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A critical analysis of the Kyoto Protocol using Monte Carlo simulation and MAGICC

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Abstract

The United Nations Framework Convention on Climate Change adopted the Kyoto Protocol in December 1997. Emissions data from national registries were used to quantify the total anthropogenic emissions of signatory parties between 1990 and 2009, found to have been reduced by approximately 18 percent of base year levels. Using IPCC Special Report Emissions Scenarios (SRES) as a practicable baseline for non-mitigation, three distinct intervention scenarios were constructed from target and observed emissions reductions under the Protocol to investigate their climatic implications against unabated anthropogenic carbon by the end of the 21st century. MAGICC Version 5.3 was used to model forecast trajectories under each scenario for both mean annual temperature and global mean sea level up to 2100, set to rise somewhere between 1.88-4.41°C and 27-45cm respectively. Temperature output, together with archival model data, was then run through a global and regional climate scenario generator (SCENGEN), displaying substantial regional temperature variability between mid-latitudes and polar regions. Secondary atmospheric CO_2 concentration data, collated from the NOAA Mauna Loa facility, were combined with Integrated Science Assessment Model (ISAM) projections for 21st century atmospheric CO_2 concentrations under the six SRES illustrative scenarios to provide model input for Monte Carlo simulation analysis. Threshold CO_2 concentrations for the prevention of irreversible climate change beyond a 2°C increase in global mean temperatures were calculated from IPCC defined assumptions under high, intermediate and low climate sensitivities. For each simulation, 1000 iterations were run in R console against intervention scenario KP18, based upon tangible emissions reductions under the Kyoto Protocol, to derive climatic threshold exceedences within a hypothetical century. At best the mitigative influence of the Protocol reduced such exceedence by a single year. For the majority of trial iterations Kyoto had no discernible influence alluding that its present implementation is likely inadequate in preventing dangerous anthropogenic interference with the climate system.

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List of Abbreviations

AAU	Assigned Amount Unit
AOSIS	Alliance of Small Island States
AR4	IPCC Fourth Assessment Report
AR5	IPCC Fifth Assessment Report
AWG-KP	Ad Hoc Working Group on Further Commitments from Annex I Parties
CDM	Clean Development Mechanism
CER	Certifies Emission Reduction
CH_4	Methane
CO_2	Carbon dioxide
COP	Conference of the Parties to the UNFCCC
.csv	Comma separated value
DDC	Data Distribution Centre
DECC	Department of Energy and Climate Change
EIA	Energy Information Administration
EIT	Economies in Transition
ERU	Emissions Reduction Unit
EUA	European Union Allowance
GCM	General Circulation Model
$GgCO_2eq.$	Gigagrams of CO_2 equivalence
GHG	Greenhouse Gas
Gt	Gigaton
GtC	Gigatons of carbon emissions
GtCe	Gigatons of carbon equivalent emissions
GUI	Graphical User Interface
GWP	Global Warming Potential
HFCs	Hydrofluorocarbons

ICAO	International Civil Aviation Authority
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
ISAM	Integrated Science Assessment Model
ITL	International Transaction Log
JI	Joint Implementation
Kz	Vertical Diffusivity
LULUCF	Land Use, Land Use Change and Forestry
MAGICC	Model for the Assessment of Greenhouse Gas Induced Climate Change (Version: 5.3)
MCS	Monte Carlo Simulation
MOP	Meeting of the Parties to the Kyoto Protocol
N_2O	Nitrous oxide
NaN	Not a number
NEED	National Energy Education Development Project
NF_3	Nitrogen trifluoride
NOAA	National Oceanic and Atmospheric Administration
PFCs	Perfluorocarbons
ppb	Parts per billion
ppmv	Parts per million by volume
ppt	Parts per trillion
R	R-project (Version: 2.14.2)
RCPs	Representative Concentration Pathways
REDD	Reducing Emissions from Deforestation and Degradation
RMU	Removal Unit
SAR	IPCC Second Assessment Report
SBI	Subsidiary Body for Implementation
SBSTA	Subsidiary Body for Scientific and Technological Advice

SCENGEN	Scenario Generator
SF_6	Sulphur hexafluoride
SRES	Special Report on Emissions Scenarios
TAR	IPCC Third Assessment Report
THC	Thermohaline Circulation
UN	United Nations
UNCED	United Nations Conference on Environment and Development
UNFCCC	United Nations Framework Convention on Climate Change
Wm^{-2}	Watts per square meter
yr	Year

Introduction

1.1 Background

Global climate change is widely acknowledged to be the defining environmental concern of the 21st century. It is beyond reasonable doubt that the anthropogenic emission of greenhouse gases (GHGs), perhaps most notably carbon dioxide (CO_2), is of discernible influence on the rate and magnitude of recent warming trends. The Kyoto Protocol is a multilateral emissions reduction agreement and an unprecedented landmark in international climate policy in terms of both scope and complexity. An extension of the United Nations Framework Convention on Climate Change (UNFCCC) Kyoto is at the forefront of the Convention's ultimate objective towards the stabilisation of GHGs in the atmosphere at a level preventing dangerous anthropogenic interference with the climate system (UNFCCC, 2012). Signatory parties are bound to an aggregated reduction commitment of around five percent below 1990 levels for a range of gases, by measure of CO_2-equivalence, to be met between 2008 and 2012.

The typical residence time of CO_2 in the Earth's atmosphere is in the order of 125 years generating a lag between emissions reduction strategies and their subsequent influence on future atmospheric composition (Brohé *et al*., 2009). This considered the gravity of informed decision making under uncertainty in the construction of effective climate policy is emphasised. Rather than postpone direct action to curb anthropogenic climate change in order to accommodate further observational confirmation, mitigation must enter into force decades before irreversible change is recognised (Webster *et al*., 2002). Climate models founded upon well-established physical principles have been utilised by the Intergovernmental Panel on Climate Change (IPCC) in their assessments of anthropogenic influences and their implications for the future. Model experiments have forecast that, even following the complete cessation of all CO_2 emitting human activity, it would take several millennia for the atmosphere to return to pre-industrial CO_2 levels (Pethica *et al.,* 2010). Uncertainties, inherent to any climatic impact assessment incorporating future emissions, are compounded by our incomplete understanding of GHG sources and sinks and the unpredictable nature of systemic adaption to climate forcing (New and Hulme, 2000).

1.2 Project Aims and Objectives

With the first commitment period of the Kyoto Protocol to expire later this year, this study aims to:

- Identify the strengths and weaknesses of an international cap and trade approach to contemporary climate policy;
- Quantify tangible emissions reductions;
- Present these reductions in real terms of their quantitative climatic impacts;
- Formulate a comparative analysis of the Kyoto Protocol taking emissions trajectories put forward by the IPCC as a benchmark for non-intervention (baseline) emissions under different illustrative scenarios;
- Propose a number of informed suggestions for a post-Kyoto discourse.

The primary objectives of this investigation are to:

- Attain a comprehensive working knowledge of the legal framework of the Kyoto Protocol and its implications for climate mitigation;
- Collate and evaluate emissions reports published by parties to the Protocol, bringing to light any disparity between reduction commitments and observed emissions;
- Run a simple climate model widely used by the IPCC to translate emissions trajectories into future global temperatures and sea level rise;
- Combine instrumental climate data and estimated projections from revised IPCC emissions scenarios with both targeted and recognised emissions reductions under the Kyoto Protocol to construct a number of pertinent mitigative intervention scenarios and evaluate their influence on future climates.

Literature Review

2.1 The Science of Climate Change

Climate change is defined by the IPCC as a statistically significant deviation in the mean state of the climate from a regional norm, caused by natural internal processes or external forcing, and persisting for an extended period of time, typically decades or longer (Solomon *et al.*, 2007). Recent warming trends are closely associated with rapidly increasing GHG emissions altering atmospheric composition and exacerbating underlying climatic variation. Natural drivers including solar insolation, orbital perturbations and volcanic activity are at most partially accountable for the rapid and substantial variation in mean global temperatures over recent decades (Barnett, 2005). Fluctuations in GHG concentrations alter the energy balance of the climate system affecting the absorption and reflection of incoming short-wave solar radiation at the Earth's surface (Figure 2.1). Satellite observations indicate that 70% of the proportion of the sun's energy that reaches the Earth is absorbed by the atmosphere and the Earth's surface at a planetary average of around 240 Watts per square metre (Wm^{-2}).The remainder is reflected back into space (Pethica *et al*., 2010).

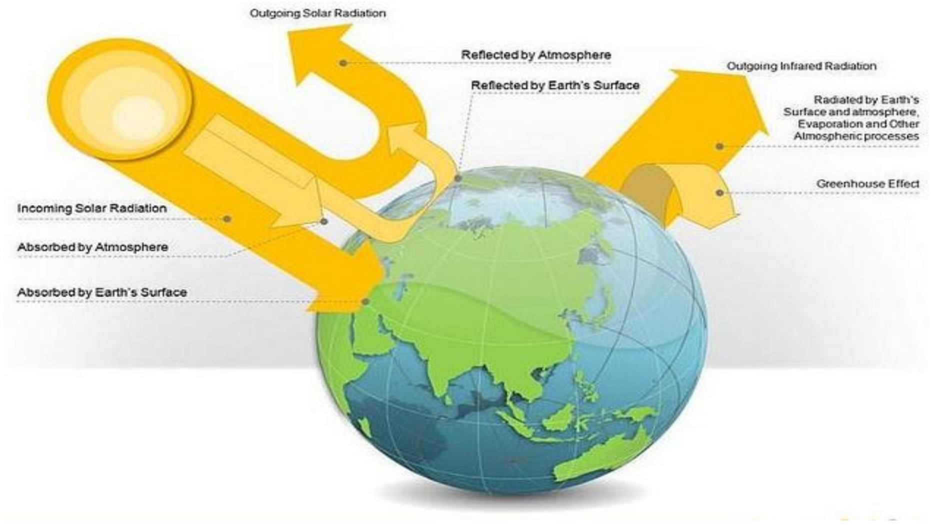


Figure 2.1: Schematic illustration of solar energy fluxes involved in the greenhouse effect (Solar Radiation and Climate Experiment, 2007).

In order to counter this absorption an equivalent flux must necessarily be emitted back in to space as infrared radiation of considerably longer wavelength than the predominantly visible and ultraviolet light from the sun. While effectively transparent to incoming solar radiation GHGs absorb and re-radiate infrared from the surface of the Earth as heat. The net effect of increasing atmospheric gases and cloud cover at higher altitudes and lower temperatures is a reduction in the efficiency with which energy is lost to space with a thermal influence on the troposphere analogous to the glass walls of a greenhouse (Pethica *et al*., 2010). The greenhouse effect is a naturally occurring phenomenon imperative to the capacity of the Earth system to sustain terrestrial life without which mean surface temperatures below the freezing point of water would prevail. However, the extent to which anthropogenic forcing has exaggerated this process shifts natural systems to the extremes of their rage of tolerance. Water vapour is among the most potent of GHGs, accountable for the majority of associated surface warming due to its abundance, followed by CO_2. Human activities bear minimal influence over the atmospheric concentration of water vapour on all but the most localised of scales.

Historical temperature records dating back to the late 19th century and the onset of the large scale production, distribution and combustion of fossil fuels present an average atmospheric warming of 0.7°C since the industrial revolution (Victor, 2001). While quantitatively small in relation to fluxes in the natural carbon cycle (Figure 2.2) the biogeochemical uptake of the anthropogenic contribution is incomplete provoking a temperature response expressed as radiative forcing, a notable and comparative imbalance in the energy budget of the climate system. It is estimated that an equivalent to four billion metric tonnes of carbon (4GtCe) of the 7GtCe released annually through anthropogenic activity remains in the atmosphere (Solomon *et al*., 2007). Atmospheric CO_2 concentration increased by only 20 parts per million by volume (ppmv) in the 8000 years preceding rapid global industrialisation to a level of 280ppmv in 1750 and has since risen to above 390ppmv (Solomon *et al*., 2007). Continuous instrumental records measured directly from the atmosphere date back to 1958 (Keeling *et al*., 1979), prior to this the relative abundance of CO_2 and other GHGs is derived from the reconstruction and analysis of paleoclimatic proxy data.

An observed shift in the isotopic composition of atmospheric carbon since the industrial revolution, concurrent with the pervasive combustion of fossil fuels, indicates an anthropogenic influence as opposed to naturally driven internal variation. The climate system is determined by the synergistic interaction of the Earth's surface with the atmosphere, the oceans and natural ecosystems. Global sea levels largely consistent with warming trends have risen at a mean annual rate of 1.8mm since 1978 and 3.1mm per year since 1993 (Soloman *et al*., 2007), partially attributed to thermal expansion, while an observable decline in polar ice extent illustrates the contribution of melting glaciers and ice sheets.

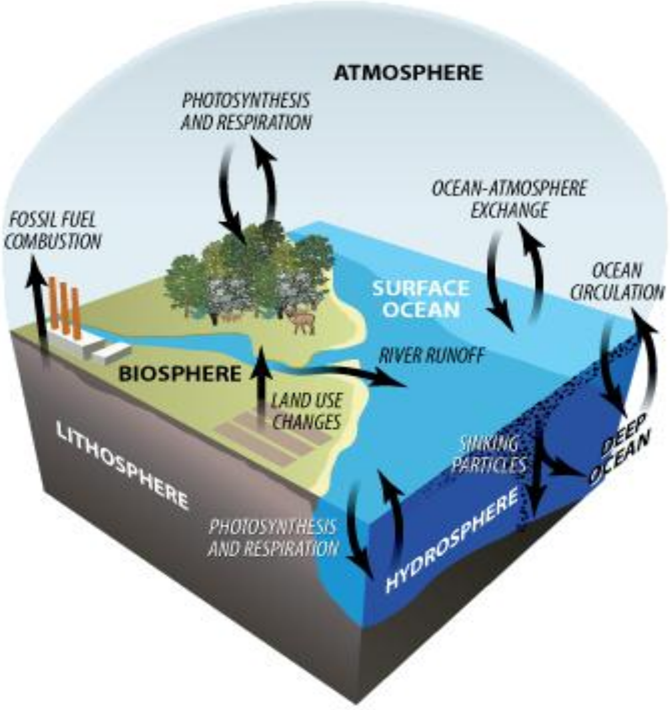


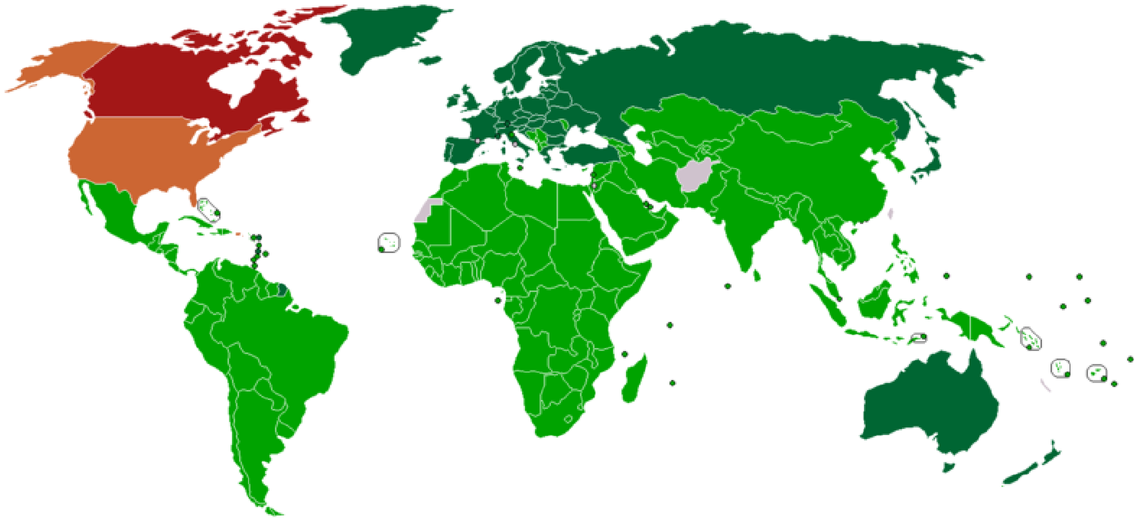
Figure 2.2: The biogeochemical processes and reservoirs of the carbon cycle (National Energy Education Development Project, 2012).

Evidence from the ice record illustrates the active role of CO_2 in the climate system through the thermally regulated uptake of carbon by oceanic, terrestrial and biological reservoirs. Gaps in contemporary knowledge of the natural biological responses to climate change and increasing CO_2 concentrations mean that the full extent of carbon sequestration by the lithosphere and ocean systems is poorly understood.

2.2 Origins of the Kyoto Protocol

In 1988 the IPCC was established in response to mounting scientific evidence, increased public interest and a growing environmental consciousness placing global climate change high on the political agenda. The United Nations Conference on Environment and Development (UNCED), more commonly referred to as the Rio Earth Summit, was hosted in Rio de Janeiro in June, 1992, during which the UNFCCC was open for signature with the ultimate objective of stabilising atmospheric GHGs and providing a reasonable baseline regarding international climate negotiations. The Kyoto Protocol was adopted in Kyoto, Japan on December 11th 1997 and entered into force on February 16th 2005, by which time "demonstrable progress" towards achieving a collective reduction in the overall emissions of signatory parties was expected to have been made

(Article 3.2). At present, 195 parties have ratified the UNFCCC 191 of which have subsequently ratified the Kyoto Protocol to the Convention (UNFCCC, 2012). Participation to the Protocol is illustrated in Map 2.1.



Map 2.1: Participation to the Kyoto Protocol as of February, 2012 where light green specifies ratification of the treaty. Areas in dark green comprise Annex I and II parties to the UNFCCC. Orange indicates no present intent to ratify. Red represents withdrawal from the Protocol and Grey, unknown (UNFCCC, 2012).

Box 2.1 **Timeline of the Kyoto Protocol**

1959 The first International Geophysical Year initiates the networks of empirical scientific research and observation upon which contemporary theories of climate change have been refined.

1979 Sponsored by the World Meteorological Organisation (WMO) the first World Climate Conference (WCC) is held in Geneva. The interdisciplinary conference assigned four working groups to integrated impact studies investigating climate variability and change.

1988 The IPCC, jointly established by WMO and the United Nations Environment Programme (UNEP), embarks upon an assessment of available scientific information to provide an evaluation of the environmental and socioeconomic consequences of climate change and to formulate appropriate response strategies (IPCC, 2007).

1990 The First Assessment Report (FAR) of the IPCC provides sufficient scientific consensus for a Second World Climate Conference to call for an international treaty on climate change (IPCC, 1990); 1990 is taken as a base year for the calculation of assigned amounts for the first commitment period of the Kyoto Protocol.

1992 UNFCCC signed at Rio Earth Summit.

1994 UNFCCC enters into force.

1995 Projections of future change from the Second Assessment Report (SAR) of the IPCC confirm the potential for anthropogenic forcing to influence the Earth’s climate at an unprecedented rate (IPCC, 1995); the first Conference of the Parties (COP1), the Berlin Mandate, takes place in Germany.

1997 The Kyoto Protocol is formally adopted at the third Conference of the Parties to the UNFCCC (COP3) in Kyoto, Japan.

2001 The Third Assessment Report (TAR) of the IPCC concludes that the adverse effects of future climate change will be most prominent (IPCC, 2001); The Marrakesh Accords are adopted at COP7 detailing the implementation of the Kyoto Protocol.

2005 The Kyoto Protocol enters into force; the first Meeting of the Parties to the Kyoto Protocol (MOP1) takes place in Montreal, Canada drafting the Montreal Action Plan with the purpose of extending the Kyoto Protocol beyond its expiration date.

2007 The IPCC’s Fourth Assessment Report (AR4) Summary for Policy Makers (SPM) states that abrupt shifts in the climate system as a result of anthropogenic change could be irreversible (IPCC, 2007); at COP13, hosted by the Government of Indonesia, parties to the UNFCCC adopt the Bali Road Map launching a two-year process with the aim of reaching an agreement on further commitments for signatory parties.

2009 Attendants of COP15 draft the Copenhagen Accords endorsing the continuation of the Kyoto Protocol and recognising that in order to avoid irreversible changes to the climate system warming should not exceed 2°C against pre-industrial temperatures.

2010 COP16 facilitates the negotiation of the Cancún Agreements including a Green Climate Fund (GCF) to assist in financing emissions reductions in developing nations.

2011 The latest round of negotiations takes place at COP17 in Durban, South Africa. The Durban Platform for Enhanced Action concludes on an agreement to prepare a binding international treaty by 2015, to take effect in 2020, for the first time incorporating both developing nations and non-signatory parties to the Protocol in emissions reduction commitments to address global climate change.

2012 Expiry of the first commitment period of the Kyoto Protocol.

2.3 Annex A

A “basket” of six long-lived greenhouse gases and halocarbons are recognised under the Kyoto Protocol, defined in Annex A of the Text of the Protocol along with defined sectors and source contributions including emissions from fossil fuels, industry, land use change and forestry. The six Annex A gases are laid out in Table 2.1. Despite the fact that the quantities in which they are emitted are far smaller than that of carbon dioxide, molecule for molecule, the five non-CO_2 GHGs are far more potent in terms of their contribution to anthropogenic climate change, accountable for 37% of the total radiative forcing of historical emissions (Shindell and Faluvegi, 2009) with an expected contribution exceeding 20% of projected warming for the 21st century (Princiotta, 2009). Present atmospheric concentrations of nitrous oxide (N_2O) are far greater than pre-industrial levels and recently recorded values for methane (CH_4) exceed the natural maximums of the last 650,000 years (Solomon et al., 2007).

Table 2.1: Greenhouse gases included under Annex A, approximate pre-industrial and present day concentrations and their estimated contribution to climate change expressed in terms of their Global Warming Potential (GWP) for a given time horizon of 100 years as stated by the UNFCCC.

Greenhouse gas Species	Global Warming Potential (GWP) 100yr	Pre-1750 tropospheric conc. (ppmv)*	Present day tropospheric conc. (ppmv)*
Carbon dioxide (CO_2)	1	280	390
Methane† (CH_4)	21	700	1870
Nitrous oxide (N_2O)	310	270	320
Hydrofluorocarbons (HFCs)	140-11,700	0	varies by substance
Perfluorocarbons (PFCs)	6,500-9,200	0	
Sulphur hexafluoride (SF_6)	23,900	0	7

* CO_2 in ppmv, CH_4 and NO_2 in parts per billion (ppb), HFCs, PFCs, SF_6 in parts per trillion (ppt).

† GWP for CH_4 incorporates indirect effects of enhanced stratospheric water vapour and tropospheric ozone.

A common rate of conversion between gases is necessary in order to draw meaningful comparisons in the assignation of multi-gas emissions targets. The Kyoto Protocol accredits GHG emissions in the context of their CO_2 equivalence and allows trade among gases based on a simplified index of individual Global Warming Potentials (GWPs). This allows for the climatic impact of an individual GHG to be expressed in terms of the quantity of CO_2 necessary to give rise to comparable atmospheric warming and, by extension, to define the CO_2 equivalence of a number of gases as a single value.

Established by the IPCC, GWP is a measure of the estimated contribution of a given mass of a gas to radiative forcing relative to, and expressed as a factor of, an equivalent mass of CO_2 (GWP 1 standardised). The numerical value for GWP depends entirely upon the specific time interval over which it is calculated, commonly 20, 100 or 500 years (Pachauri and Reisinger, 2007), introducing arbitrary value judgements regarding the extent of future commitments to limiting radiative forcing from a decadal to centennial timeframe. A 100 year time horizon is used in the calculation of GWP under the Protocol. The index is limited in its ability to incorporate a number of species dependant properties including radiative efficiency and rate of removal by sinks from atmospheric circulation, the latter is rarely precisely quantified and consequently GWPs are at best an informed estimation (Godal and Fugelstvedt, 2002).

Only rarely are non-CO_2 GHGs explicitly addressed in climate policy. A basket approach promotes compliance compared to an entirely carbon-centric agreement as multi-gas mitigation is less costly to implement than a CO_2 exclusive approach (Gillett and Matthews, 2010). The inclusion of five additional GHGs markedly eases the commitment for most industrialised nations, accounting for approximately 20 percent of total Annex B base year emissions (Grubb *et al.*, 1999). By example, base year (1990) CO_2 emissions for the United Kingdom equated to 0.59Gt (DECC, 2009) yet the inclusion of non CO_2 GHGs in the Kyoto basket of emissions results in a 0.78Gt total of CO_2-equivalents for the calculation of assigned amounts under the first commitment period of the Protocol.

2.4 Annex B

Signatory parties to the UNFCCC are categorised according to their respective priorities and commitments under the protocol based on a construct of “common but differentiated responsibility” (UNFCCC, 1992). Annex I includes Industrialised nations and countries with economies in transition to a market economy (EIT parties) that have agreed to reduce emissions committed to the adoption of national policies to limit anthropogenic emissions and to protect and enhance sinks and reservoirs of GHGs. Annex II parties consist of the industrialised countries of Annex I, but not those with economies in transition. Under the Convention developed countries are required to provide the necessary framework to finance emissions reducing activities in developing countries and the resources to facilitate their adaptation to global climate change. Additionally, Annex II parties are obliged to take “all practicable steps” towards the promotion of the advancement and transfer of environmentally sound technologies to EIT member states and developing nations. Non-annex parties recognised under the UNFCCC, predominantly developing nations, are not restricted by the Protocol. Many are perceived to be particularly vulnerable to the potential effects of climate change in small island states, low lying coastal regions and areas particularly disposed to desertification and drought. Others are more susceptible to the adverse economic impacts of responding to these changes, being heavily dependent on national income from the fossil industry and commerce.

Annex B of the Kyoto Protocol provides an inventory of 37 parties bound to a reduction commitment and their respective quantified emissions limitation as a percentage of their base year emissions which, in some circumstances, equates to a net increase in overall emissions. The Annex identifies EIT parties and is essentially interchangeable with Annex I of the UNFCCC with the exception that Belarus and Turkey are not included in Annex B, as they had not yet ratified the Convention at the time of Kyoto, in addition to those parties whose recognition under Annex I was accepted during the proceedings.

2.5 Ultimate Objective

Both the Kyoto Protocol and its parent convention share the ultimate objective of stabilising atmospheric GHG concentrations at a level that will prevent dangerous anthropogenic inference with the climate system (Article 2) and hold that this should be achieved within an appropriate timeframe allowing for the natural adaptation of ecosystems to climatic variability, ensuring food security and supporting sustainable economic development (UNFCCC, 1992). Where the Convention and the Protocol diverge is that, while the framework simply established a set of general principles, no specifics were finalised. These were to be decided upon through subsequent Conferences of the Parties (COPs) to the UNFCCC. The date and location of each COP to date is summarised in Table 2.2. The Protocol, adopted at COP3 in 1997, provided binding agreements and individual reduction commitments. Limitations negotiated by signatory parties equate to an aggregate aim of reducing overall Annex B emissions by at least 5% below 1990 levels in the first commitment period from 2008-2012 (Article 3).

2.6 Conferences of the Parties

Member countries have met on an annual basis following the entry into force of the UNFCCC acting as the prime authority of the Convention. Each year all parties meet for a period of two weeks to review the implementation of the Convention with guidance from the Subsidiary Body for Implementation (SBI), to evaluate the state of the climate and the progress that has been made towards achieving the ultimate objective. National communications and emissions inventories are reviewed. Decisions are adopted to promote effective measures to tackle climate change and negotiate substantive commitments for the future under the counsel of the Subsidiary Body for Scientific and Technological Advice (SBSTA). Since December 2005, COPs have served as the Meeting of Parties to the Kyoto Protocol (MOPs). Parties to the Convention that have not yet ratified the Protocol are permitted to participate as observers to meetings related to Kyoto.

Table 2.2: Conferences of the Parties to the UNFCCC

Session	Date	Host
COP 1	March 1995	Berlin, Germany
COP 2	July 1996	Geneva, Switzerland
COP 3	December 1997	Kyoto, Japan
COP 4	November 1998	Buenos Aires, Argentina
COP 5	October 1999	Bonn, Germany
COP 6	November 2000	The Hague, Netherlands
COP 6 (resumed.)	July 2001	Bonn, Germany
COP 7	October 2001	Marrakech, Morocco
COP 8	October 2002	New Delhi, India
COP 9	December 2003	Milan, Italy
COP 10	December 2004	Buenos Aires, Argentina
COP 11/MOP 1	November 2005	Montreal, Canada
COP 12/MOP 2	November 2006	Nairobi, Kenya
COP 13/MOP 3	December 2007	Bali, Indonesia
COP 14/MOP 4	December 2008	Poznań, Poland
COP 15/MOP 5	December 2009	Copenhagen, Denmark
COP 16/MOP 6	November 2010	Cancún, Mexico
COP 17/MOP 7	November 2011	Durban, South Africa

COP18 serving as the eighth Meeting of the Parties to the Kyoto Protocol is set to commence from the 26th of November 2012 in Qatar. The Ad Hoc Working Group on Further Commitments from Annex I Parties (AWG-KP) is responsible for the negotiation of a post-Kyoto agreement.

2.7 Entry into Force

The Kyoto Protocol became binding under international law in February 2005, 90 days after the date of ratification by Russia. The US was responsible for 36 percent of Annex I 1990 emissions holding a *de facto* veto over the advancement of the protocol (Dessai, 2005). Following the US refusal to ratify, Russian participation was integral to the prerequisite laid out in the text of the Protocol that entry into force must follow the signature of 55 Annex I parties which were together jointly accountable for 55 percent of the total CO_2 emissions for Annex I nations in 1990. This meant that no single country could block entry into force. Annex 1 involvement was critical to the Protocols environmental standing. Following Australia’s signature in 2007 the US became the only Annex B party not to ratify.

2.8 First Commitment Period

Within the overall emissions reduction commitment among Annex B parties of at least 5 percent below 1990 levels between 2008 and 2012, no uniform target for each member state was officially established. Instead individual targets were negotiated, based upon national ability to reduce emissions and the probable impact on domestic economy, ranging from an 8 percent reduction in a number of instances to a notable increase in the cases of both Iceland and Australia. While generally expressed in relation to 1990 levels (Article 3) under certain circumstances this was waived to allow parties whose emissions fluctuated greatly around that time, or EIT parties, to select a less penalising base year. This was intended to promote the participation of parties whose emissions fell rapidly prior to 1990, in many cases as a result of declining industrialisation at the collapse of the former Soviet Union. A further technicality allowed for the selection of 1995 as a base year instead of 1990 for fluorinated gases due to their higher levels following the Montreal Protocol in 1987 and the progressive ban of a range of ozone depleting substances including chlorofluorocarbons (CFCs) subsequently replaced by potent GHGs. (Article 3) Parties with economies in transition (EITs) could select any base year to meet their commitments. The significance of setting emissions reduction targets over a several year period rather than a single date is to accommodate for interannual variability, cold winters and, by extension, increased fossil fuel consumption and irregularities in GHG emissions.

2.9 Flexibility Mechanisms

Through the notion of “common but differentiated responsibility” the Kyoto Protocol demanded more of industrialised nations while providing flexible market based mechanisms by which a collective emissions reduction could be met. These included Emissions Trading, Joint Implementation (JI) and the Clean Development Mechanism (CDM). Annex B parties can supplement their domestic activities towards meeting their reduction commitments by adding “emissions credits” to their assigned amounts. The various credits or carbon assets acknowledged under the Kyoto Protocol are summarised in Table 2.3.

Recognising the global nature of climate change each of these was designed to encourage the least costly of emissions reduction strategies, regardless of location, while promoting those actions which best enhance development through technological advancement and economic investment, essentially defining an atmospheric commons. Each mechanism was intended to impede the rate of increase in GHG concentrations and necessarily involved private entities acting on an international level to cap and report their emissions (Grubb *et al*., 1999). Detailed provisions for the implementation of the Protocols flexibility mechanisms were adopted at COP7 in 2001 and became known as the “Marrakech Accords”. Emissions trading and the formation of carbon market are likely to form the foundation for subsequent commitment periods (Rosales, 2008).

Table 2.3: The various carbon assets recognised under the Kyoto Protocols emissions trading schemes

Carbon Asset	Description
Assigned Amount Unit (AAU)	Units issued to Annex B parties for the first commitment period
Certified Emission Reduction (CER)	Unit of emissions reduction created through CDM projects
Emission Reduction Unit (ERU)	Unit of emissions reductions created through JI projects
European Union Allowance (EUA)	Unit issues to installation under the EU European Trading Scheme (ETS)
Removal Unit (RMU)	Unit of emissions reduction created through carbon sinking projects

2.9.1 Emissions Trading: “The Carbon Market”

Under Article 17 of the Protocol, parties included in Annex B are permitted to partake in the trade of emissions credits supplemental to domestic reduction efforts to fulfil their emissions commitments. Surplus units of a country’s assigned amount, equivalent to one tonne of CO_2 permitted but not utilised, can be sold to parties exceeding their reduction targets, in so doing creating a carbon market. (UNFCCC, 2012). In addition to units from actual emissions reductions, those generated from land use change and forestry activities, joint implementation projects and the clean development mechanism can be transferred from one party to another. As an effort to ensure a country's emissions credits are not oversold, rendering itself unable to meet its own reduction targets, a commitment period reserve of carbon assets is required of all parties to be maintained in its national registry to a value of no less than 90 percent of its assigned amount. Trade in carbon as an instrument of policy towards the achievement of individual targets redistributes emissions between parties while maintaining an approved total allowance and can occur at both regional and national levels. While introducing the notion of additionality, Article 17 is brief and neglects to define the proportion of a commitment permitted to be achieved through emissions trading. Countries radically opposed to domestic cuts, most notably the US, are resistant to negotiations of a quantitative cap on supplemental emissions trading.

The largest collaborative agreement currently in operation is the European Union emissions trading system, accounting for around 45 percent of all EU CO_2 emissions (Environment Agency, 2011) and founded upon individual National Action Plans approved by the European Commission. At present, the carbon market is the fastest growing industry in the world. Currently trading in over US$200 billion worth of carbon, World Bank projections expect that by 2020 the carbon economy will exceed $2,000 billion (Godin *et al.*, 2007).

To date, signatory parties have largely failed to establish comprehensive measures improving domestic energy efficiency. An effective emissions trading scheme provides a financial incentive to reduce national emissions below the assigned amount as the price received for surplus emissions credits in a free market economy could greatly exceed the initial investment in efficient technologies.

2.9.2 Joint Implementation

Introduced in Article 6 of the Protocol, Joint Implementation is one of two innovative project based mechanisms feeding into the carbon market enabling cooperative emissions reducing activities to be put into practice. First proposed during UNFCCC negotiations, JI enables collaborative projects to be implemented jointly between Annex I parties provided both participants are parties to the Kyoto Protocol, often involving industrialised nations acting with EIT countries. Contrary to emissions trading, JI activities must be additional to what would have been undertaken, resulting in measurable long term benefits that would not have occurred otherwise, while sharing the intention of evening the costs of reducing emissions. The mechanism was established on the grounds that further reductions by parties that had already introduced national measures to limit growth in their GHG emissions would be expensive relative to countries that had as yet taken no action. It is therefore arguably more lucrative to reduce emissions in countries where there exist opportunities for improving efficiency or establishing the infrastructure necessary for renewable energy systems in place of outdated technologies. Eligible projects include fuel substitution to less carbon intensive alternatives, improvements in the transport sector and reductions in methane emissions.

Most of the parameters for JI projects are left to the host party to define in the approval and verification of activities as no comprehensive international guidelines have been established. The Protocol contains provisions for the inclusion of land use, land use change and forestry activities (LULUCF) in calculating carbon mitigation efforts. Under JI Annex B parties are permitted to implement projects which enhance the anthropogenic removal of atmospheric GHGs by sinks to generate Emissions Reduction Units (ERUs). Quantified emissions reductions achieved through the Protocols flexibility mechanisms and their trade between parties are monitored and tracked independently through a computerised International Transaction Log (ITL). Supplementary to individual national registries the ITL is expertly reviewed under the UNFCCC to ensure compliance.

2.9.3 The Clean Development Mechanism

Essentially the CDM is joint implementation between an industrialised nation with an emissions reduction commitment and a developing country without one. Under Article 12 the purpose of the CDM is to promote sustainable development through investment in clean technologies and activities while providing Annex B parties with cost effective opportunities to achieve their emissions targets with Certified Emissions Reduction units (CERs). Unlike Article 6 for JI projects, advocating both the improved reduction of emissions and enhanced removal by sinks of atmospheric GHGs, Article 12 only states that CDM activities must deliver additional reductions. Whether sink projects from LULUCF activities should be incorporated is under negotiation. CERs generated through CDM activities prior to the first commitment period since 2000 are permitted to be recognised in compliance with achieving emissions targets to promote the early investment in emissions reducing technologies.

The protocol also specifies that a share of all proceeds from CDM projects should be allocated to offering financial assistance to developing countries particularly vulnerable to the adverse effects of climate change. The Adaptation Fund is reliant on a two percent levy on all certified emissions reductions derived from the CDM (UNFCCC, 2012).In order for a party to be in compliance with the Protocol in meeting its reduction commitments its total emissions must not exceed its assigned amount during 2008-2012. The instruments of JI, emissions trading and the CDM can both add to and subtract from this allocation. Figure 2.3 below displays the provisions by which a party's assigned amount for the first commitment period can be calculated.

Assigned Amount	=	Base Year[1]	×	QEL[2]	×	5[3]	+/-	LULUCF[4]	+/-	Flexibility Mechanisms[5]

[1] Gross GHG emissions in base year (1990 or other)
[2] Quantified Emissions Limitation a percentage of base year
[3] Number of years in first commitment period (2008-2012)
[4] Emissions absorbed/released as a result of Afforestation/reforestation/deforestation since 1990
[5] Emissions bought/sold through emissions trading (2008-2012); ERUs transferred through JI projects (2008-2012); CERs from CDM activities (2000-2012)

Figure 2.3: Calculation of a party's Assigned Amount for the first commitment period of the Kyoto Protocol.

2.10 Loopholes and Criticisms of the Kyoto Protocol

While acting towards a collective goal the Protocol is hardly free from controversy, simultaneously described as both the most robust environmental compliance system ever adopted (Wang & Wiser, 2002) and "a tragedy and a farce" from the outset by Greenpeace spokesperson Bill Hare. Additional to the modest and environmentally inadequate GHG emissions targets of the first commitment period, final negotiations of the Kyoto Protocol failed to resolve the specifics of the three flexibility mechanisms and the use of carbon sinks by industrialised parties to achieve their individual commitments. Consequently a number of notable loopholes have been identified with the potential to overwhelm and undermine the Protocol, elements that could sanction GHG emissions far above Kyoto's intentions. In the absence of the observable flaws in the Protocol, Annex B could practicably achieve a substantial reduction relative to 1990 emissions whereas if they persist unabated a net increase is expected (Rogelj and Meinshausen*,* 2010).

2.10.1 Criticisms of the Clean Development Mechanism

Unlike Joint Implementation and emissions trading where carbon credits are offset by a comparable deficit, CERs generated through CDM projects are additional to the assigned amount of the acquiring party, increasing the aggregate assigned amount for Annex B. Effectively the CDM allows for industrialised nations to continue emitting at their original level provided they offer financial support for reductions elsewhere. This "pay to pollute" mentality externalises the costs of climate mitigation, outsourcing responsibility by affording no incentive to decide on the best practices in terms of efficiency and sustainability. Furthermore, Article 12 allows Annex B parties to log CERs generated from projects implemented prior to the first commitment period in achieving their reductions commitments for that time. This pre-commitment banking increases legitimate emissions even more allowing industrialised nations to take less domestic action. At present industrialised nations are responsible for a proportion of historical per capita emissions far greater than developing regions (Brohé *et al.,* 2009).

It can be argued that the CDM impinges on a nation's right to develop raising the notion of what has been termed "CO_2lonialism".

2.10.2 "Bubble" Emissions Trading

Article 4 of the Protocol allows Annex B parties to fulfil their emissions commitments jointly provided that their combined emissions do not exceed their total assigned amount. This provision was initially incorporated in order to accommodate the EU as a unique international organization in an agreement dubbed the "EU bubble". It is however plausible that a number of parties including Canada, Japan, Australia the United States and Russia, having formed a collective largely opposed to the development of strong compliance mechanisms and quantitative caps on domestic emissions, could develop into an Article 4 type bubble, potentially establishing a back door trading scheme and bypassing the more stringent rules on emissions trading defined in Article 17.

2.10.3 Emissions Banking

If a country does not emit the whole of its assigned amount by the end of the first commitment period it is permitted to carry the unused portion over into subsequent commitment periods. This is known as emissions banking, the primary implication of which being an overall decrease in potential long term reductions as the Protocol accommodates an increase in emissions following a low polluting period. Assigned Amounts are issued annually but they can be used to cover emissions in any year within the same commitment period. Banking is allowed since unsurrendered allowances are still valid for compliance in the next years of the same phase under Article 3.13.

2.10.4 "Hot Air"

Best explained by example, Russia's reduction commitment to sustain emissions at 1990 levels is easily met even in the absence of any mitigative action following the substantial decline in emissions since that time through widespread deindustrialisation after the collapse of the former Soviet Union. Trade in emissions credits requiring no additional abatement measures introduce "hot air" into the carbon market where other parties use purchased credits to lessen their domestic limitations in meeting their emissions targets (Dessai and Hulme, 2001).

2.10.5 LULUCF and REDD

The inclusion of carbon sinks in the calculation of domestic CO_2 allows a net emissions increase to be offset by anthropogenically enhanced absorption through afforestation and reforestation activities. However, the uncertainties involved in quantifying sequestered CO_2 and in estimating a sinks capacity for long term carbon storage renders the achievement of emissions limitations effectively unverifiable. RMUs derived from LULUCF activities rarely reflect any additional sequestration or tangible emissions reductions, often allocated as windfall credits to parties under the Protocol, decreasing domestic efforts required in meeting Annex B targets (Schlamadinger *et al.,* 2007). Consideration of the saturation and non-permanence of natural sinks holds that accelerated biospheric carbon sequestration is not comparable to reducing direct emissions to the atmosphere (Meinshausen *et al.*, 2006) as the long term survival of biological sinks cannot be guaranteed, natural variability within the biosphere regarding carbon sinks provides an uncertain foundation upon which to construct a framework for climate mitigation. Comprehensive policy measures are integral to utilising the benefits of offsetting emissions while limiting adverse effects on biodiversity and ecosystem services. Reducing Emissions from Deforestation and Degradation (REDD) is a UN collaborative programme in developing countries. Carbon abatement aside, REDD has established an international framework against poverty through conserving biodiversity.

2.10.6 Gross-net, Net-net Accounting

Typically the gross emissions and carbon fluxes within an ecosystem are large but it is the net effect that matters most for the atmosphere (Grubb *et al.,* 1999). Small errors in measuring the gross fluxes can lead to large errors estimating the net (Watson *et al*., 2000). While reduction commitments under the Protocol are quantified based upon gross emissions compliance is measured as net emissions from sources and removals by carbon sinks. Since gross-net accounting does not compare the rate of emissions or sequestration there is no offset between the base year and commitment period (Schlamadinger *et al.,* 2007).

2.10.7 Aviation Bunker Fuels and Shipping

Partially attributed to the limitations of accountability within the existing framework of the UNFCCC, GHG emissions from marine transportation and international aviation are not considered under the Kyoto Protocol. Since negotiations first began in 1991 no consensus has been met on how these emissions should be allocated between countries. Instead, Article 2.2 implies that the International Civil Aviation Authority (ICAO) and the International Maritime Organisation (IMO) shall pursue the issues of national responsibility. The accounting procedure for road transport emissions states that the party accountable is the country within which the fuel was sold. Even taking the elevated potency of emissions at altitude into consideration, International shipping and aviation combined currently only constitute an estimated 5-7% of total GHG emissions (Brohé *et al.,* 2009).

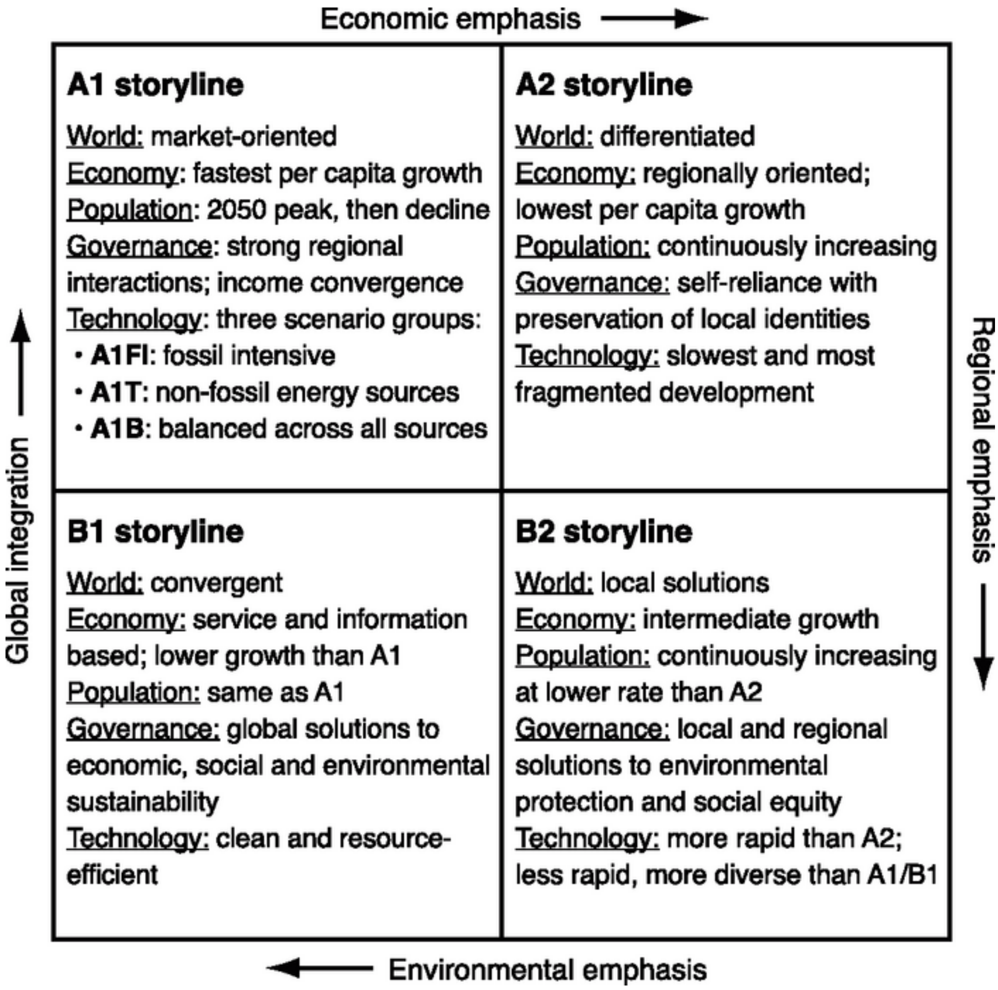
2.10.8 Non-compliance

At present the Kyoto Protocol lacks a substantive non-compliance mechanism with binding consequences for failing to meet individual commitments. The notion that as an international agreement the Kyoto Protocol is legally binding is largely misleading in that if a party exceeds its assigned amount the penalties associated with non-compliance are no more regulated than the initial emissions reduction commitment. Furthermore, the individual party is responsible for setting the limitations for subsequent commitment periods and can use this to compensate for any penalty accrued from the previous providing only a weak incentive to comply with the obligations of the Protocol.

2.11 Special Report on Emissions Scenarios

The IPCC Special Report on Emissions Scenarios (SRES), published in 2000, developed a number of plausible scenarios designed to provide input data for the evaluation of the climatic implications of future GHG emissions trajectories and the assessment of prospective mitigation adaptation strategies (Nakićenović, 2000). The report provides a detailed overview of forty non-mitigation scenarios, each with an increasing path of radiative forcing during the twenty-first century and structured into six subgroups based around common qualitative storylines. The SRES scenarios were intended to illustrate a broad spectrum of alternative future storylines within a demonstrable range of what the IPCC consider to be the major underlying driving forces of emissions scenarios. A distinction is drawn between scenarios and emissions pathways.

Where the latter focuses solely on emissions, a scenario represents a more complete description of feasible future states of the world including demographic change, socioeconomic development, resource exploitation and the rate and direction of technological advancement (Nakićenović, 2000). It is noted within the report that it would be inappropriate to draw averages across scenarios within a subgroup because such a mean would combine alternate projections for socioeconomic development and would therefore fail to be internally consistent. Moreover, discrete subgroup averages do not reflect the full range of possible emissions pathways. Instead, four designated ‘marker’ scenarios together with two scenarios from the A1 family form the six ‘illustrative’ scenarios that were selected and reviewed in more detail for use in climate change simulations. These six illustrative scenarios, summarised in Figure 2.4, have been used extensively by climate modelling groups and are the basis for most climate projections in the Third and Fourth IPCC Assessment Reports (McKibben *et al.*, 2004). While no relative probabilities were attributed to any of the IPCC emissions scenarios in the final report given the difficulty in assigning subjective possibilities to radically opposing qualitative storylines they were not intended to be considered equally likely yet the interpretation of a number of authors has assumed this to be the case (Wigley & Raper, 2001). While the SRES projections accommodate for progressive environmental policy they do not explicitly include policies involving the either regulation of GHG emissions or adaptation to climate change.



A1 storyline World: market-oriented Economy: fastest per capita growth Population: 2050 peak, then decline Governance: strong regional interactions; income convergence Technology: three scenario groups: • **A1FI**: fossil intensive • **A1T**: non-fossil energy sources • **A1B**: balanced across all sources	**A2 storyline** World: differentiated Economy: regionally oriented; lowest per capita growth Population: continuously increasing Governance: self-reliance with preservation of local identities Technology: slowest and most fragmented development
B1 storyline World: convergent Economy: service and information based; lower growth than A1 Population: same as A1 Governance: global solutions to economic, social and environmental sustainability Technology: clean and resource-efficient	**B2 storyline** World: local solutions Economy: intermediate growth Population: continuously increasing at lower rate than A2 Governance: local and regional solutions to environmental protection and social equity Technology: more rapid than A2; less rapid, more diverse than A1/B1

Figure 2.4: Summary of characteristics for SRES marker scenarios (IPCC, 2007).

A comparison of year 2000 emissions based on officially reported data with the SRES 2000 estimated values bring to light substantial discrepancies. For total global anthropogenic emissions, excluding emissions derived from land use change, this disparity was between five and six percent of SRES 2000 values. Estimates based on officially reported data generally emerge to the very low end, and even below the IPCC AR4 estimated uncertainty ranges of other global emission inventory exercises. For anthropogenic land-use related emissions the relative discrepancy is an order of magnitude larger, with emissions based on officially reported data being ninety percent lower than SRES estimates in 2000 and below all uncertainty ranges of other emission inventories. Some explanations for these discrepancies include the often limited capacity of non-Annex I countries to construct extensive national inventories over their territories, inventories that do not encompass all GHGs and sectors and strategic issues related to compliance and the negotiation of future assigned amounts.

2.12 Previous Studies

Unprecedented in both nature and complexity, relatively few studies exist in the literature at the time of the Kyoto Protocol regarding the environmental implications raised by such an agreement. Prior to COP4 Parry *et al*. (1998) suggested that Kyoto targets would reduce warming by just 0.05°C by 2050 failing to incorporate fast developing non-signatory nations likely to be substantial future emitters. Here, adaptive measures were advocated, stating that GHG reductions cannot be the sole response to the threat of global climate change. Reilly *et al*. (1999), using integrated global-systems model outputs, suggested that a multi-gas limitation mechanism, as opposed to the notion of CO_2-equivalence applied in the Kyoto Protocol, could greatly reduce the costs of compliance with minimal impediment to the Protocol's mitigative potential. While an extrapolation of existing commitments to 2100 presents little disparity under either strategy, a more stringent agreement provides a substantial improvement towards climatic stability under a multi-gas policy (Reilly *et al.,* 1999). From this they come to suggest that the 100-year GWPs utilised in defining CO_2-equivalence under the Protocol are inadequate.

Wigley (1998) considered the influence of a number of post-Kyoto scenarios in meeting emissions limitations through both CO_2 and CH_4 reductions on temperatures and sea level. He concluded that in all cases the consequences were negligible (Wigley, 1998). No studies to date have come to a definitive verdict as to whether the compounded uncertainties and additional administrative burden associated with a multi-gas trading mechanism overwhelm the mitigative advantages of improved flexibility and ease of compliance in policy-making. Representing uncertainty under divergent climate scenarios is an extensively researched field in its own right. Dessai and Hulme (2001) resumed Wigley's original investigation of a post-Kyoto agreement presenting the first fully probabilistic assessment of the Protocol and subsequent emissions trajectories.

2.13 Motivation and Significance

With the expiration of the first commitment period of the Kyoto Protocol in sight an evaluation of the triumphs and shortcomings of the existing agreement becomes an important first step towards meaningful negotiations for a post-Kyoto abatement strategy. Constructed in the absence of additional climate mitigation policies IPCC emissions trajectories provide an appropriate baseline from which to draw comparisons concerning GHG reduction targets and future atmospheric concentrations.

While Wigley (1998) made use of IS92 scenarios, a predecessor to the SRES projections drawn from the IPCC second assessment report, the climatic implications of non-CO_2 GHGs and the cooling influence of sulphate aerosols have since been recognised. This considered the revised SRES provide a more comprehensive estimation of emissions baselines updated in light of observational data and an improved understanding of climate system response and global economic reform. Developed for the third assessment report SRES scenarios were used in the most recent fourth assessment report published in 2007 and are broadly comparable in range to more recent studies in terms of their projections of global economic growth and GHG emissions (Solomon *et al.*, 2007). Advancements in the field of integrated assessment modelling have made it possible to incorporate total emissions, land use change and economic activities in the construction of future scenarios (Dessai and Hulme, 2001).

While the context of this investigation is not incomparable to earlier publications its timing presents an advantage as, where previous studies were reliant on assumptions of opposition and compliance, published national registry data can be analysed to evaluate actual emissions trajectories under the Protocol. From this their implications for the future can be considered using a Model for the Assessment of Greenhouse gas Induced Climate Change (MAGICC). With negotiations for a second commitment period well under way tentative conclusions drawn from such an assessment could gauge the adequacy of the direction and severity of proposed commitments offering an informed course of action to be pursued after 2012.

Methods

3.1 Data Collection

The body of this investigation was based upon the interpretation of secondary climate data and publicly available national emissions registries to look beyond the carbon market and evaluate the emissions reductions of the Kyoto Protocol. Net Annex B emissions were then integrated with a number of future emissions trajectories and the revised scenarios run through a simple climate model to determine tangible climatic impacts for the future. Finally, model output data underwent Monte Carlo Simulation (MCS) analysis to determine the risk in a hypothetical century of irreversible, catastrophic climate change exceeding thresholds presented by the IPCC.

3.1.1 UNFCCC Annex B Emissions Data

Under Article 7 of the Kyoto Protocol each party included in Annex B is required to submit a national inventory of anthropogenic GHG emissions, removal by sinks and transactions of carbon assets through the Protocol’s flexibility mechanisms in order to verify compliance with its limitation commitments. GHG data made publically available by the UNFCCC are derived from official net emissions reports of parties to the Convention.

Communications published to date provide annual emissions data from a base year (generally 1990) through to 2009 providing a 20 year dataset for evaluation. All data are recorded in gigagrams of CO_2-equivalence ($GgCO_2$eq.).

3.1.2 IPCC Data Distribution Centre

GHG forcing data derived from SRES emissions scenarios were retrieved from the IPPC Data Distribution Centre (DDC).

SRES authors recommend that of the 40 emissions trajectories of the Special Report any evaluation should include at least the six illustrative scenarios. This investigation utilises predicted decadal averages of total anthropogenic CO_2 emissions for scenarios A1FI, A1B, A1T, A2, B1 and B2 expressed in gigatons of carbon (GtC). Annual CO_2 emissions estimates from 1990-2009 relative to SRES trajectories are represented in Figure 3.1.

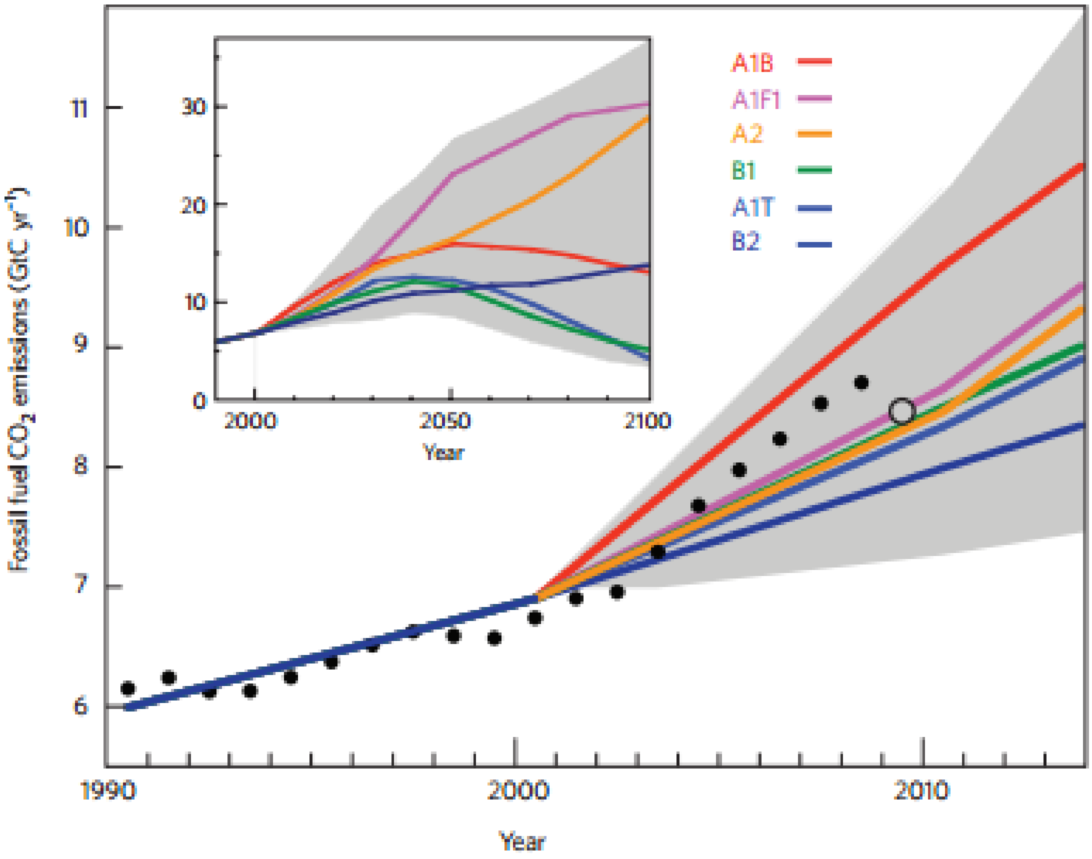


Figure 3.1: Estimates of annual CO_2 emissions in gigatons of carbon per year (GtC yr^{-1}) for 1990–2008 (black circles) and for 2009 (open circle). Beyond 2000 each point falls well within the range of all 40 SRES scenarios (grey shaded area) and of the six SRES illustrative marker scenarios (Pachauri and Reisinger, 2007).

For each illustrative scenario trajectories of atmospheric CO_2 up until 2100 have been proposed using a number of carbon cycle models. This investigation draws from projections derived from the Integrated Science Assessment Model (ISAM), a global upwelling-diffusion model used in the IPCC second assessment report for analyses exclusive to CO_2 (Harvey *et al.,* 19997). This particular model was selected as it is configured to a range of climate sensitivities comparable to those used throughout this investigation (1.5-4.5°C) (Houghton *et al.*, 2001). Estimated global CO_2 concentrations for the 21st century, expressed as parts per million per volume, are laid out in the IPCC third assessment report presented as decadal means and freely available through the DDC.

3.1.3 Historic CO2 Concentration Data

Atmospheric CO_2 data was collated from the Mauna Loa facility of the National Oceanic and Atmospheric Administration (NOAA). Since 1958 direct measurements have been obtained at an altitude of 3400m in the subtropics. Monthly means derived from daily averages are recorded as dry air mole fractions expressed as parts per million by volume (Tans, 2012).

From these, decadal means were determined so as to provide a comparable scale to those of projected CO_2 concentrations as a basis for trajectories to be subjected to MCS analysis.

3.2 Intervention Scenarios

Using SRES as a credible baseline “business as usual” scenario, under which fossil fuels are anticipated to maintain their dominance in the global energy sector and additional climate policies beyond those in place at the time of SRES publication were not considered, the six illustrative trajectories were revised in conjunction with the GHG emissions dataset described in section 3.1.1. From these adjusted projections a number of pertinent intervention scenarios were constructed to incorporate the net effect of Kyoto’s targets and accomplishments. These provided the input data for the simple climate model to estimate climatic responses between present day and the year 2100.

3.2.1 KP 5

Intervention scenario KP5 is based upon the aggregate Annex B emissions target for the first commitment period of the Kyoto Protocol at 5.2 percent below base year levels. Article 3.1 of the Protocol stated that the overall reduction should be "at least 5 percent". Therefore, for the calculations here a 5 percent reduction from 1990 levels is assumed to be met and stabilised by 2010. Subsequently, a further 5 percent reduction in each ten year commitment period thereafter is considered using the previous decadal mean as a base year.

3.2.2 KP 18

Accountable CO_2 emissions, including removals from LULUCF activities, represent a tangible reduction from total Annex B base year levels of 17.6 percent by 2009. For the purpose of the calculation of intervention scenario KP 18, an estimated 18 percent reduction from 1990 levels is assumed to be met and stabilised by 2010. A further 18 percent reduction in each subsequent ten year commitment period is calculated. Once again the previous decadal mean is utilised as a base year.

3.2.3 KP 40

Pledges by parties to the Protocol for a second commitment period target range from 20-40 percent of base year levels to be met by 2020 (UNFCCC, 2011). The upper bounds of these pledges are in accordance with the findings and suggestions of the IPCC AR4 report. From this a combined 40 percent reduction is taken as an optimistic assumption for the calculation of intervention scenario KP 40. The observed 18 percent reduction of KP 18 is left untouched from 1990-2010, extrapolated to a 40 percent reduction from base year levels by 2020. Furthermore a 40 percent reduction is assumed for each subsequent commitment period. Alternate decades are reduced by 40 percent with reference to previous alternate decades as a base year (e.g. 2100 uses 2080). Decades between base years are calculated as a mean of those either side.

Each of the above scenarios are further branched into two divergent trajectories. Respective percentage reductions are expressed as both an Annex B target, in accordance with contemporary climate policy, and a global target in an effort to quantify the reduction implications of a universal mitigation policy. For Annex B scenario calculations the assumption was made that the contribution of signatory parties to global emissions remained proportionate to that of 1990 base year emissions and the percentage reductions adjusted accordingly.

For the global scenarios percentage reductions were subtracted from total SRES baseline emissions. As CO_2 is the dominant driver in all IPCC forcing scenarios the assumption was made that targets were met through CO_2 emissions reductions alone.

3.3 An Introduction to Climate Modelling

Any climate model is an attempt to represent the climate system in terms of the basic biogeochemical principles that drive it, to better understand these processes and to forecast the effects of their interactions (McGuffie and Henderson-Sellers, 2005). A numerical model can be regarded as a series of equations expressing the fundamental laws of these principles. The boundary conditions for some baseline state to these calculations are derived from observational data or output data from other simulations. In more complex climate system models all of the interactions between the individual components of the climate system must be assimilated. This in itself raises the issue of appropriate resolution as these interactions operate on vastly different timescales ranging from daily fluctuations to centennial variability. Spatial resolution is a function of both the availability of data and the computational capacity at hand. While model output at a finer resolution is generally presumed to be more accurate climate models can be both slow and expensive to run and the output can only ever be approximate due to large errors in the simulation of regional feedbacks, although it is widely held that regional errors do not compromise the validity of the global response to CO_2 forcing. Provided that the key components are simulated and that energy at upper atmosphere remains balanced, the model will construct a global equilibrium largely independent of regional variation (Shackley *et al*., 1998). At the forefront of recent climate change research, global climate models or General Circulation Models (GCMs) of the utmost complexity are gridded, computer based models, illustrated in Figure 3.2, that attempt to replicate the mechanics of climate in three dimensions (Viner, 2000). More recent experiments have investigated the climatic response to radiative forcing through multi-century integrations, the results of which could be assigned to specific calendar years, from which future scenarios can be constructed. Ideally the selection of a climate change scenario would focus on not only the interactions between climate variables, but also the relationships between other important scenario variables such as sea level rise and atmospheric CO_2. Such a scenario should also include estimates of changes in these variables to ensure that it remains internally consistent since they are likely to have substantial environmental impacts.

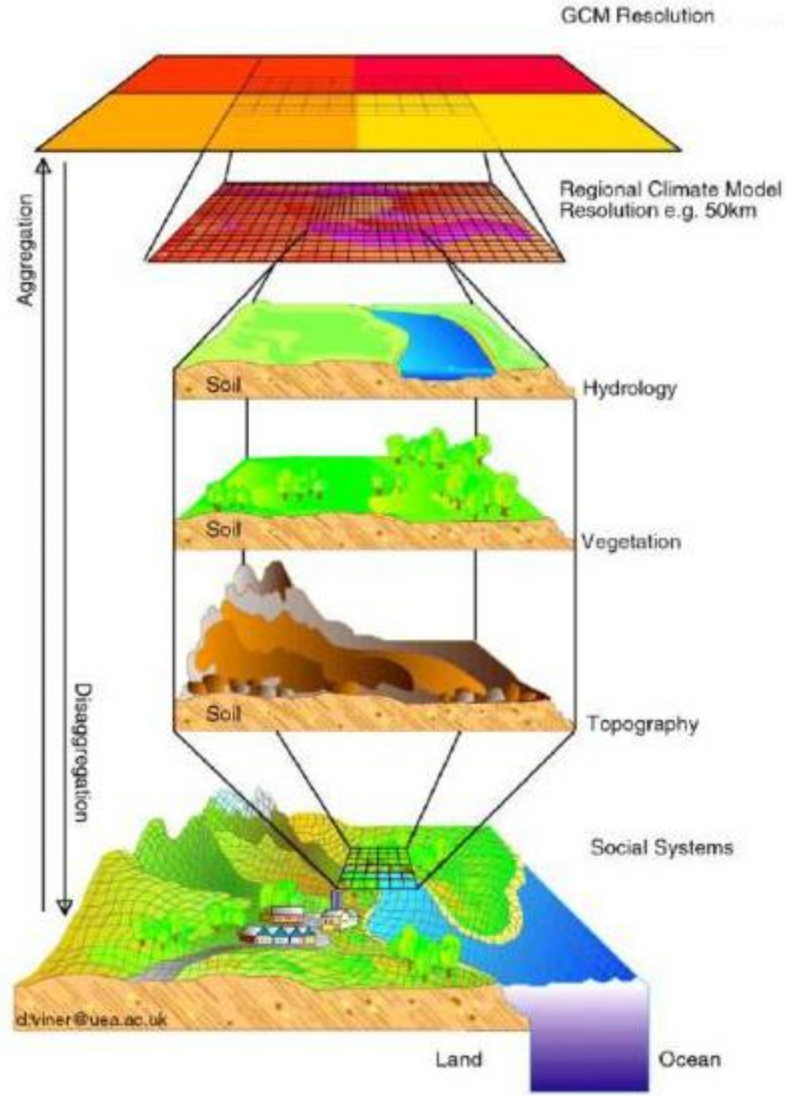


Figure 3.2: Spatial resolution discrepancy at various system levels of a complex GCM (Viner, 2000). © Copyright 2000, Climatic Research Unit

Atmospheric CO_2 concentration is a key driver of climate change. GCMs have been used to simulate the consequences of increased atmospheric CO_2 on global climate, both an abrupt doubling of CO_2 and under time-dependent simulations in which the CO_2 concentration is incrementally increased over a number of model years (Shackley *et al*., 1998). In GCM experiments, however, these are strictly speaking CO_2-equivalent concentrations representing the combined forcing effect of all GHGs, the actual CO_2 concentration will be less than that stated. Many studies make the mistake of assuming that actual doubling of CO_2 concentrations and doubled CO_2-equivalent concentrations have an identical effect on climate (Feenstra *et al*., 1998).

3.4 MAGICC Version 5.3

Widely used by the IPCC in their assessment reports the Model for the Assessment of Greenhouse gas Induced Climate Change (MAGICC) is a box model developed by Tom Wigley comprising an ocean component and a reduced-complexity gas-cycle element that collectively forms a standard upwelling diffusion model (McGuffie and Henderson-Sellers, 2005). MAGICC calculates mean annual surface temperatures and global mean sea level to allow the user to determine future climate implications as predicted by fully comprehensive climate models for a number of forcing scenarios for GHG emissions (Raper *et al*., 1996; Roslej *et al.*, 2012).

Users are able to specify which emissions scenarios to use, or to define their own, and alter a number of model parameters through a graphical user interface (GUI). An earlier version of MAGICC (4.1) was used throughout the IPCC TAR to evaluate impact of various emission scenarios. The model was designed to be used in conjunction with SCENGEN, a global and regional climate Scenario Generator, but can be used on its own with no loss of function. Two scenarios must be selected for MAGICC to run one iteration. Here MAGICC is used to model the SRES baseline emissions scenarios against the six intervention scenarios described in section 3.2 to calculate global mean temperature and sea level change up until 2100. To add a scenario to the existing library each new trajectory and corresponding parameters constructed in excel were saved in .GAS format recognisable by the MAGICC subdirectory.

3.5 SCENGEN

SCENGEN uses output from MAGICC together with archival GCM climate change data to construct geographically defined future projections for changes in the mean state of climate. In producing these projections SCENGEN combines climate change information with empirical baseline climate data of mean observed values from 1980-1999. The results are displayed as maps on a 2.5x2.5 degree latitude/longitude grid (Wigley, 2008). User-defined features in the construction of future climate projections include a future date, climatic variables and the model results selected from the SCENGEN library.

3.6 Model Parameters

MAGICC parameterises a number of fundamental atmospheric and ocean processes to allow the model to emulate the behaviour of a considerably more complex GCM. Emissions scenarios seem to be fairly independent of these variables, yet if the parameters are not statistically independent this assumption could lead to a higher estimation of uncertainty in the model response (Shackley *et al.*, 1998; Dessai and Hulme, 2001). In this investigation only the climate sensitivity parameter is amended from its default value in MAGICC. More recent IPCC estimates recognise 3.0°C as most likely and this value is therefore assumed in all calculations. SCENGEN will be used to construct a global map of mean annual temperatures for the year 2100 under the six SRES illustrative marker scenarios.

3.6.1 Carbon Cycle Model and Climate Feedbacks

These variables allow the investigation of non-climatic uncertainties in the carbon cycle model by assigning the mean value of net LULUCF CO_2 emissions for 1980 baseline data as high, mid or low. The default value for this is 1.1GtC per year, the best estimate of the IPCC Second Assessment Report, though the true value is subject to considerable uncertainty ranging from 0.4 – 1.8GtC per year. Selecting a high value leads to lower atmospheric carbon concentrations and vice versa. Subsequent IPCC reports have put forward different estimates for these parameters yet when climate feedbacks are included CO_2 concentrations are comparable to those of later approximations. The net effect of these feedbacks is positive so their inclusion, the default case, leads to higher concentrations than would be obtained otherwise.

3.6.2 Aerosol Forcing

An increasing anthropogenic aerosol load in the atmosphere influences regional air quality, decreasing the amount of solar radiation reaching the Earth's surface.

This "global dimming" is not universal in extent, having an observable urban bias (IPCC, 2007). Future aerosol emissions diminish in each of the SRES scenarios.

Constraints on carbon emissions through limiting the burning of fossil fuels are likely to be automatically correlated with lower non-CO_2 emissions from common sources, generally resulting in a notable decrease in both CO_2 and aerosol emissions (Meinshausen *et al.*, 2009). MAGICC considers four aspects of aerosol forcing detailed in its model parameters. The default values used in the IPCC TAR are presented in parentheses expressed as Watts per square meter (Wm^{-2}) but can be altered to represent higher or lower forcing. Direct forcing ($-0.4Wm^{-2}$) refers to the clear sky effect of sulphate aerosols derived from SO_2 emissions formed from fossil fuel combustion. Indirect forcing ($-0.8Wm^{-2}$) is subject to greater uncertainty. Biospheric forcing ($-0.2Wm^{-2}$) as a result of aerosols emitted during biomass combustion is equivalent to the sum of both Fossil and Organic Carbonaceous aerosol forcing (FOC). Forcing is assumed to run parallel to SO_2 emissions and gross LULUCF emissions. The separate components of aerosol forcing cannot be individually defined, rather input as high, mid or low values of total forcing.

3.6.3 Climate Sensitivity (ΔT_{2x})

The main source of uncertainty for projecting global warming is the climate system response to a doubling of atmospheric CO_2 concentration and the extent to which the global equilibrium temperature will change with sustained radiative forcing. While not a physical quantity directly measurable through empirical observation, climate sensitivity can be estimated with different indirect methods (Roslej *et al*., 2012). IPCC AR4 concluded that climate sensitivity is likely in the range of 1.5°C to 4.5°C (New and Hulme, 2000), though values substantially higher than 4.5°C cannot be excluded more recent studies have supported these estimates (Solomon *et al.*, 2007). Climate sensitivity illustrates the global surface temperature response on a centennial timescale incorporating feedback due to water vapour, cloud cover and surface albedo. The default mode in MAGICC is to run each emissions scenario three times at sensitivities of 1.5, 2.6 and 4.5°C, a range comparable to IPCC TAR best-estimates.

3.6.4 Thermohaline Circulation and Vertical Diffusivity

A key determinant of oceanic thermal expansion and global temperature change, Thermohaline Circulation (THC) can be defined within MAGICC parameters as either variable or constant. The default state is representative of a moderate variable slowdown of the THC at a rate equivalent to the median of THC results for the GCMs used to calibrate MAGICC. Vertical diffusivity (Kz) is the speed at which ocean mixing transports heat energy from surface waters into the deep ocean. A critical driver of both temperature change and thermal expansion Kz is parameterised in MAGICC at a default value of $2.3cm^2s^{-1}$ again comparable to the median value for the GCMs.

3.7 Monte Carlo Simulation Analysis

A Monte Carlo Simulation approach to decision making can be utilised in order to determine future risk. By defining prior probabilities for the model parameters, taken from empirical data examples, and randomly sampling these parameters through multiple iterations according to a pre-defined frequency distribution (New and Hulme, 2000) future scenarios can be forecast.

Such simulations are a valuable tool for investigating uncertainty within poorly defined systems, such as the global climate, with limited observational data. These uncertainties are incorporated with the addition of standard errors.

3.7.1 R Project

R (Version: 2.14.2) is a software for statistical computing and graphical display freely available in source code form under Gnu public licence. The R console comprises a computer language and interpreter that executes this code and a system for plotting computer graphics through a GUI (Adler, 2010). R requires data to be loaded into the memory working directory before processing in .csv (comma separated value) format.

In this investigation MCS analysis was carried out in R on the six SRES illustrative marker scenarios and revised trajectories under the observed 18% reduction KP 18 intervention scenario to estimate the impact of the Kyoto Protocol on atmospheric CO_2 concentration over a hypothetical century. Each was calculated under three different climate sensitivities, 1.5, 3.0 and 4.5, representing a range comparable to that put forward by the IPCC. While R is efficient in its statistical analysis, the computing time for the construction of MCS models is substantial in comparison to a typical statistical application (Soetaert and Petzoldt, 2010). 1000 iterations were run for each of the simulations.

For each scenario the summary dataset was composed of decadal Mauna Loa CO_2 concentration data, described in Section 3.1.3, and the ISAM estimates for global atmospheric CO_2 concentrations for the 21st century outlined in Section 3.1.2. A model fit was applied to each scenario through the R package *ismev* to obtain the maximum likelihood estimates for a number of model parameters, referred to as location or mean, shape and scale, and their corresponding standard errors. The visual diagnostics for the model output can be used to interpret distribution of data and quality of the data fit through probability, quantile, return level and density plots.

MCS incorporates tiers of uncertainty in the form of standard error in each of the model parameters. This allows for numerous simulations of values close to the maximum likelihood estimates in a manner respective of the standard error. A specific trend was added to each scenario illustrative of annual changes in CO_2 concentrations under a particular trajectory. An initial estimate from the IPCC of a 2°C increase relative to preindustrial global temperatures has been widely determined in climate policy to be an upper limit beyond which the risk of dangerous interference with the climate system and irreversible climate change are expected to increase rapidly (Solomon *et al.*, 2007). An atmospheric CO_2 concentration threshold was calculated for each climate sensitivity considered, based on the roughly logarithmic relationship between CO_2 concentration and surface temperature using Equation 3.1 outlined overleaf.

Equation 3.1: Calculation of threshold atmospheric CO_2 ($P_{stab.}$) for a 2°C increase relative to preindustrial global temperatures where P_{280} represents a preindustrial reference CO_2 concentration of 280ppmv and ΔT_{2x} corresponds to climate sensitivity.

$$\frac{P_{stab.}}{P_{280}} = 2\left(\frac{\Delta T_{stab.}}{\Delta T_{2x}}\right)$$

These thresholds, summarised in Table 3.1, were superimposed on each of the Monte Carlo simulations as matrices representative of "alarm" criteria. These act as a critical level beyond which the 2°C ceiling is likely to be surpassed to obtain a proportion of exceedences within the 1000 iterations under each scenario and subsequently draw assumptions for a simulated hypothetical century.

Table 3.1: Threshold atmospheric CO_2 concentrations for a 2°C increase relative to preindustrial global temperatures under three climate sensitivities.

Climate Sensitivity	Threshold CO_2 conc. (ppmv)
1.5	747
3.0	373
4.5	249

Results

4.1 Observational Annex B Emissions Data

Kyoto targets over all parties equate to a reduction to 95% of base year GHG emissions with individual national commitments ranging considerably from -28% for Luxembourg to an increase of 27% for Portugal. Emissions from fossil fuel combustion between 1990 and 2009 for Annex B parties relative to reduction targets for the first commitment period are displayed in Figure 4.1. Latvia demonstrated the greatest decrease of -63.8% while the most notable growth in fossil emissions was Australia's 51.8% increase.

From base year GHG emissions equivalent to $17.7GtCO_2$, total Annex B emissions including removal by LULUCF activities were cut by approximately 17.6% by 2009 to $14.6GtCO_2$-eq.

This declining trend is presented in Figure 4.2 against global CO_2 emissions data obtained from the US Energy Information Administration's International Energy Statistics. Despite Annex B GHG reductions subsequent to the implementation of Kyoto, global figures display a continuation of the increase in anthropogenic emissions of CO_2 observable since the industrial revolution rising from 21.6Gt in 1990 to 30.4Gt in 2009. These values are representative of CO_2 emissions only. The CO_2-equivalent emissions for non- CO_2 GHGs included under the Kyoto Protocol on a global scale would be considerably greater. However, if a CO_2-equivalence based upon radiative forcing is calculated accurately for a basket of GHGs, it is reasonable for the temperature and sea level implications of the Kyoto Protocol to be estimated from the CO_2 case (Wigley, 1998).

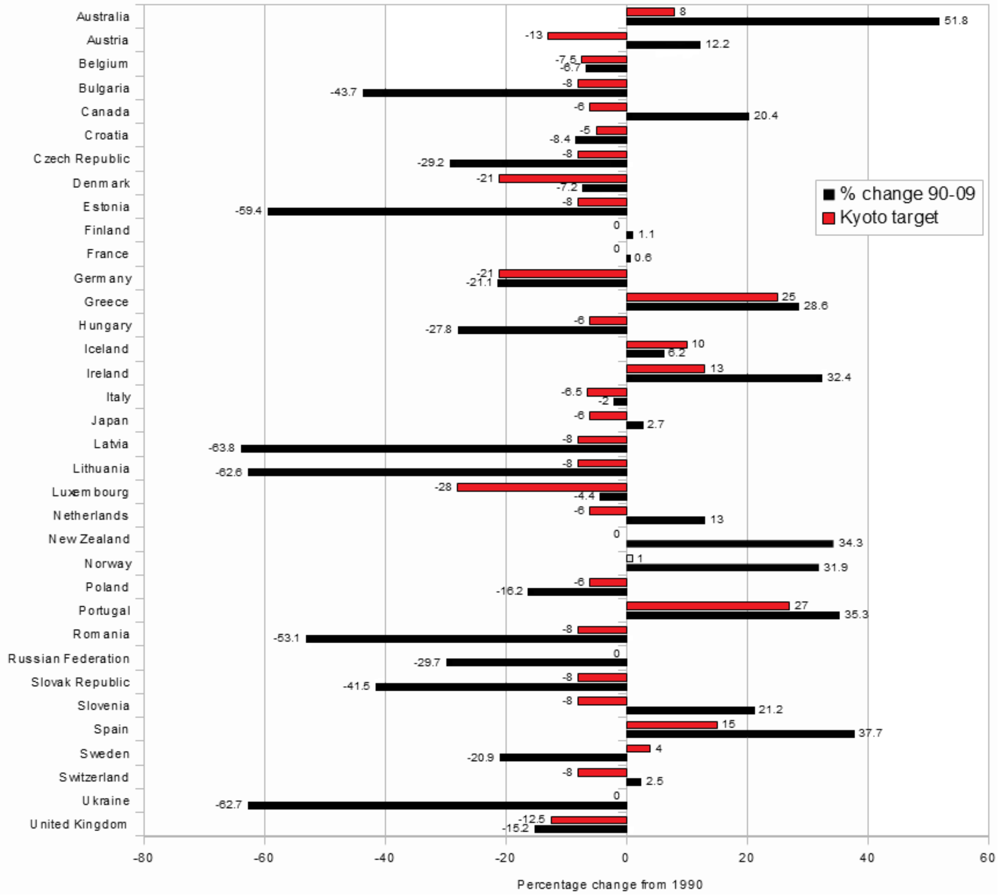


Figure 4.1: Percentage change in Annex B CO_2-equivalent emissions from fossil fuel combustion and Kyoto Protocol targets from 1990-2009 (International Energy Agency. 2011).

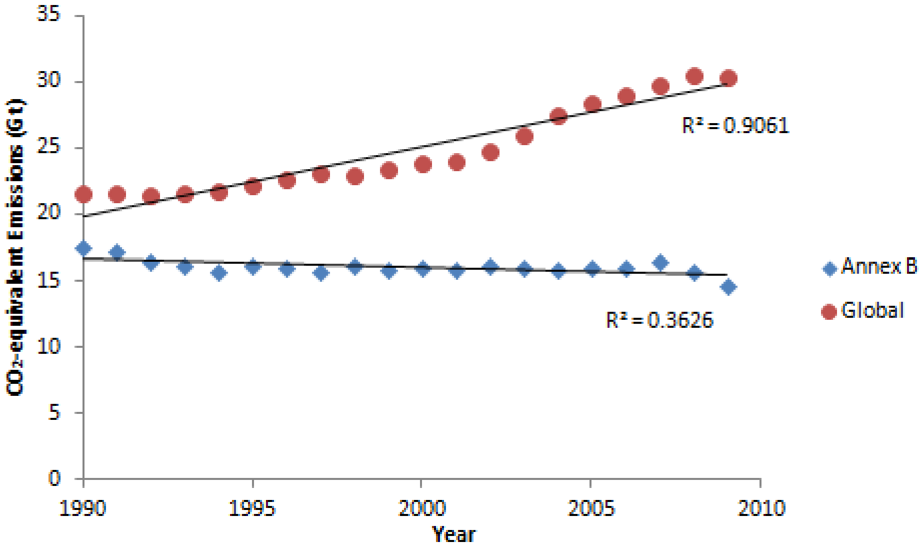


Figure 4.2: Net Annex B CO_2-equivalent emissions, including removal by LULUCF activities, and total global anthropogenic CO_2 emissions from 1990-2009.

4.2 Intervention Scenario Emissions Data

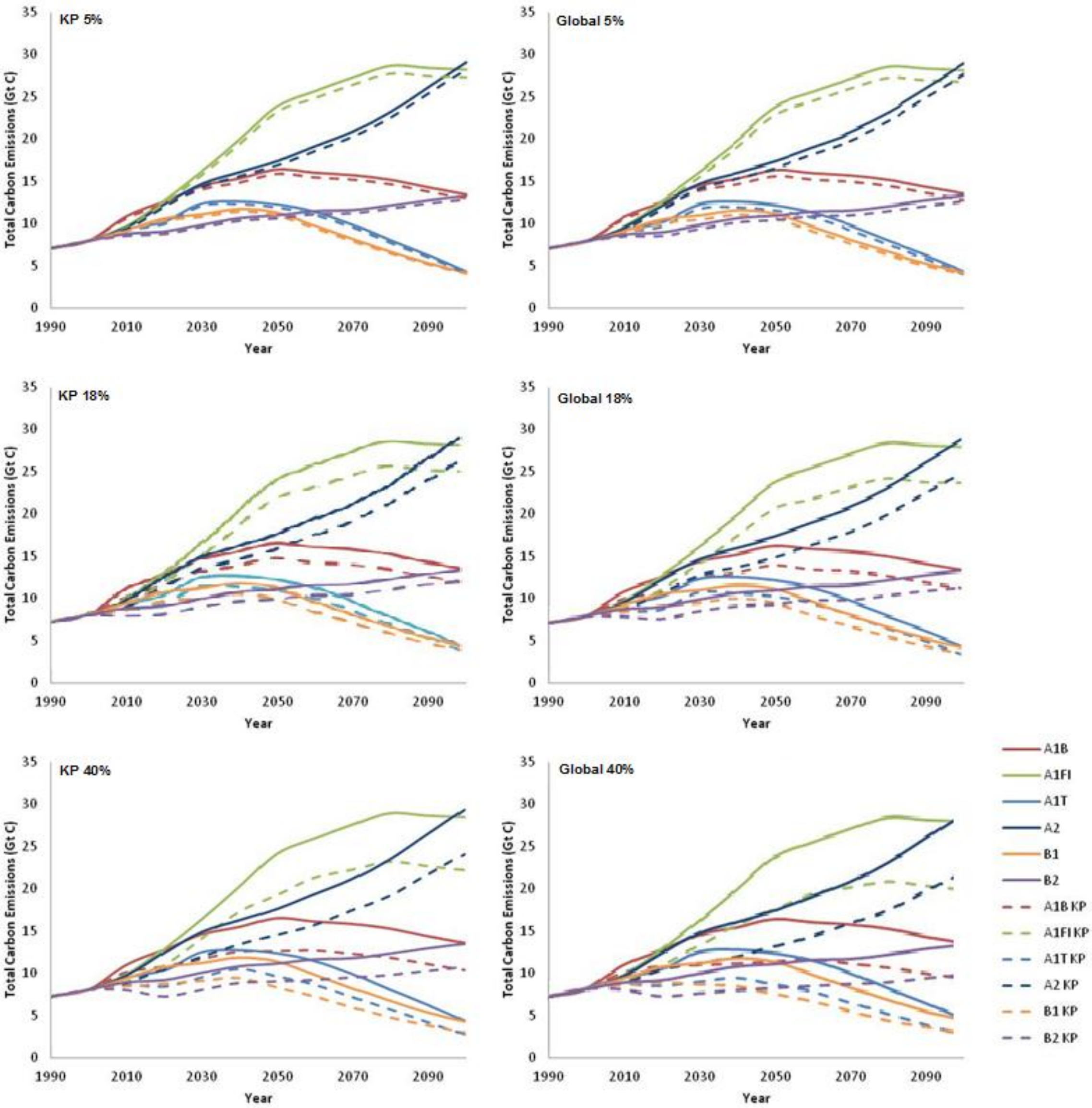


Figure 4.3: Total carbon equivalent emissions (Gt) up to year 2100 for Kyoto intervention scenarios against six SRES illustrative scenarios.

Emissions under each of the intervention scenarios vary substantially and are presented in Figure 4.3. Total emissions are governed by which SRES illustrative trajectory they are applied and the extent to which mitigation is implemented, whether on a global scale or solely by signatory parties, the former evidently yielding greater reductions.

In each case the consequences of intervention are most prominent under SRES A1FI and A2 proportional to their high future emissions projections. SRES A1T and B1 provide the minimum total emissions by year 2100 from 2000 levels irrespective of intervention in terms of both quantity and extent, further discussed in Section 5.2.

4.3 Mean Global Temperature and Sea Level Rise by 2100

4.3.1 Climatic Changes by 2100 under SRES AIFI

Under an unmitigated SRES A1FI a 4.41°C increase in global mean temperature is anticipated by 2100 with a global range of -0.47 to 13.21°C illustrated in Map 4.1. Under the most stringent intervention scenario (KP 40) this mean falls just below 4°C. A 45cm rise in average sea height is reduced to just above 40cm.

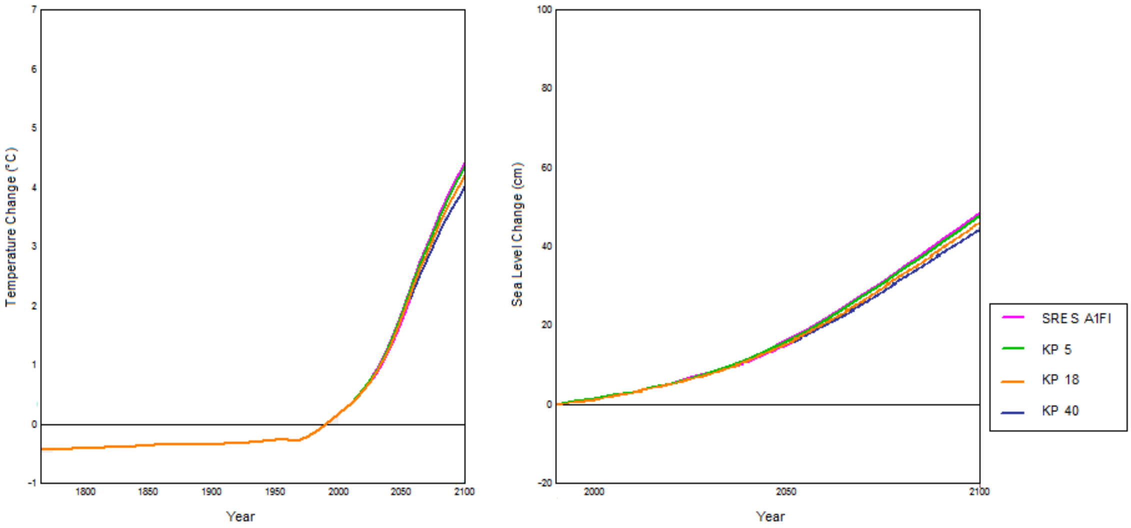
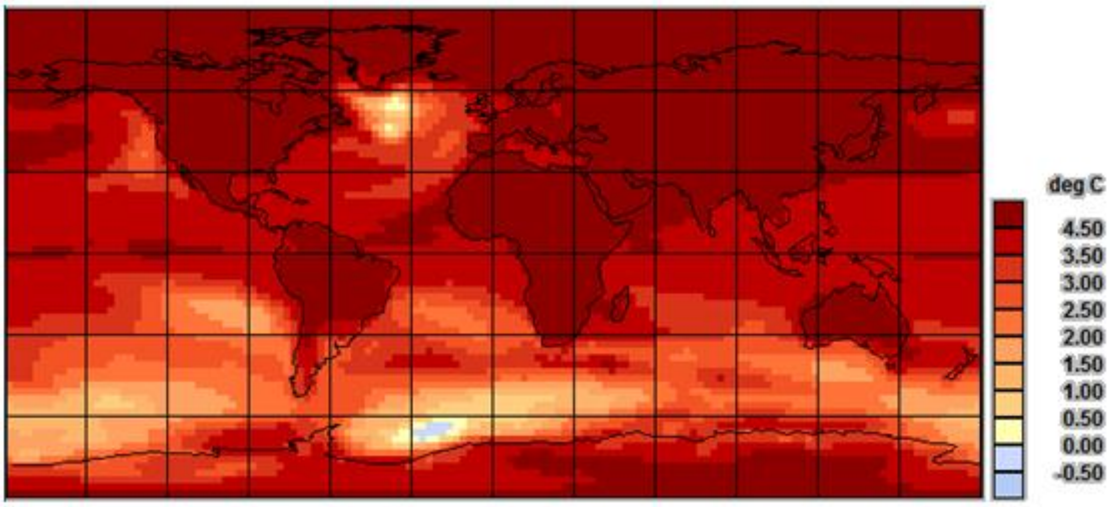


Figure 4.4: Temperature and sea level change with reference to 1990 levels under SRES A1FI and three hypothetical mitigation intervention scenarios.



Map 4.1: Spatial variation in mean global temperature rise by year 2100 under SRES A1FI accounting for the cooling effect of aerosols. Global Range: -0.47 to 13.21°C, Global Mean ΔT: 4.41°C, Models: CCSM--30; GFDLCM20.

4.3.2 Climatic Changes by 2100 under SRES A1B

In the absence of additional climate mitigation under SRES A1B a 2.96°C increase in global mean temperature is projected over the 21st century. Such radiative forcing is adequate to provoke a 36cm rise in average sea height from year 2000 levels. The significant spatial variation in temperature rise by 2100 is illustrated in Map 4.2 with a global range of -0.27 to 8.40°C. Even under KP 40 a mean temperature increase of just below 2.5°C is anticipated and on average sea level rise remains above 30cm.

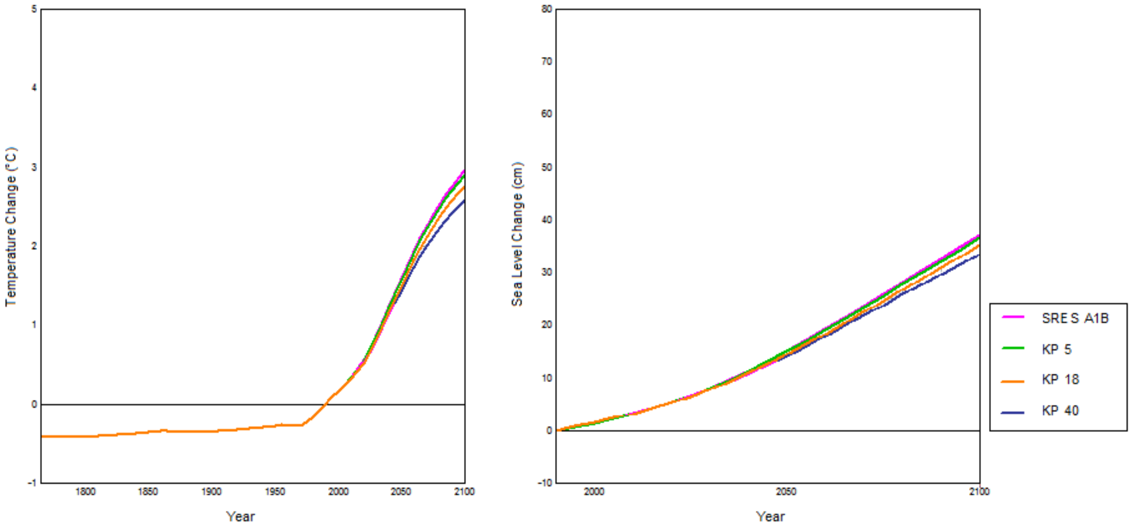
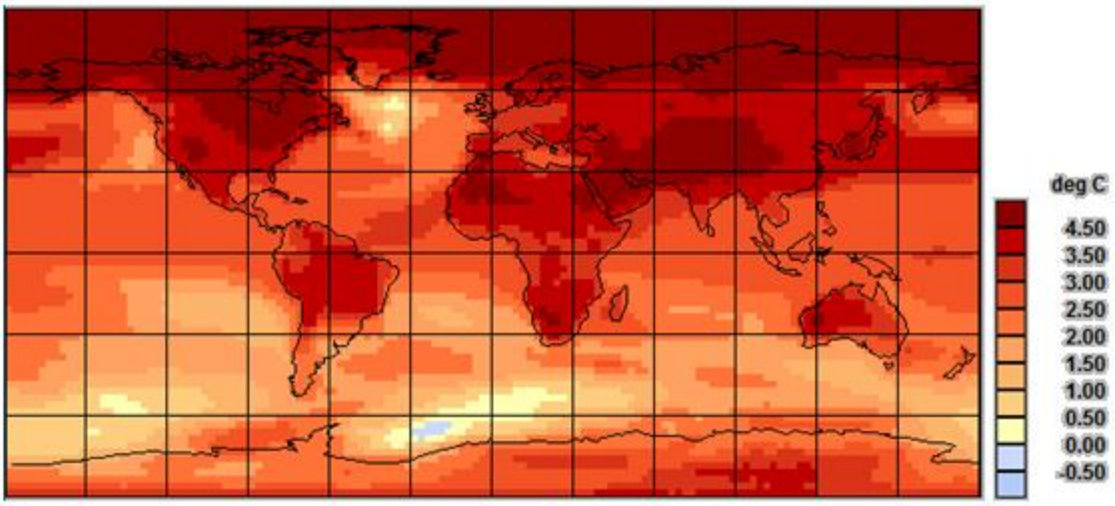


Figure 4.5: Temperature and sea level change with reference to 1990 levels under SRES A1B and three hypothetical mitigation intervention scenarios.



Map 4.2: Spatial variation in mean global temperature rise by year 2100 under SRES A1B accounting for the cooling effect of aerosols. Global Range: -0.27 to 8.40°C, Global Mean ΔT: 2.96°C, Models: CCSM--30; GFDLCM20.

4.3.3 Climatic Changes by 2100 under SRES A1T

SRES A1T demonstrates a mean 2.48°C rise in temperatures, ranging from -0.12 to 6.73°C globally, presented in Map 4.3. The global mean remains above 2°C under each intervention scenario. Unmitigated such an increase is projected to induce a rise in sea level of around 33cm whereas under KP 40 this change remains below 30cm by 2100. Among the lowest emitting SRES trajectories, associated forcing enables the rate of increase in mean temperature to decline at an earlier point in the 21st century relative to other scenarios. This is illustrated in the temperature curve of Figure 4.8.

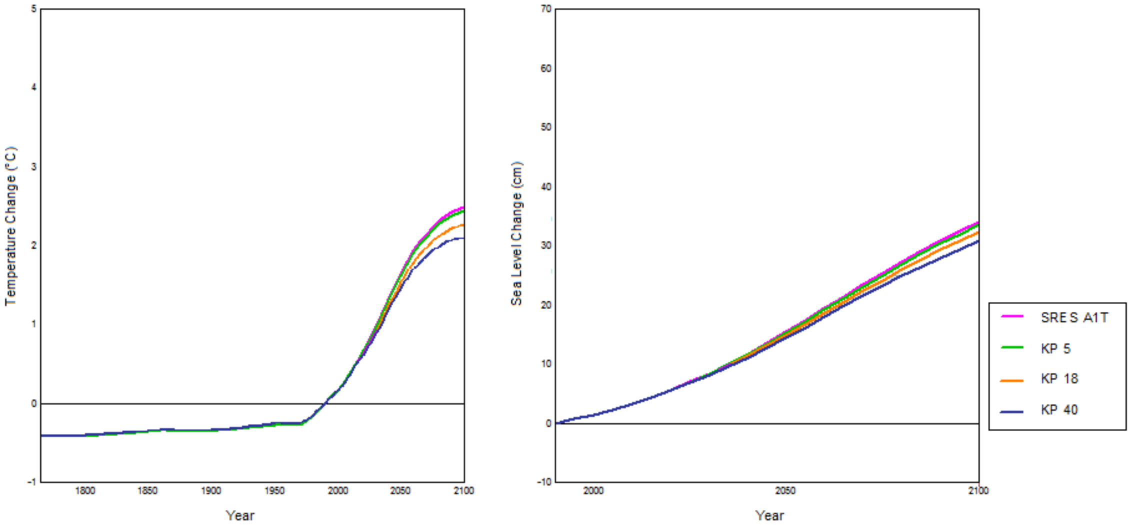
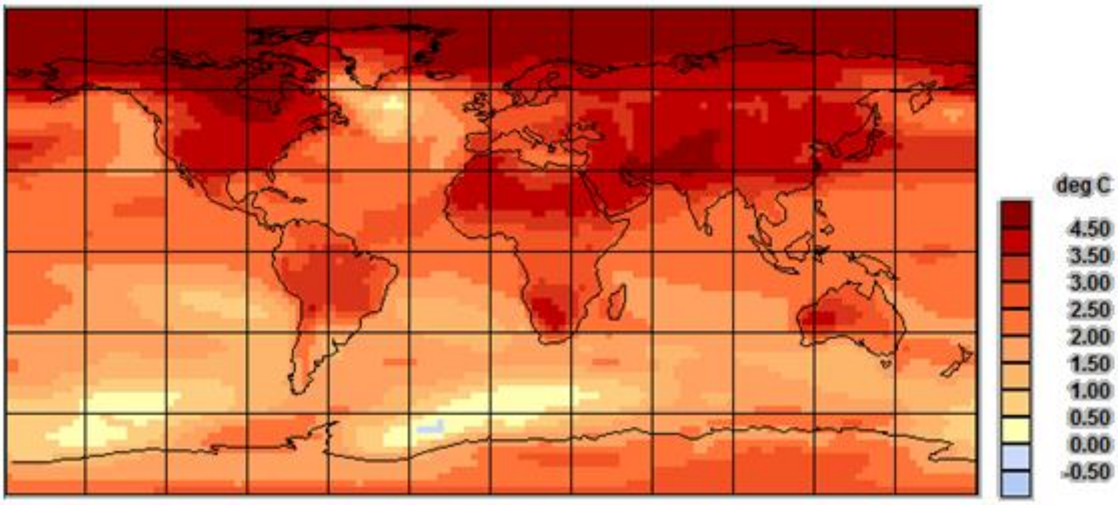


Figure 4.6: Temperature and sea level change with reference to 1990 levels under SRES A1T and three hypothetical mitigation intervention scenarios.



Map 4.3: Spatial variation in mean global temperature rise by year 2100 under SRES A1T accounting for the cooling effect of aerosols. Global Range: -0.12 to 6.73°C, Global Mean ΔT: 2.48°C, Models: CCSM--30; GFDLCM20.

4.3.4 Climatic Changes by 2100 under SRES A2

SRES illustrative marker A2 equates to a 3.81°C increase in mean global temperatures by 2100. This mean remains above 3°C under each mitigative scenario. The sharp upward trajectory in mean global temperatures observable in Figure 4.7 displays the rate of change over the 21st century. Map 4.4 is illustrative of regional temperature variation ranging between -0.52 and 11.79°C. In terms of change in sea level an average increase of 42cm under non-intervention conditions falls below 40cm under both KP 18 and KP 40.

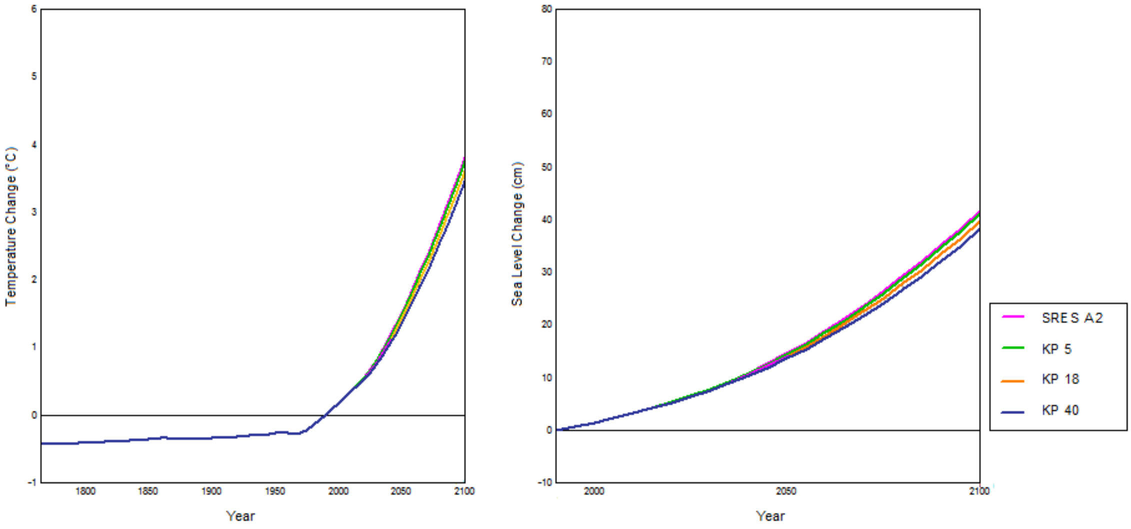
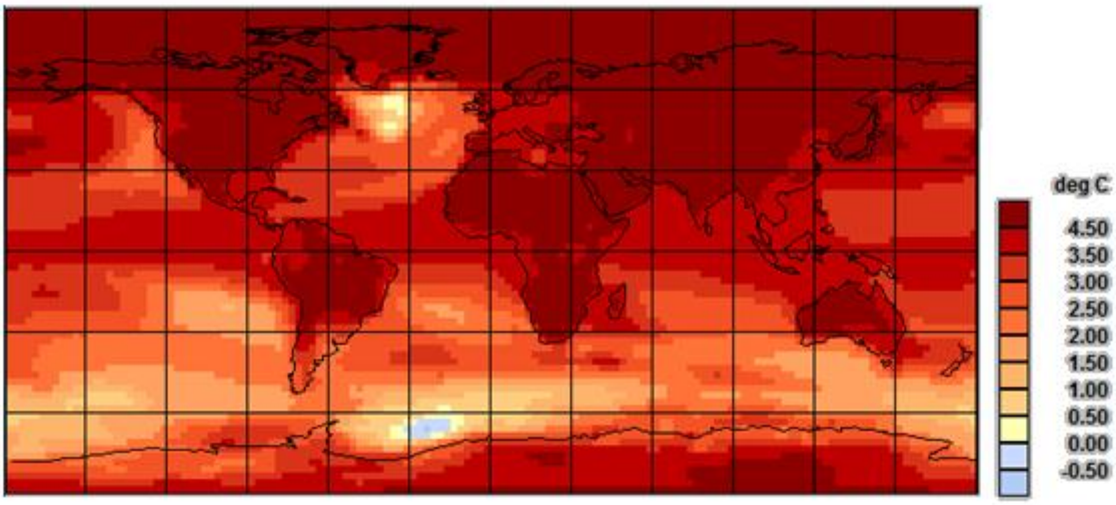


Figure 4.7: Temperature and sea level change with reference to 1990 levels under SRES A2 and three hypothetical mitigation intervention scenarios.



Map 4.4: Spatial variation in mean global temperature rise by year 2100 under SRES A2 accounting for the cooling effect of aerosols. Global Range: -0.52 to 11.79°C, Global Mean ΔT: 3.81°C, Models: CCSM--30; GFDLCM20.

4.3.5 Climatic Changes by 2100 under SRES B1

2100 global temperature increase under SRES B1 ranges from -0.16 to 5.14°C, shown in Map 4.5, with a mean of 1.88°C. A mean reduced to just above 1.5°C under KP 40. The implications for global sea level under no additional climate mitigation efforts bring about an approximate 27cm rise by the end of the 21st century and an increase below 25cm under the sustained carbon abatement of KP 40.

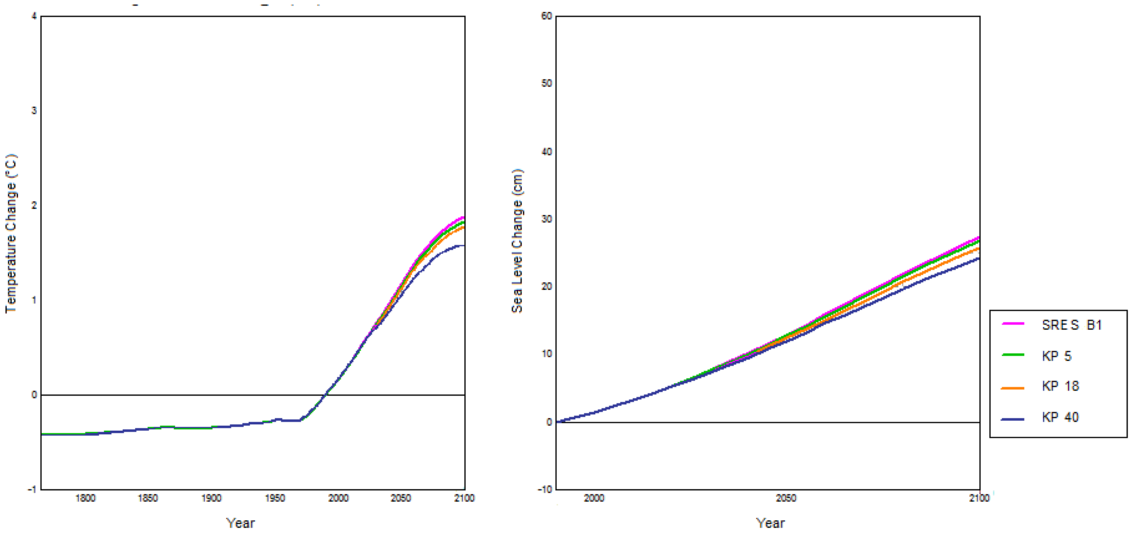
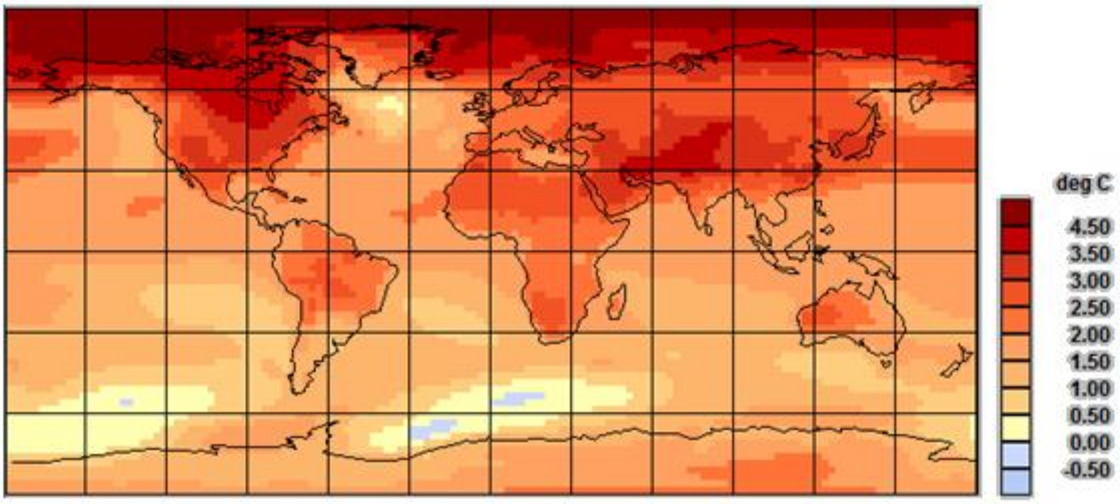


Figure 4.8: Temperature and sea level change with reference to 1990 levels under SRES B1 and three hypothetical mitigation intervention scenarios.



Map 4.5: Spatial variation in mean global temperature rise by year 2100 under SRES B1 accounting for the cooling effect of aerosols. Global Range: -0.16 to 5.14°C, Global Mean ΔT: 1.88°C, Models: CCSM--30; GFDLCM20.

4.3.6 Climatic Changes by 2100 under SRES B2

SRES B2 emissions attribute to an average 2.6°C increase in mean temperatures by 2100 ranging from -0.33 to 7.71°C regionally, displayed in Map 4.6. Under each additional mitigative trajectory the anticipated mean remains within this range at a level above 2°C. In terms of global sea levels mean increase is kept below 30cm under more severe climate policy implementation relative to a mean 33cm under baseline SRES conditions.

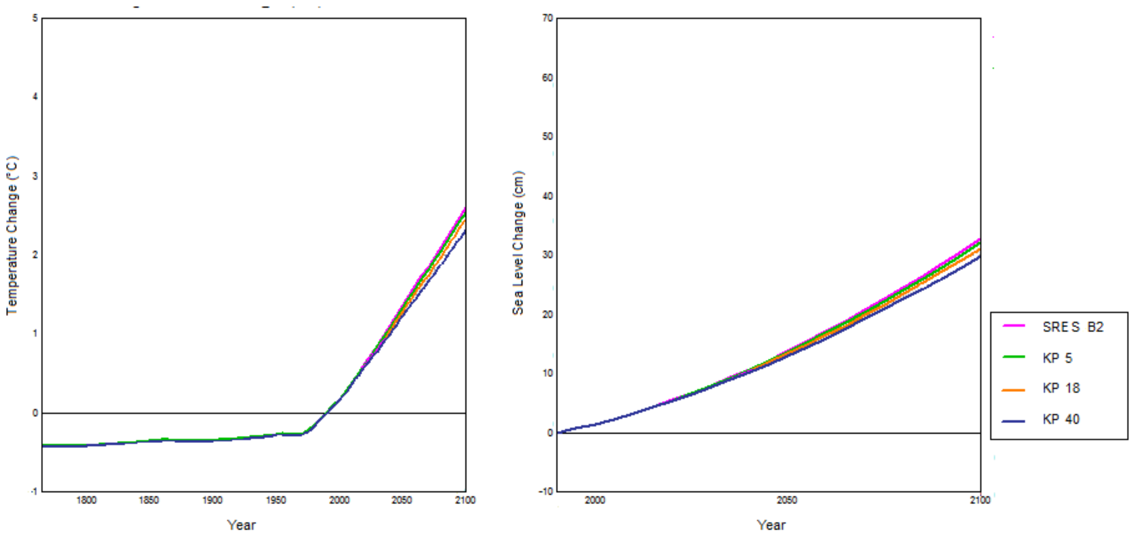
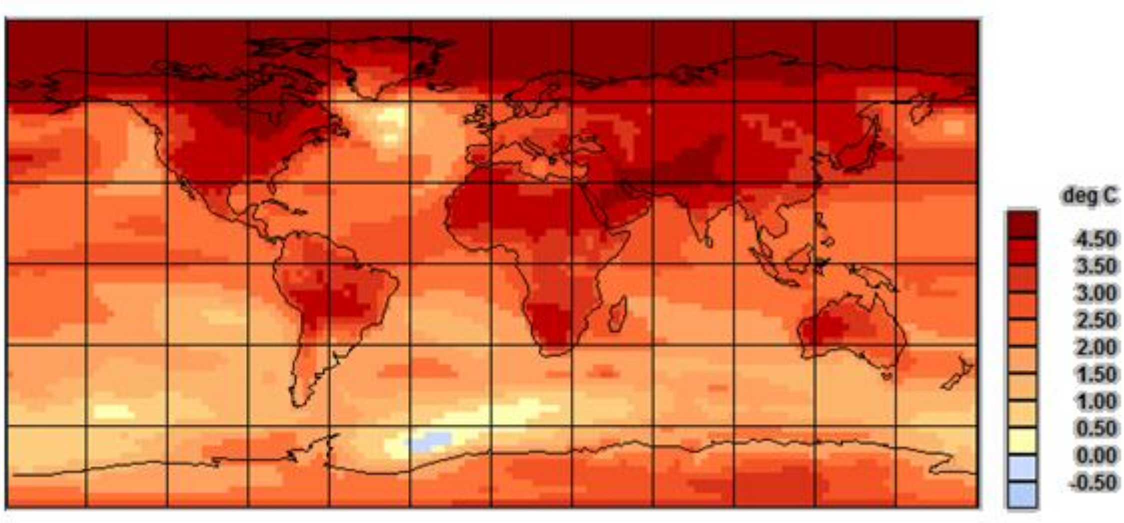


Figure 4.9: Temperature and sea level change with reference to 1990 levels under SRES B2 and three hypothetical mitigation intervention scenarios.



Map 4.6: Spatial variation in mean global temperature rise by year 2100 under SRES B2 accounting for the cooling effect of aerosols. Global Range: -0.33 to 7.71°C, Global Mean ΔT: 2.6°C, Models: CCSM--30; GFDLCM20.

4.4 Monte Carlo Simulation Results

The results of the atmospheric CO_2 concentration Monte Carlo simulations intended to determine the mitigative impact of the Kyoto Protocol are displayed in Table 4.1. This information is presented in terms of the number of years in a hypothetical century in which atmospheric CO_2 is projected to exceed a specific threshold concentration dependant on climate sensitivity, as stated in Section 3.7.1 in Table 3.1, beyond which irreversible and catastrophic global warming is anticipated. At a climate sensitivity of 1.5 the number of years demonstrating concentrations above 747ppmv ranges from 21 under A1FI to just 3 years under the B1 marker scenario. Incorporating the current impact of the Protocol reduces this number by a maximum of one year, having no effect under SRES A1B or B1.

At a climate sensitivity of 3.0, considered most likely to accurately represent the climate system (Solomon *et al.*, 2007), between 83 and 94 years out of 100 resulted in concentrations exceeding 373ppmv under SRES B1 and A1FI respectively. With the Kyoto Protocol, the greatest reduction is again just one year where irreversible climate change is averted under SRES A1B, A2 and B2.

At a climate sensitivity of 4.5, 100 years of a hypothetical century demonstrate catastrophic warming under both non-intervention and post-Kyoto conditions as the 249ppmv threshold was exceeded before empirical records began.

Table 4.1: Number of years in a hypothetical century atmospheric CO_2 concentration exceeds threshold inducing irreversible and catastrophic warming (2°C increase relative to pre-industrial baseline) under six SRES illustrative scenarios and varying climate sensitivities. "None" indicates no additional climate policy; "KP" represents a continued 18% reduction in emissions in each commitment period

Climate Sensitivity	**1.5**		**3.0**		**4.5**
	None	**KP**	**None**	**KP**	**None**
A1FI	21	*	94	*	100
A1B	6	6	91	90	100
A1T	4	3	85	85	100
A2	9	8	93	92	100
B1	3	3	83	82	100
B2	4	3	87	87	100

The A1FI simulations incorporating the influence of the emissions reductions of the Kyoto Protocol on future climate change resulted in NaN (not a number) programming errors of indeterminate values in the R output. Values are therefore left unstated, denoted by an asterisk in Table 4.1.

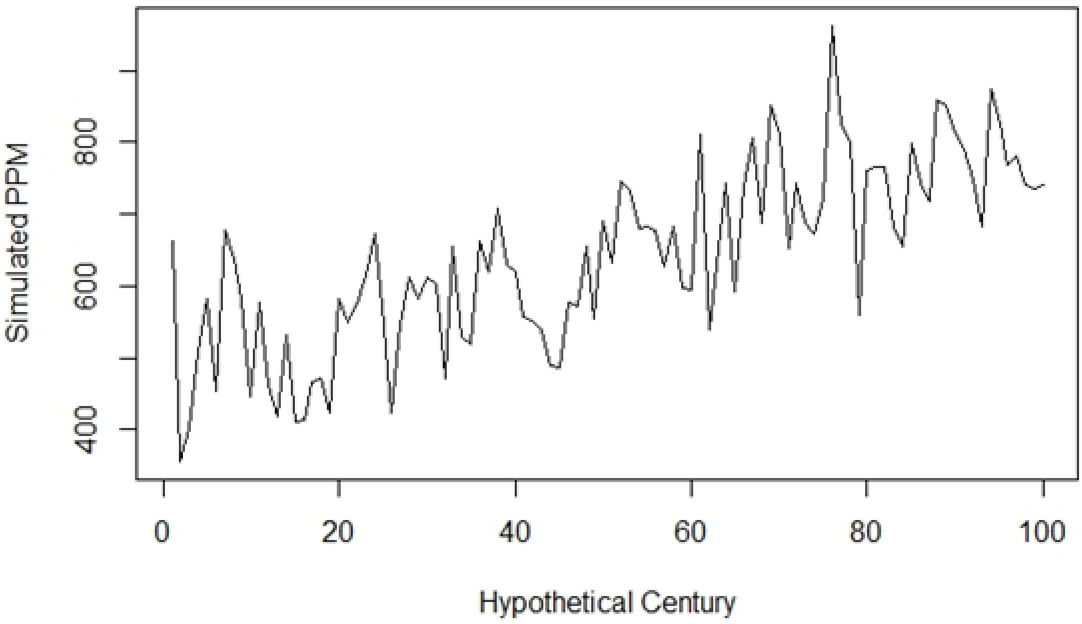


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Figure 4.10: Example Monte Carlo Simulation of atmospheric CO_2 concentrations for a hypothetical century under SRES A1FI

An illustrative sample Monte Carlo Simulation output is presented in Figure 4.10. Each simulation underwent 1000 iterations. As to the interpretation of such data the exceedences are not representative of a literal forecast of future events, rather a trend applied to numbers generated randomly within a reasonable boundary respective of the standard error. This investigation does not attempt to assign relative probabilities as to which of the scenario trajectories will come about but investigates the ramifications of each on a case by case basis.

Discussion

5.1 Global GHG Emissions and the Kyoto Protocol

Since the formal adoption of the Kyoto Protocol in 1997 global CO_2 emissions from the combustion of fossil fuels increased by 31 percent, from 23.1Gt to 30.3Gt per year (EIA, 2009). In terms of national targets however, Annex B countries exceeded their Kyoto commitments. In 2009, their aggregate emissions were approximately 18 percent below base year levels. This decline is chiefly attributable to the economic failure at the collapse of the former Soviet Union, the consequences of which remain prominent. In 2009 emissions from EIT parties were around 54.4 percent below 1990 levels including LULUCF activities (UNFCCC, 2011). While neither resulting from technological advancement nor revised emissions policy, the final text of the Protocol did not stipulate mandatory adjustment according to volatile financial circumstances. It is likely that Annex B would have been able to cut its collective emissions by at least five percent independent of the Soviet Union. The present economic climate will no doubt prove to have a significant influence over recent trends in emissions. Global CO_2 emissions decreased by 0.5Gt between 2008 and 2009 (IEA, 2011), yet recent literature suggests that the impacts of the global financial appear to have been short lived. Rapidly increasing emissions from emerging economies and a return to an upward trajectory of emissions in developed nations have offset previous reductions achieved under the Kyoto Protocol facilitating an increased rate of growth in global emissions (Peters *et al*., 2012). These divergent trends led developing nations to be accountable for a larger proportion of total global emissions than Annex I parties for the first time in 2008.

The recent large-scale expansion of China's coal-fired power generation capacity has played a key role the accelerated growth of global emission (Princiotta, 2009). On CO_2 emissions alone China produces the largest contribution emitting more than the US and Canada combined but supports over 75 percent of the world's outsourced emissions (Peters *et al*., 2012). The US remains prominent among the larger economies in terms of per capita emissions with 18 tonnes of CO_2 emitted per person in contrast to China's six (IEA, 2011).

With this in mind compliance must necessarily be calculated in terms of consumption rather than net emissions from production within national boundaries. Effective global mitigation is not possible without an effort combining the major emerging economies of the developing world (Princiotta, 2009). Australia's substantial overshoot of its reduction commitments presented in Figure 4.1 can perhaps be explained by the fact that in 2005, by which time parties were expected to have achieved demonstrable progress towards their individual commitments, the Prime Minister expressed that Australia no longer intended to ratify the treaty on the grounds that the Protocol failed to incorporate 70% of global emissions (IEA, 2005). During negotiations in Durban, Australia stated that it would not participate in a second commitment period under Kyoto until a more comprehensive agreement is finalised inclusive of all major emitters.

5.2 Intervention Scenarios and SRES

The prominence of the impacts of intervention under SRES A1FI and A2 in terms of total emissions over the 21st century is proportional to their high future emissions projections. The A1 scenario supposes a world of rapid economic growth, a global population which peaks around 2050 and the introduction and advancement of more efficient technologies. A1 diverges into three alternative directions of technological change with A1FI depicting a sustained dependence on fossil intensive technologies. A2 assumes a diverse world with high population growth and slow economic development. SRES A1T and B1 display the minimum total CO_2 emissions by 2100 irrespective of intervention due to the focus of the A1T scenario on non-fossil resources and the convergent world of B1 with a global population equivalent to that of A1 but with the more rapid development in economic structure towards a service and information economy. The intervention scenarios KP 5, KP 18 and KP 40 display an increasingly apparent emissions reduction under each SRES trajectory due to their proportionate calculation with a more evident impact if implemented on a global scale as opposed to Annex B compliance alone.

5.3 21st Century Change in Global Temperature and Sea Level

All temperature change and sea level rise presented in Section 4.3 is expressed relative to year 2000 levels. Under each SRES projection the intervention scenario KP 5, based on targeted reductions for the first commitment period, has little to no influence on year 2100 climate. The mitigative extent of the intermediate KP 18 and the more stringent KP 40 intervention scenarios is largely dependent on which emissions trajectory unfolds while remaining within non-intervention ranges of temperature change. Generally this change is not uniformly observed, displaying substantial spatial variability with greater warming at the poles and a lesser extent in mid-latitudes and equatorial regions.

Figure 5.1 illustrates Mann *et al.*'s “Hockey stick” trend for northern hemisphere temperatures over the past 1000 years, reconstructed from multi-proxy climate data. Their findings suggested that rising temperatures throughout the 20th century contradict a millennial-scale cooling trend largely consistent with long term radiative forcing (Mann *et al.*, 1999). For the most part the MAGICC output temperature projections are an extrapolation of this trend. Under B1 and the three alternative A1 scenarios the rate of temperature increase begins to decline towards the end of the 21st century whereas under A2 and B2 the upward trajectory displays no indication of diminishing. This could be a consequence of the continuous population growth exhibited in both A2 and B2 storylines.

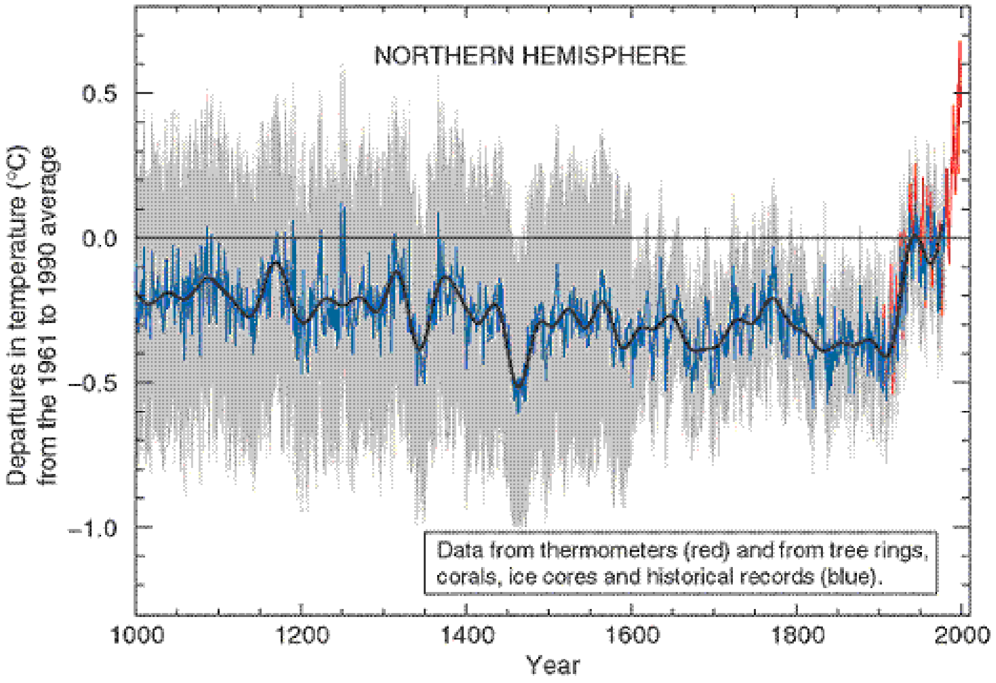

Figure 5.1: Mann *et al*.'s "hockey stick". A multi-proxy temperature reconstruction for the Northern Hemisphere over the past millennium. Confidence bands are depicted by blue line with grey shading. The red line is observational temperature data from empirical sources (IPCC, 2001).

The fossil intensive A1FI scenario displays both the maximum temperature range upper limit and the greatest mean temperature increase by 2100 at 13.21°C and 4.41°C respectively. A mean increase reduced to just below 4°C under KP 40. The B1 mean temperature rise of 1.88°C remains above 1.5°C with extensive mitigation but represents the best case scenario in terms of limiting global temperatures to below critical levels. SRES A1T and B2 also display a mean temperature increase of below 2°C under KP 40.

Regarding changes in sea level the global mean is set to rise somewhere between 27 and 45cm by 2100. The greatest increase is again under the A1FI scenario, limited to below 40cm under KP 40, while with equally stringent mitigation mean sea level rise could remain below 25cm under SRES B1. The global maximum sea level for 2100 is likely to greatly exceed these values. In a fully comprehensive assessment of emissions trajectories incorporating oceanic expansion and ice dynamics sea level rise might fall between 75cm and 1.9m (Vermeer and Rahmstorf, 2009). It is anticipated that global sea level rise will be sustained at a rate exceeding that of the 20cm increase observable over the past century as a result of the thermal expansion of the oceans (Pethica *et al.,* 2010). The Alliance of Small Island States (AOSIS) is a coalition of low lying small island nations, party to the Kyoto Protocol, deemed particularly vulnerable to rising global sea levels. These small islands, chiefly in the Pacific, Caribbean and Indian Ocean, are accountable for just 0.6% of global CO_2-equivalent emissions (IEA, 2011) and under no obligation to cut emissions under the Protocol. At the entry into force of the Kyoto Protocol AOSIS proposed a "safe emissions corridor", limited to a 2°C increase in mean global temperatures and 20cm sea level rise between 1990 and 2100, of a 25% reduction in Annex 1 emissions (Alcamo *et al.,* 1997). In this investigation the KP 40 intervention representing a

40% reduction in Annex B emission imposed on each of the SRES illustrative marker scenarios exceeds this “safe” sea level rise in all cases.

5.4 Atmospheric CO_2 Concentration and the Kyoto Protocol

The ultimate objective, shared by both the UNFCCC and the Kyoto Protocol, was to achieve the stabilisation of atmospheric GHG concentrations at a level preventing dangerous anthropogenic interference with the climate system. Based upon IPCC AR4 estimates of global temperature increase inducing abrupt and irreversible climate change a 2°C limit relative to preindustrial temperatures was agreed upon at COP15 in Copenhagen, 2009. While the negative effects of global climate change are observable today with temperatures approximately 0.7°C above preindustrial levels (Solomon *et al.*, 2007) the impacts of a mean increase above 2°C would likely exceed the adaptive capacity of many natural systems and further increase the human cost of mitigation and response.

The results of the Monte Carlo Simulation analysis of the six SRES illustrative marker scenarios and the intervention of the Kyoto Protocol to date, presented in Section 4.4, indicate that at present the efforts of the Protocol are inadequate in their impacts on the atmospheric GHG concentrations. When compared to non-intervention SRES baselines the additional influence of Kyoto reduces the exceedence of concentration thresholds inducing irreversible change by a single year out of a hypothetical century. For the majority of trial iterations the Protocol has no observable influence.

The IPCC proposes that in order to stand a 50% chance of remaining below this 2°C threshold CO_2-equivalent atmospheric GHG concentration must not exceed 450ppmv. CO_2 stabilisation below this level would require the combustion of fossil fuels to be phased out entirely by the end of the 21st century replaced with renewable energy industries. Furthermore, radiative forcing of non-CO_2 GHGs would need to be stabilised at their present concentrations, in the case of N_2O and HFCs, or further reduced for CH_4 (Harvey, 2007).

5.5 Implications for Climate Policy

A founding premise of the Kyoto mechanism was the notion that emissions mitigation is a global commons problem requiring universal consensus and the assumption that national efforts would be driven by binding international commitments. However, there is little evidence that this has been the case outside the European Union. Negotiations in Cancún at COP16 in 2010 offered parties the opportunity to implement voluntary action plans for 2020 targets. While presently these pledges are insufficient to ensure parties are on track towards limiting global warming to 2°C above preindustrial levels it is unlikely that adequate, durable agreements develop fully formed from such negotiations, rather they evolve over time. The Kyoto Protocol was little more than an attempt to short-circuit this process. It has been settled upon that a second commitment period shall begin on January 1st, 2013 until December 31st, 2017 with individual national commitment pledges ranging from 5 to 40 percent reductions by 2020 relative to base year emissions (UNFCCC, 2011).

Though climate models are widely considered to be sufficient in investigating the impacts future climate change, value judgements associated with the formation of comprehensive climate policy is greatly influenced by factors unquantifiable in purely scientific sense. The adequacy of present environmental policy making is dependent upon the representation of these factors (Shackley *et al.*, 1998).

Climate projections for IPPC AR4 were founded on the intercomparison of coupled model simulations based on SRES. Subsequently, a set of four Representative Concentration Pathways (RCPs) have been constructed for use in model comparisons under the fifth assessment report (AR5). Such revisions to both models and scenarios could render the interpretation and comparison of AR5 findings with previous literature more challenging (Roslej *et al.*, 2012).

Under each of the illustrative scenarios global mean temperature and sea level projections for divergent mitigative interventions are virtually indistinguishable until well into the 21st century. It is however reasonable to assume that reducing global emissions to a level significantly lower than business as usual trajectories will prove to be a preferable alternative to the economic and environmental costs of inaction.

5.6 Limitations

5.6.1 Technical Limitations to the Method

The input datasets utilised by climate models such as those incorporated in MAGICC are rarely of sufficient accuracy to comprehensively define the environmental parameters they investigate. This considered there are innate uncertainties in any results they can yield (McGuffie and Henderson-Sellers, 2005). Simple climate models are valuable tools for the illustration of the impacts of global change in manner which is easily interpreted but there are conclusions which cannot be drawn in the absence of a more comprehensive model. Shackley *et al.* (1998) stated that simple climate models are essential for understanding but useless for prediction.

Webster *et al*. (2002) identified a limitation to the use of Monte Carlo methods in climate change science which they termed “cold start”. There is inertia inherent to both GCMs and the climate system itself meaning that to start “cold” from the year 2000 with adjusted values for climatic parameters would require the revision of historical forcings in order to yield meaningful projections.

A simple confidence interval was applied to the maximum likelihood estimates used as input parameters for the MCS analysis, created using the central limit theorem. The confidence interval for a number of the model parameters straddle zero and therefore cannot be regarded as statistically significant to 95% confidence.

5.6.2 Quantifying Uncertainties

Prominent throughout this investigation, uncertainty is endemic to climate change research. Measures must be taken to adequately quantify these uncertainties if results are to be truly useful in policy making (Dessai and Hulme, 2001). Historical climate records dating back to the emergence of the large scale combustion of fossil fuels in the late nineteenth century are vulnerable to errors resulting from changes in sampling methods. Satellite data since the1970s do not perfectly correlate with earlier ground data and the integration of multiple datasets compounds empirical errors. The estimated uncertainty in the Mauna Loa dataset described in Section 3.1.3 corresponds to disparities in the standard deviations of the monthly means and the annual growth rate obtained is comparable to independently calculated global trends (Tans, 2012). Future trajectories regarding fossil fuel use are a function of population dynamics, policy implementation and economic and technological development. To minimise ambiguity, likelihood estimates bracket possible outcomes into descriptive scenarios of optimal response or non-intervention approaches with the aim of evaluating the consequence of inaction (Singer *et al*., 2008). The expert judgement of the IPCC defines likely and very likely to represent a probability exceeding 66% and 90% respectively. Uncertainties regarding the physical impact on the climate system itself are subject to future and historical radiative forcing, terrestrial carbon cycle responses, ice dynamics, ocean circulation, climate sensitivity and regional variation.

5.6.3 Assumptions and Biases

Biases can emerge in the accounting of national emissions registries submitted by signatory parties from the uncertainties and technical limitations of accurately defining emissions and removals from LULUCF activities. Disparate sample coverage between the northern and southern hemisphere render climate data vulnerable to weighting errors where measurements are more numerous. Heat island effects introduce an upward urban bias raising local temperatures as a result of increased industrial activity and transport emissions. Threshold atmospheric GHG concentrations deemed critical for the prevention of dangerous climate change have been met with controversy calling for a traceable account from policymakers justifying the selection of emissions trajectories and model sensitivities (Schneider, 2001). Wigley and Raper (2001) falsely assumed uniform likelihood across all of the SRES projections in assigning probability estimates to future changes in global temperature and sea level. Webster *et al*, (2002) question the illustration of climate policy, often modelled in terms of permanent decision making, while it would be more appropriately depicted as sequential revisions responding to advancements in understanding and contemporary issues.

5.6.4 Inaccuracies in Unit Conversion

Available emissions data is presented in different units and formats depending on source. Calculation errors may have emerged from the conversion of non-CO_2 GHG emissions into CO_2-equivalent values based on GWP and the mass calculations between carbon and CO_2.

The consideration of both metric and imperial measurements, the quantification of data in gigagrams (Gg) and million metric tons of carbon, and their subsequent conversion into gigatons for comparison with UNFCCC base year data followed accounting guidelines put forward by both the IPCC and Kyoto itself.

Conclusion

In accomplishing the primary aims of this investigation an evaluation of the successes and failures of the Kyoto Protocol relies entirely upon context. In terms of the achievement of binding targets under the first commitment period of the Protocol the admittedly modest aggregated reduction commitments of 5% were exceeded, with an observable decrease in Annex B emissions of approximately 18% between 1990 and 2009. Regarding the ultimate objective of the UNFCCC, however, the present implementation of the Protocol has proven inadequate in preventing dangerous anthropogenic interference with the climate system. Capping global temperature increase below a 2°C mean relative to preindustrial levels will likely permit adaptive efforts by human systems in response to changing global climates at a reasonable economic cost. However, the adaptive capacity of natural systems to rapid changes in climate may be exceeded prior to such a threshold at a catastrophic environmental cost. MAGICC output regarding mean temperature and sea level rise under SRES illustrative marker scenarios suggests that the reductions necessary for the stabilisation of atmospheric GHG concentrations likely to reasonably constrain climate change lie beyond the upper limit of the restrictions pledged by parties for a second commitment period. These values do not represent maxima and both temperature and sea level rise will continue beyond 2100.

In this investigation, Monte Carlo simulation analysis of the impact of the Protocol to date suggested that the present extent of implementation is insufficient. At best catastrophic climate change is prevented in a single year of a hypothetical century, depending on both the climate sensitivity and emissions trajectory selected. MAGICC assessment of the mitigative influence of the KP 40 intervention scenario, representative of the maximum proposed reductions for the future, was entirely dependent upon which SRES trajectory developed over the next century. Mean temperature increase by year 2100 under the A1T, B1 and B2 scenarios remained below 2°C. Recognising the previous failings of the Protocol, and bridging the rift between observational geophysical information and the political realities of policymaking, is imperative to the negotiation of emissions reduction targets and the construction of a meaningful post-Kyoto discourse.

The mindset that agreements must be both international and binding has limited the pursuit of alternative mitigation. It is important to recognise that, as in any negotiation, the large number of parties involved and the vast disparities regarding responsibilities and agendas reduce the common denominator for agreement (Diringer, 2011). Particularly considering that in actual fact approximately 80% of total global emissions are attributable to fewer than 20 countries (IEA, 2011), the most significant of which failed to ratify the protocol to begin with. In the early stages of negotiation additional parties only serve to hinder the development of an effective agreement (Prins and Rayner, 2007).

Future climate change projections are dependent upon emissions trajectories, spatial variation, the adaptation of natural processes and cycles additional to the adequacy of the human response. The considerable uncertainty involved in anticipating climate change necessitates the continuous improvement of methods of both analysing and quantifying these uncertainties (Webster and Solokov, 2000). However, as acknowledged in the text of the UNFCCC, decision making under uncertainty does not justify inaction (Toth *et al*., 2001).

While it is too late to prevent substantial change to the global climate system it is vital that these impacts are moderated through the implementation and vigilant compliance of a mitigative framework greatly superior to existing climate policy in its commitments.

Further Investigation

The 1990 to 2009 Annex B emissions dataset used in this investigation is representative of the most extensive publically available information to date. A full evaluation of the Kyoto Protocol is impractical until the complete data for the first commitment period of 2008-2012 is published. Regarding the climatic implications of emissions trajectories a comprehensive analysis, incorporating the uncertainties involved in parameters including the natural responses of the terrestrial carbon sink and ocean circulation, would yield more meaningful results than variable climate sensitivities alone. A complex multi-gas assessment would be more appropriate than a method limited to CO_2-equivalences based upon the GWPs of non-CO_2 GHGs (Reilly *et al.,* 1999). The assignation of low probabilities to rapid, non-linear climate system responses could account for events such as a substantial shift in thermohaline circulation of the large-scale collapse of the world's ice sheets (Dessai and Hulme, 2001). In terms of the construction of appropriate intervention scenarios and emissions pathways, Roslej *et al.* (2011) proposed a number of "harmonisation methodologies" designed to offset the discrepancies inherent in combining historical and projected values for climate model parameters. The expert review of the Working Groups and First Lead Authors meetings for the IPCC AR5 have begun, on track be completed in 2013/2014. Proposed amendments to Annex A of the Protocol include the addition of Nitrogen trifluoride (NF_3). A comparable investigation subsequent to this research project, in addition to the availability of complete first commitment period data, could evaluate the negotiations for the continuation of the Kyoto Protocol initiated at COP13 and the development of the Bali Roadmap.

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