chemical species, each of their total lifetimes, mixing ratios, relative susceptibility to photolysis, the mean age of atmospheric air masses, and other physico-chemical atmospheric processes (including the effects of increased GHG concentrations on atmospheric dynamics and stratospheric ozone levels). As such, calculation of an EESC figure based on the scenario data here is beyond the scope of this thesis.

Fleming et al. (2020) modelled various scenarios for future $CFC\text{-}11_{\text{-eq}}$ emissions and found that the ozone depletion response was strongly linear across time and emission rates. Moreover, this linear relationship could be expressed in the following simple metric: for every

1,000 Gg increase in cumulative CFC-11 emissions, expected total ozone depletion would be between −0.34 DU (−0.11%) and −2.6 DU (−1.0%), for global/annual and Antarctic spring total ozone, respectively (Fleming et al. 2020). This finding suggests that the counterfactual ODS consumption scenarios simulated here would lead to substantially larger ozone depletion and severely delayed signs of recovery than was experienced in reality, but any comparison with Fleming et al. (2020) would require conversion of the scenario-based ODS consumption results into inferred ultimate emissions.

In an attempt to quantify what level of ultimate emissions may have resulted from the hypothetical ODS consumption scenarios simulated under the climate regime, direct emissions factors (EF) and release fractions (RF) from ODS 'banks' were used to convert the annual consumption figures into ODS emissions (Lickley et al. 2020). The results from the conversion process, as described in Chapter 5, are shown in Table 38 and the inferred emissions are visualised in Figure 22. For the purposes of this conversion, pre-scenario historical cumulative emissions and 'banks' pre-dating any of the scenarios were ignored.

Table 38: Scenario results for ODS production, emissions and 'banks' (1986 baseline)

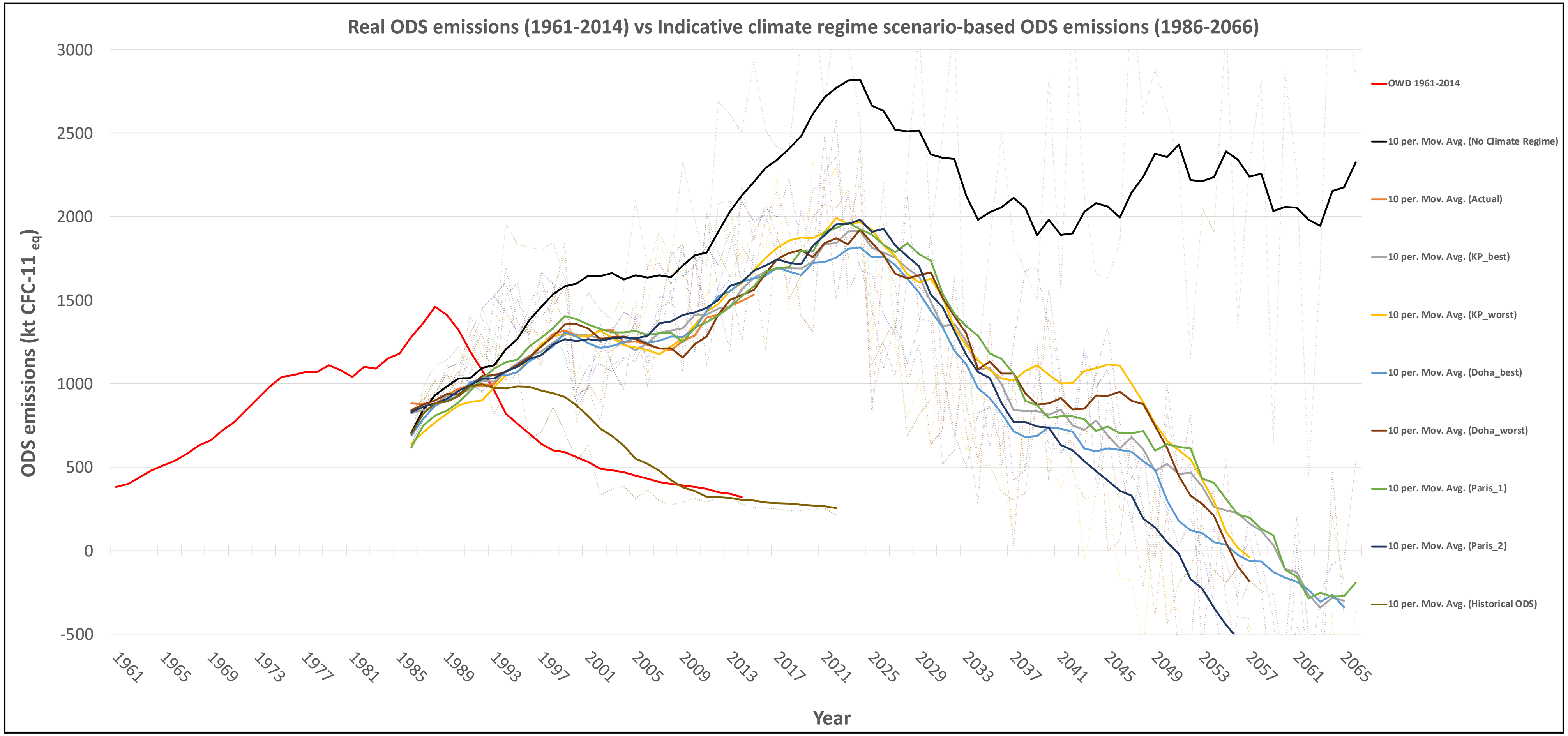
Scenario	***Total cumulative production (ODP t)***	***Additional production (ODP t)***	***Remaining 'bank' (ODP t)***	***Total cumulative emissions (ODP t)***	***Time step (years)***	***Average annual emissions (ODP t / year)***
Historical ODS	1.31E+07	0	7.84E+05	1.23E+07	34	3.62E+05
No Regime	2.72E+08	2.59E+08	1.19E+08	1.54E+08	80	1.92E+06
Actual GHGs	4.93E+07	3.62E+07	1.53E+07	3.39E+07	29	1.17E+06
KP_best	1.25E+08	1.12E+08	6.37E+07	6.17E+07	79	7.81E+05
KP_worst	1.23E+08	1.10E+08	5.43E+07	6.92E+07	71	9.75E+05
Doha_best	1.19E+08	1.06E+08	6.26E+07	5.63E+07	79	7.13E+05
Doha_worst	1.19E+08	1.06E+08	5.29E+07	6.59E+07	71	9.29E+05
Paris_1	1.34E+08	1.21E+08	6.75E+07	6.61E+07	80	8.26E+05
Paris_2	1.07E+08	9.35E+07	6.10E+07	4.55E+07	80	5.69E+05

Despite the necessarily crude methodology due to the loss of differentiation between ODS Annex group data as a result of the scenario development process, the results seem somewhat accurate based on several comparisons. Firstly, the shape of the inferred emissions data here resembled the general shape of the inferred real-world emissions data from 1961-2014 (Hegglin et al. 2015; Ritchie and Roser 2018a), shown as the red 'OWD 1961-2014' line in Figure 22. The cumulative total emissions for that period was 3.75E+07 ODP t, with a sub-total of ~2.05E+07 ODP t for the relevant period from 1986-2014. This compares with ~1.19E+07 ODP t 'emitted' under the 'Historical ODS' scenario from 1986-2014, which is at least the same order of magnitude. (This is despite the crude emissions assumptions and lack of any relevant lifetime removal for the shorter 'Historical ODS' scenario, let alone any modelling of relevant dynamic atmospheric processes.) By further comparison, Liang et al. (2008) estimated cumulative emissions of the dominant CFCs (CFC-11, CFC-12 and CFC-113) from 1960-2004 at 2.5E+07 ODP t.

Meanwhile, using the same UNEP ODS consumption data, but accounting for the different ODS and their relative EF and RF values, Papst (2018, 6) estimated 'reachable' global ODS banks from 1990 to 2014, with a peak in 2009-2011 at around 6.5E+06 ODP t. The results here ranged from ~10^5 ODP tonnes ('Historical ODS') to ~10^8 (No Regime), with most of the other scenarios' remaining bank figures in the order of ~10^7 ODP tonnes. That the 'Historical ODS' scenario result was approximately one order of magnitude smaller than Papst's estimate based on the same data source suggests the method used here led to a significant underestimate. This is probably attributable to Papst's ability to account for the differentiation between ODS groups that was lost in the case of the other scenarios considered here. However, Papst's results were likely also underestimates, given that the methodology only considered the 'reachable' bank, excluding emissions 'lost' to landfill and illegal dumping.

More revealing context comes from comparisons between inferred average annual scenario emissions estimates and the historical emissions figures cited by Ritchie and Roser (2018b) and Liang (2008). Average annual emissions for the 'No Regime' and 'Actual GHGs' scenarios were comparable to annual (natural and anthropogenic) ODS emissions during peak real-world ODS emissions in the 1980s (~10^6 ODP $t.year^{-1}$). Meanwhile, the inferred average annual emissions for the other scenarios listed in Table 38 were comparable to estimated real-world emissions in 1993 (9.6E+05 ODP $t.year^{-1}$; *cf:* 'KP_worst' and 'Doha_worst'), in 1994 (8.2E+05 ODP $t.year^{-1}$, *cf:* 'Paris_1'), in 1995 (7.6E+05 ODP $t.year^{-1}$, *cf:* 'KP_best' and 'Doha_best'), and in 2000 (5.6E+05 ODP $t.year^{-1}$, *cf:* 'Paris_2'). All of these inferred emissions rates dwarf the unexpected increase in fugitive CFC emissions (~10^4 ODP $t.year^{-1}$) observed in 2014-2017 (Montzka et al. 2021) and other residual bank emissions figures cited in the literature in recent years (Lickley et al. 2020).

Figure 22: Inferred ODS emissions from climate regime-based ODS consumption scenarios



Noting all of the above limitations with the estimated emissions data, but as a final hypothetical exercise, the estimated corresponding levels of stratospheric ozone depletion were calculated using the linear relationship described by Fleming et al. (2020) and the scenario-derived total cumulative $CFC\text{-}11_{eq}$[316] emissions. The results are shown in Table 39.

Table 39: Estimated ozone depletion from climate regime-derived cumulative ODS emissions

Scenario	***Total cumulative emissions (ODP t)***	***Estimated resultant global ozone depletion (DU)***	***Proportionate global loss (300 DU baseline) (%)***	***Estimated resultant Antarctic ozone depletion (DU)***	***Proportionate Antarctic loss (220 DU baseline) (%)***
Historical ODS	1.23E+07	-4	-1%	-32	-15%
No Regime	1.54E+08	-52	-17%	-400	-182%
Actual GHGs	3.39E+07	-12	-4%	-88	-40%
KP_best	6.17E+07	-21	-7%	-160	-73%
KP_worst	6.92E+07	-24	-8%	-180	-82%
Doha_best	5.63E+07	-19	-6%	-146	-67%
Doha_worst	6.59E+07	-22	-7%	-171	-78%
Paris_1	6.61E+07	-22	-7%	-172	-78%
Paris_2	4.55E+07	-15	-5%	-118	-54%

Recall from Chapter 1 that one DU is equal to a 0.01 mm thick layer of ozone at standard temperature and pressure (0 °C, 1 atm). Globally averaged, the ozone layer is about 300-500 DU thick and human-induced stratospheric ozone depletion caused approximately 5% reduction globally between 1970 and the mid-1990s (Wuebbles 2022). Most of the scenarios here would cause at least that much average global ozone depletion, with estimated global reductions in the range 5-17%.

Meanwhile, the usual definition of the 'ozone hole' is that region south of 60°S latitude in the Antarctic, where average ozone levels are below 220 DU (Krummel and Fraser 2021). Prior to the phenomenon of human-induced stratospheric ozone depletion, ozone levels typically ranged between 250-350 DU in this region and NASA recorded a near-record minimum of 136 DU there in 2017 (Blumberg 2017). The estimated Antarctic losses from the scenario-derived hypothetical cumulative emissions here would be at least 54%, through to a catastrophic complete ('182%') reduction.

[316] See 'ODP' in Glossary of Terms: 1 t $CFC\text{-}11_{eq}$ = 1 ODP t.

In short, all of the above results, despite their limitations, indicate that the climate regime scenarios described here would have most likely led to a dystopian alternate world in which significant stratospheric ozone loss continued over decades into the 21st century. This would have had devastating human and environmental health effects (Titus, EPA, and UNEP 1986; Sunstein 2007). Fortunately, this was a 'world-avoided' by effective ODS control measures achieved in reality under the ozone regime (Morgenstern et al. 2008; Newman et al. 2009).

6.7 Contextual differences between the two regimes

There are many contributing factors that could explain the very different directions in which the ozone and climate regimes have evolved. However, the following key differences between the surrounding circumstances of each regime appear most relevant. Notably, several of these factors remain substantially similar to those identified by Winfried Lang, another former diplomat involved with negotiating the ozone regime, over 30 years ago (Lang 1991).

6.7.1 Saturation of the economy

'*… what we've learned the hard way is that they are necessary but insufficient conditions to say that the two can be managed in similar ways, and* [one] *of the key reasons… is the fact that… you only had… in the order of a dozen, probably, chemical companies, worldwide, making the* [ODS]*, so it was… straightforward to think about controlling production... but it isn't just that, all the more important really is the fact that although chlorofluorocarbons are used in lots of different applications within our economy, no one would ever say that chlorofluorocarbons were the… mainstay or the basis for our economy, and the real fundamental problem is that…* ***when you look at carbon emissions versus GDP you see a very strong relationship, where the wealthiest nations emit the most carbon****, because they, they first of all need the energy to become wealthy, and second of all, once they become wealthy, they become very avid consumers, so all that snowballs to mean that there's an economic link there that is just far, far deeper than it ever was for the chlorofluorocarbons. And what that means is that* ***the two major producing countries are not going to agree to a serious binding protocol and I think we learned that the hard way over many years of negotiation****, I mean the Kyoto Protocol was sort of a brave attempt to model a climate protocol to at least get started on a climate protocol in a way that was similar to… the Montreal Protocol, and you know it, it did achieve some important successes.*'

- Professor Susan Solomon, 27 July 2021

(emphasis added)

The extent to which ODS- and GHG-generating activities are linked to economic activities differs considerably. Although both kinds of substances are emitted as an inextricable part of human economic activity, ODS have a narrower range of applications. This is despite ODS being used in all manner of everyday materials and equipment, such as aerosol cans, refrigeration appliances, firefighting foams and insulation materials. By contrast, GHGs are generated directly and indirectly by the vast majority of contemporary human economic activities: from a farmer's fields, to a consumer's (plastic) plate, in electricity generation and industrial processes and most modes of transport. Simply put, most activities in modern developed economies are saturated with GHGs. Some progress has been made in a number of developed countries towards a *relative* decoupling of growth in production- and consumption-based GHG emissions from growth in national gross domestic product (GDP) (Haberl et al. 2020). However, this is still not enough; a universal and *absolute* decoupling is required as a 'logical necessity', in order to achieve the dual goals of GDP growth and sustainability, including the PA global average temperature goals (Haberl et al. 2020, 2). Others question whether such a decoupling is even possible (Parrique et al. 2019).

Any attempt to wean society off the atmospherically damaging substances under both the ozone and climate regimes is therefore closely connected with development issues and economic inequality. Indeed, Article 4(7) of the UNFCCC makes plain that: '*economic and social development and poverty eradication are the first and overriding priorities of developing country parties*'. This nexus lies behind the repeated references to technology transfer, capacity-building, 'developmental needs' (in the ozone regime) and 'sustainable development' (in the climate regime), which reflected compromises between 'developing' and 'developed' States (Biniaz 2016, 9). Such references also reflect and reinforce other international law, including human rights law and every person's entitlement to realise their full economic, social and cultural rights, through national effort, international cooperation and in accordance with each State's resources (United Nations General Assembly 1948, Art 22). Yet, unlike the relatively efficient technology transfer and development assistance provided under the ozone regime,[317] the climate regime consists of the inefficient and ineffective Clean Development Mechanism (Victor 2011, 253–54; Mehling 2018, 14, 44) and Joint Implementation regime under the KP, as well as the as-yet unfunded USD$100 billion Green Climate Fund.

Given the strong correlation between GHG emissions and GDP growth, developing countries were understandably reluctant to agree to any binding absolute GHG emission reductions during negotiations on the KP (Sunstein 2007, 21; Biniaz 2016, 21). However, even

[317] Recall that the MLF has disbursed about USD$4 billion since it was established.

if such binding emissions reductions could have been agreed, all States must have been cautious to agree to any finite 'delay' or postponement in compliance with the required reductions. This is because unequal patterns of development remain stubbornly entrenched. As shown in Table 40, the less developed countries have only attained the same approximate level of development as the next highest group of countries, despite the passing of 20 to 30 years. Moreover, despite being a prominent part of the Sustainable Development Goals, any perception of progress on the eradication of poverty has been forcefully debunked (Alston 2020), even before the COVID-19 pandemic. It follows that no reasonable developing State could credibly strike an agreement on an absolute future emissions reduction, like the 10-year delay agreed under the MP, in circumstances where GHG emissions remain so strongly associated with national levels of development and poverty eradication justifiably remains an 'overriding' policy priority.

Table 40: Human Development Index data for recent decades

	Human Development Index (HDI)								**Average annual increase in HDI per decade (%)**			
	1990	**2000**	**2010**	**2014**	**2015**	**2017**	**2018**	**2019**	**1990 - 2000**	**2000 - 2010**	**2010 - 2019**	**1990 - 2019**
Very high *human development*[a]	0.78	0.83	0.87	0.89	0.89	0.89	0.90	0.90	0.55	0.52	0.35	0.48
High *human development*[b]	0.57	0.63	0.71	0.73	0.74	0.74	0.75	0.75	1.04	1.15	0.73	0.98
Medium *human development*[c]	0.43	0.49	0.57	0.60	0.61	0.62	0.63	0.63	1.29	1.50	1.12	1.31
Low *human development*[d]	0.35	0.38	0.47	0.50	0.50	0.51	0.51	0.51	1.00	2.08	1.03	1.38
Developing *countries*	0.52	0.57	0.64	0.67	0.67	0.68	0.69	0.69	1.00	1.18	0.79	1.00
Least developed *countries*	0.35	0.40	0.49	0.51	0.52	0.53	0.53	0.54	1.33	1.95	1.07	1.46
Small island developing *states*	0.60	0.65	0.71	0.72	0.72	0.72	0.73	0.73	0.76	0.89	0.34	0.67
'Developed' *countries (OECD)*	0.79	0.84	0.87	0.89	0.89	0.90	0.90	0.90	0.61	0.46	0.33	0.47
World[e]	0.60	0.64	0.70	0.72	0.72	0.73	0.73	0.74	0.69	0.82	0.59	0.71

[a] 66 States. [b] 53 States. [c] 37 States. [d] 33 States. [e] Average for 189 countries, including Hong Kong SAR China and the State of Palestine. No data for: Korea (Democratic People's Republic of), Monaco, Nauru, San Marino, Somalia and Tuvalu.

All data derived from (UNDP 2020, 350)

6.7.2 Available substitutes

The availability of substitute products and alternative technologies is another stark difference in the factual matrix surrounding each regime. In the case of ODS, only a few firms were responsible for the vast majority of production (Lang 1991, 167–68; Prof. Susan Solomon 2021), including the American company DuPont, the largest producer, and the British company Imperial Chemical Industries (Sunstein 2007, 9–10). Despite initial attempts at denial, these firms eventually pivoted in the face of adverse public opinion and political opposition, and particularly once they came to appreciate that the development of alternative substances was an economic opportunity for them (Sunstein 2007; Prof. Susan Solomon 2021).

There are similarities between the highly concentrated ODS producers and the most prominent fossil fuel producers, including the Organisation of the Petroleum Exporting Countries (OPEC) oil cartel and multinational corporations like Exxon Mobil, Lukoil, Saudi Aramco, Sinopec and Shell. The fossil fuel industry has also infamously engaged in prolonged and organised attempts to deny the problem of human-induced climate change (Oreskes and Conway 2010). However, the public and political momentum for action on reducing GHG emissions has not led to anywhere near the same success as it did for cuts to ODS consumption. Further, the fossil fuel industry is all too aware that just as 'the stone age did not end because the world ran out of stones, and the oil age will not end because we run out of oil' (The Economist 1999). The risk of 'stranded assets' has grown increasingly obvious to all (IPCC 2018, 323, 461; Prof. Susan Solomon 2021), but action by non-State actors appears more likely to be driven by the finance and insurance sectors than the fossil fuel producers themselves (IPCC 2018, 43, 317–18, 378; Ghaleigh 2021, 90). If developing countries are left with stranded assets, this is likely to compound their existing development challenges (Collier 2015, 428).

Nevertheless, there is cause for optimism due to the stunning decrease in the levelized costs of energy[318] of solar and wind power relative to other conventional sources of energy over the last decade (Roser 2020).

6.7.3 Perceived immediacy of issues

Several factors point to the very different ways in which the issues of stratospheric ozone depletion and anthropogenic climate change have been perceived. First, recall the overarching objectives of the two regimes from Chapter 3.2 and note the different emphasis on

[318] Which accounts for both the capital and ongoing lifetime costs.

elimination of *emissions* and risk or likely risk to human and environmental *health* (under the VCPOL) versus the stabilisation of *concentrations* and natural *adaptation* to a changed future climate (under the UNFCCC). Second, it is important to distinguish between climate and its instantaneous manifestation, the weather, yet by doing so, this might make the climate seem distant and amorphous. Further, whereas the 'ozone hole' was perceived by people as a 'threat to their very survival' (Lang 1991, 167), future climate change projections suggest that there will be distinct 'winners' and 'losers' regionally, even if the globally averaged net effects are negative (Sunstein 2007, 47-54). Although the global youth climate movement may mark a more recent shift in public perception on climate risks, this all suggests that the potent force of public opinion has had very different effects under each of the two regimes here (Sunstein 2007, 44-46).

6.7.4 Scope of international negotiations

As noted earlier, the number of UN Member States has grown by 125% since 1990 and each of these States is equal under the principle of sovereign equality in Article 2(1) of the UN Charter. Although the sample size here is small and a broader generalisation is therefore inherently risky, there was dramatic growth in the size of delegations attending the international conferences that led to the KP and the PA, compared to that for the MP (refer Table 33). This also coincides with a proliferation in the number of MEAs (refer Figure 10). Taken together, this adds considerable tension between, on the one hand, sovereign equality and the need for broad participation, and the need to find agreed normative rules for State conduct on the other. Thus, the much larger number of delegates participating in a growing number of international negotiations seems a material change in circumstances between the MP, the KP and the PA.

Moreover, while researching this thesis, the author was fortunate enough to undertake two internships within the UN system in Vienna and in New York City. From personal experience, it was far more likely that 'new' language would be accepted in a negotiation, if the proponent could point to it having been accepted in some other multilateral UN forum. This is consistent with what Biniaz (2016, 20) refers to as 'borrowing' and the practice of 'recycling' the text used in international trade agreements (Seiermann 2018). This all suggests considerable endogeneity within the UN multilateral system and increased coherence between the texts of certain international agreements, in contrast to the results of this case study.

One of the significant limitations of this study was the narrow scope of only considering the agreed and ratified texts of the implementing agreements. This prevented analysis of the wider web of other amendments, adjustments, relevant decisions of the meetings of the parties and even draft texts used in negotiations. That was a necessary compromise on scarce resources and personal ability. However, when deployed astutely, text-as-data analysis offers the potential to 'see through' the sheer volume of such texts. Therefore, there appears to be considerable scope for text-as-data analysis to further investigate and compare the texts of international environmental agreements.[319] There is already an established MEA effectiveness literature on 'pushers' and 'laggards' (Underdal 2012) and 'critical mass governance' (Kemp 2015) in international environmental negotiations. This neatly parallels the 'rule-makers' and 'rule-takers' discourse in text-as-data analysis of international trade and investment law (Alschner and Skougarevskiy 2015; Seiermann 2018). In the context of this case study, the US and EU (among other powerful delegations) took polar opposite negotiating positions on the ozone and climate regimes (Sunstein 2007), which might be reflected in textual trends that are imperceptible to a human reader.

More broadly, the UN Commission on International Trade Law has recently proposed to consider climate change mitigation, adaptation and resilience goals in its future texts.[320] Given continued calls for 'carbon clubs' (Victor 2011; Carraro 2016) and the history of trade restrictions under the MP, this would appear to be a logical area for further research.

Thus, one of the implied findings from this case study is that further research making wider use of text-as-data analysis pioneered by Alschner and Skougarevskiy (2015) in the field of international investment and trade law, would be worthwhile in the future study of MEAs. To that end, the existing full-text databases of *EcoLex* and the *IEADB* would appear to already offer the necessary infrastructure only recently established for trade laws by Alschner, Elsig, and Polanco (2021).

[319] See discussion in Chapter 0.
[320] See UN General Assembly Resolution 76/471, para. 10.

7 Conclusions

In the words of the IPCC (2021), this thesis has sought to provide 'multiple lines of evidence' through its mixed methods approach. To recap the results by reference to the research questions and hypotheses, as follows:

1. How do the operative clauses of the Montreal Protocol (with its London (1990), Copenhagen (1992), Montreal (1997) and Beijing (1999) amendments) compare to the Kyoto Protocol and Paris Agreement?

   H_0: The Montreal Protocol and its amendments (in 1) contained more rigorous and binding obligations over time than the Kyoto Protocol and Paris Agreement.

Through text-as-data analysis and detailed legal analysis, the null hypothesis that the MP contained far more rigorous and binding language than the KP or the PA cannot be rejected. This was evidenced by absolute word counts and Jaccard distances derived by text-as-data analysis, as well as detailed comparisons and legal analysis between key provisions of both regimes. Further, given limited empirical evidence of any relationship between the degree of legal 'bindingness' and State behaviour, and the radically different approach of the PA within the prevailing dichotomous theory of international agreements, the robustness of the hypothesis itself could now be questioned.

2. How does the party ratification rate, in terms of number of parties but also parties' share of global ODS / GHG emissions, compare between the Montreal Protocol (with amendments in 1), and the Kyoto Protocol and Paris Agreement?

   H_0: Party ratification rates differ widely between the Montreal Protocol (with amendments in 1) and the Kyoto Protocol and Paris Agreement, in terms of both the number of ratifying parties and their share of global ODS / GHG emissions.

Once again, the null hypothesis cannot be rejected. This held true across both metrics: number of ratifying parties and their representative contribution to global emissions. The historical interval between agreements under the climate regime had important implications for the future development of the PA's five-year NDC cycle.

3. How would global GHG emission trajectories develop under ‘theoretical’ emission rates comparable to the ODS emissions reductions achieved under the Montreal Protocol (with amendments in 1)?

   H_0: Global GHG emissions would drop sharply over the next three decades and lead to compliance with the primary goals of the Paris Agreement.

Based on the ozone regime-derived scenario data here, the null hypothesis can be rejected. This is not due to any lack of ambition in the required reductions under the MP, but rather that global GHG emissions would have *already* dropped sharply from a 1990 baseline, with only marginal further reductions in the next three decades. Further, the vast majority of ozone regime-derived scenarios demonstrated consistency with the primary goals of the PA.

4. How would global ODS emissions have otherwise evolved, assuming (counterfactual) similar ratification rates and emissions as observed for GHGs under the Kyoto Protocol and Paris Agreement?

   H_0: Global ODS emissions would have increased, leading to widespread stratospheric ozone loss on a global scale.

Based on the climate regime-derived scenario data here, the null hypothesis cannot be rejected. This is because global ODS consumption and inferred ODS emissions would increase substantially from a 1986 baseline under all scenarios. However, the ‘Paris_2’ scenario did at least suggest that the world would achieve zero ODS emissions, eventually. In any event, all scenarios would result in tremendous reductions in stratospheric ozone levels.

In conclusion, at a time when respect for international law has been shaken to its core and the challenge of climate change appears as insurmountable as ever, this thesis offers hope. In the words of US international lawyer Louis Henkin, it is hoped that this thesis will serve as a timely reminder that:

‘*Almost all nations observe almost all principles of international law and almost all of their obligations almost all of the time*’.

(Henkin 1979, 47)

8 Literature

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