Carbon Dioxide Emission Pathways Avoiding Dangerous Ocean Impacts

by

Karin F. Kvale

BSc, Indiana University, 2005

A Dissertation Submitted in Partial Fulfillment of the
Requirements for the Degree of

Masters of Science

in the School of Earth and Ocean Science

University of Victoria

Carbon Dioxide Emission Pathways Avoiding Dangerous Ocean Impacts

by

Karin F. Kvale
BSc, Indiana University, 2005

Supervisory Committee

Dr. A. Weaver, Supervisor (School of Earth and Ocean Science)

Dr. K. Meissner, Supervisor (School of Earth and Ocean Science)

Dr. M. Winn, Member (School of Business)

Dr. K. Zickfeld, Outside Member (Canadian Centre for Climate Modelling and Analysis)

Supervisory Committee

Dr. A. Weaver, Supervisor (School of Earth and Ocean Science)

Dr. K. Meissner, Supervisor (School of Earth and Ocean Science)

Dr. M. Winn, Member (School of Business)

Dr. K. Zickfeld, Outside Member (Canadian Centre for Climate Modelling and Analysis)

Abstract

Radiative forcing by increased atmospheric levels of greenhouse gases (GHGs) produced by human activities could lead to strongly undesirable effects on oceans and their dependent human systems in the coming centuries. Such dangerous anthropogenic interference with the climate system is a possibility the UN Framework Convention on Climate Change (UNFCCC) calls on nations to avoid. Unacceptable consequences of such interference could include inundation of coastal areas and low-lying islands by rising sea level, the rate of which could exceed natural and human ability to adapt, and ocean acidification contributing to widespread disruption of marine and human food systems. Such consequences pose daunting socioeconomic costs, for developing nations in particular.

Drawing on existing literature, we define example levels of acceptable global marine change in terms of global mean temperature rise, sea level rise and ocean acidification. A global-mean climate model (ACC2), is implemented in an optimizing envi-

ronment, GAMS, and coupled to an economic model (DICE). Using cost-effectiveness analysis and the tolerable windows approach (TWA) allows for the computation of both economically optimal CO_2 emissions pathways as well as a range in CO_2 emissions (the so-called "emissions corridor") which respect the predetermined ceilings and take into account the socio-economically acceptable pace of emissions reductions.

The German Advisory Council on Global Change (WBGU) has issued several guardrails focused on marine changes, of which we find the rate and absolute rise in global mean temperature to be the most restrictive (0.2℃ per decade, 2℃ total). Respecting these guardrails will require large reductions in both carbon and non-carbon GHGs over the next century, regardless of equilibrium climate sensitivity. WBGU sea level rise and rate of rise guardrails (1 meter absolute, 5 cm per decade) are substantially less restrictive, and respecting them does not require deviation from a business-as-usual path in the next couple hundred of years, provided common assumptions of Antarctic ice mass balance sensitivity are correct. The ocean acidification guardrail (0.2 unit decline relative to the pre-industrial value) is less restrictive than those for temperature, but does require emissions reductions into the coming century.

Table of Contents

Supervisory Committee **ii**

Abstract **iii**

Table of Contents **v**

List of Tables **vii**

List of Figures **viii**

I Background 1

1 Introduction **2**

2 Observed Changes in the Marine Climate **4**

2.1 Global Mean Temperature 4

2.2 Sea Level Rise 8

2.3 Ocean Acidification 14

3 Projected Changes in the Marine Climate: Impacts on Humans and the Environment **19**

3.1 Human Vulnerability to Marine Change 20

3.2 WBGU Guardrails 29

4 A Historical Perspective on Climate Change Policy 33

4.1 Concern About Carbon Dioxide 34

4.2 Climate Stabilization and Limiting Emissions 35

4.3 Setting Climate Targets 36

5 Integrated Assessment and Decision-making Frameworks 39

5.1 Interpreting Article 2 - what is dangerous interference? 39

5.2 Implementing Article 2- decision making frameworks 45

II New Work 52

6 Model Description 53

6.1 ACC2 54

6.2 DICE 71

7 Results 75

7.1 Cost-effectiveness Analysis 75

7.2 Tolerable Windows Approach 83

8 Conclusions 87

Bibliography 93

List of Tables

5.1 Dangerous Climate Change Benchmarks 40

6.1 Components of Sea Level Rise by SRES Scenario 68

List of Figures

2.1 Land-surface air temperature anomalies, 1850 to 2005 5

2.2 Annually-averaged global mean sea level, 1870 to 2001 9

2.3 Estimated contributions to global sea level change 11

2.4 Changes in ocean surface pCO_2 16

2.5 The ocean carbon cycle pumps 18

3.1 Projected mean surface warming for SRES scenarios 23

3.2 Projected mean global sea level rise for SRES scenarios 24

3.3 Projected global surface pH change for SRES scenarios 27

5.1 External versus internal definitions of dangerous climate change . . . 43

6.1 ACC2 schematic 55

6.2 Sea level contribution of glaciers and land ice 59

6.3 Comparison of different methods for calculating thermal expansion in ACC2 62

6.4 Thermal expansion throughout the water column 63

6.5 Sea level rise using different AIS mass balance sensitivities 66

6.6 ACC2 SRES scenarios 67

6.7 Contributions to Sea Level Rise at 2100 69

6.8 ACC2 Thermal Expansion 70

6.9 ACC2/DICE schematic 74

7.1 Cost-effective pathways for WBGU temperature guardrails 78

7.2 Cost-effective pathways for sea level rise 79

7.3 Cost-effective pathways for sea level rise rate, multiple sensitivities and scenarios 81

7.4 Cost-effective pathways for ocean acidification 83

7.5 Optimal economic pathways respecting the acidification guardrail . . 84

7.6 Tolerable window emission corridor 86

Part I

Background

Chapter 1

Introduction

Dramatic changes are underway in global climate. Human activities are emitting greenhouse gases (GHGs), increasing the atmospheric concentration beyond historical limits. These GHGs are trapping more long-wave radiation near the Earth's surface, causing global ocean and land temperatures to rise, accelerating the melting of ice, and increasing mean sea level. Among the GHGs, carbon dioxide (CO_2), stands out as a primary culprit in causing the greenhouse effect. Increasing carbon dioxide concentrations have another byproduct, equally concerning because the effects are poorly understood- the acidification of the global ocean. These globally-observed changes have regional-scale effects, such as enhanced severe weather patterns, melting of sea ice and glaciers, and coral reef bleaching, to name a few. These regional effects have substantial local implications, as changes to the water and carbon cycles affect even the foundations of natural systems. There are important societal implications as well, as humans rely a great deal on the natural environment for survival. As the body of knowledge grows regarding the possible worsening effects of an increasingly altered climate state, so does concern over how to avoid the most drastic possibilities. Intergovernmental collaboration on this topic was proclaimed by Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC), which calls for the avoidance of "dangerous anthropogenic interference with the climate system"

(*UNFCCC* 1992). So far, the majority of dialog has focused on avoiding dangerous climate change within terrestrial systems. In agreement with the German Advisory Council on Global Change (*WBGU* 2006), we argue that the vulnerability of oceans deserves equal attention under the UNFCCC, as they are an important component of the hydrosphere and support significant biodiversity.

In order to recognize the importance of the global marine system and define ways to avoid dangerous change within it, we define globally-aggregated, economically-optimal CO_2 emissions pathways and tolerable windows corridors which avoid dangerous global mean temperature and sea level rise and rates of rise, and dangerous ocean acidification. The dangerous thresholds we use are those recommended by the *WBGU* (2006), and can be thought of as guardrails, just like the barriers along highways which keep cars on the roadway. These guardrails will not prevent collisions; climate change even within their range has the potential to adversely affect a large proportion of the global population. The purpose of the guardrails is to protect the most vulnerable natural and human populations from destruction, and so are relevant to the 1.2 billion people living within 100 km of the coast and less than 100 m above sea level (*Small and Nicholls* 2003), as well as to the over 1 billion people who rely on fish as their main animal protein source (*Pauly et al.* 2005). As human utilization of coastal ecosystems is projected to increase into the 21st century (*Nicholls et al.* 2007), avoiding dangerous anthropogenic interference takes on increased importance, for developed and developing nations alike.

Chapter 2

Observed Changes in the Marine Climate

Oceans are of tremendous importance in the global climate, and like terrestrial systems, have experienced rapid changes in recent decades. These changes are both temporally and spatially variable, but global trends indicate increasing surface temperatures, rising sea levels, increasing acidity, freshening in the polar regions and salinification in the tropics (*Bindoff et al.* 2007). These changes are being and will continue to be felt throughout the Earth system as the oceans are a significant sink in the carbon cycle, absorb a large amount of the incoming solar radiation, drive the water cycle, and host a large proportion of the planet's biological diversity. The objective of this section is not to provide an overview of all possible changes which could or are taking place in oceans worldwide, only those which are relevant to our study and which are felt at a global scale. These include global trends in surface air temperature, sea level rise and the rate of sea level rise, and ocean acidity.

2.1 Global Mean Temperature

2.1.1 Observed Changes

A relatively reliable instrumental record exists for temperatures around the globe starting in the 1850s and continuing through present day (*Trenberth et al.* 2007). Though consistency is poor and spatially biased toward the North Atlantic in the

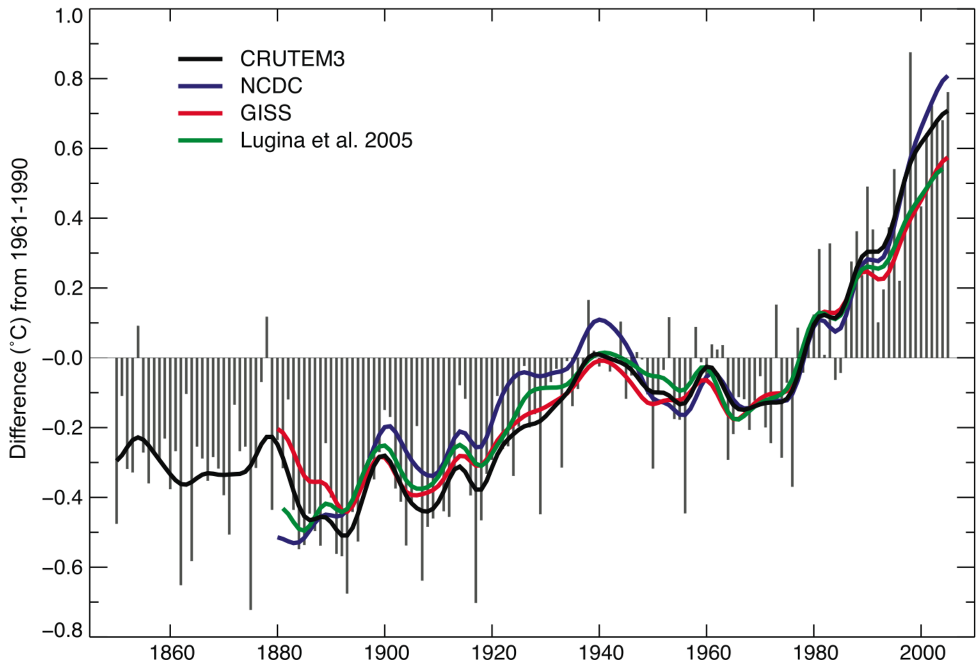

Figure 2.1: Global anomalies of land-surface air temperature in ℃, relative to the 1961 to 1990 mean for CRUTEM3. Black line is smoothed decadal variation of CRUTEM3, based upon *Brohan et al.* (2006) and updated by *Trenberth et al.* (2007). The colored lines are other datasets for comparison (blue: NCDC, *Smith and Reynolds* (2005); red: GISS, *Hansen et al.* (2001); green: *K.M. Lugina* (2005)). Figure from *Trenberth et al.* (2007).

older records, global trends are visible (see Figure 2.1). Relatively little change in global temperatures occurred prior to around 1915, and what variability was present is either attributable to natural processes or is likely due to sampling error (*Trenberth et al.* 2007). Starting in the 1910s and continuing until the 1940s, global temperatures increased 0.35℃ (*Trenberth et al.* 2007). This warming was followed by a slight cooling of 0.1℃, and then another episode of warming (increasing 0.55℃) until present (*Trenberth et al.* 2007). Strongly suggestive of an upward trend, 11 of the 12 warmest years have occurred in the last 12 years, with the two warmest years on record being 1998 and 2005 (*Trenberth et al.* 2007). As might be expected, the rate of warming is accelerating, and the past 50 years experienced a rate almost twice that of the last 100

(0.13±0.03℃ versus 0.07±0.02℃) (*Trenberth et al.* 2007). Changes to the global mean temperature can have strong reverberations throughout the Earth system as global warming is accompanied by strong regional variability which can bring new thermal extremes, shortened seasons, and altered atmospheric and oceanic circulations, all of which destabilize dependent systems like the biosphere, cryosphere, and hydrosphere.

2.1.2 Physical Impacts

Increases in global mean surface temperatures are enhancing the melting of land ice, which is increasingly contributing to eustatic (adding volume) sea level rise. Global land surface temperatures are also closely linked to ocean temperature, and global sea surface temperatures have warmed approximately 0.6℃ since the 1950s (*Bindoff et al.* 2007). As global surface temperatures have risen over the past century, the heat content of the oceans has risen too. From 1961 to 2003, the heat content of the upper 3,000 m has increased $14.2 \pm 2.4 \times 10^{22}$ J, which corresponds to an average warming of 0.037℃ (*Bindoff et al.* 2007). The increasing heat content of the global oceans is contributing to their steric (decreasing density) expansion, which is the major contributor to date of global sea level rise.

Warming of surface waters is also contributing to episodic coral reef bleaching, where a positive anomaly of roughly 1℃ over the seasonal average causes the death of symbiotic algae, whitening the reef structure. A 0.1℃ rise in regional sea surface temperatures leads to a 35% increase in geographic extent, and a 42% increase in intensity of bleaching events in the Caribbean (*McWilliams et al.* 2005). About 16% of the world's corals died during the exceptionally warm summer of 1998, most of them in the western Pacific and Indian Oceans (*Wilkinson* 2004). Reef bleaching leads to a decline in biological as well as structural diversity and a shift in fish species and coral species composition, though often anthropogenically-induced warm temperatures are only one stressor among a number of others, such as pollution and inter-decadal natural variability (*Rosenzweig et al.* 2007).

Warmer waters are also affecting managed and unmanaged fisheries throughout the global oceans, as patterns in net primary productivity are responding to regional temperature shifts (*Rosenzweig et al.* 2007; e.g. *Grebmeier et al.* 2006, *Walther et al.* 2002). Not only are fish moving, but so are the seabirds and marine mammals which depend upon them, as well as pathogens and invasive species (*Grebmeier et al.* 2006, *Walther et al.* 2002). In the northern Bering Sea, the climate is transitioning from arctic to subarctic, causing pelagic communities (fish) to move northward into historically benthic (sea ducks, marine mammals) territory (*Grebmeier et al.* 2006). Species' timing is also changing, as winters become less severe and shorter, and summers longer (*Walther et al.* 2002). Shifts in both life cycle timing and geographic relocation do not always agree across species, which can lead to a decoupling between trophic levels and functional groups, with cascading effects throughout the food web (*Edwards and Richardson* 2004).

Enhanced tropical cyclone activity is another byproduct of increasing sea surface temperatures, and cyclones have become more intense since 1970 in all ocean basins (*Webster et al.* 2005). Recovery from cyclones can be slow for economies and natural environments, increasing overall regional vulnerability to storm damage. For example in 2005, Hurricane Katrina destroyed 388 km^2 of wetlands, levees and islands surrounding New Orleans, thereby reducing the ability to the region to withstand future storms (*Barras* 2006). The economic cost of the storm exceeded 100 billion USD (NOAA 2007), and three years after Katrina's landfall, recovery efforts are still ongoing. Storms also impact coral reefs both through physical damage to the structures as well as by suspending sediments, which decrease the amount of light available for photosynthesis (*Rosenzweig et al.* 2007). More powerful storms are associated with greater reef destruction (*Gardner et al.* 2005), which can decrease coastline resistance to future storms and jeopardize reef communities. On average, coral cover is reduced by 17% in the year following a hurricane impact, and a reef will not show signs of recovery for about 8 years (*Gardner et al.* 2005).

2.1.3 Mechanisms of Change

Atmosphere Ocean General Circulation Models (AOGCMs) are a useful tool for detecting recent climate change, and attributing it to human activity. AOGCMs have found overall that simulations run with natural forcing alone cannot explain the observed temperature trends. Changes in anthropogenic greenhouse gases and aerosols must also be included (*Hegerl et al.* 2007). Quantitative attribution of recent (1900s to 1990s) warming to anthropogenic sources varies somewhat between models, but is about 0.9℃ for greenhouse gases and about -0.3℃ for other anthropogenic forcings (a net positive), with a negligible contribution from natural sources (*Hegerl et al.* 2007). These conclusions are robust, and were found using models of varying complexity and with multiple types of data analysis (*Hegerl et al.* 2007).

2.2 Sea Level Rise

2.2.1 Observed Changes

For most of human civilization, sea level has remained relatively constant. The end of the last ice age around 21ka brought about a rise in global sea level of about 120 m, a change which occurred over many thousands of years, and which stabilized two to three thousand years ago (*Bindoff et al.* 2007). During this stable period, the rate of sea level rise only varied between 0 to 0.2 mm yr^{-1} (*Bindoff et al.* 2007). Equilibrium lasted until the mid-19th century, whereupon sea level began to slowly rise (*Bindoff et al.* 2007), Figure 2.2. This rise was recorded first with tide gauges, and later using satellite altimetry (*Bindoff et al.* 2007). Together, these two methods are revealing a compelling acceleration of sea level change in recent decades. Tide gauges record sea level began rising in the 19th century, rose slowly in the 20th century (at a global average of 1.7 ± 0.5 mm yr^{-1}), and accelerated in the 21st (*Bindoff et al.* 2007). Satellite measurements since 1993 record an average global rise of 3 mm yr^{-1} (*Bindoff*

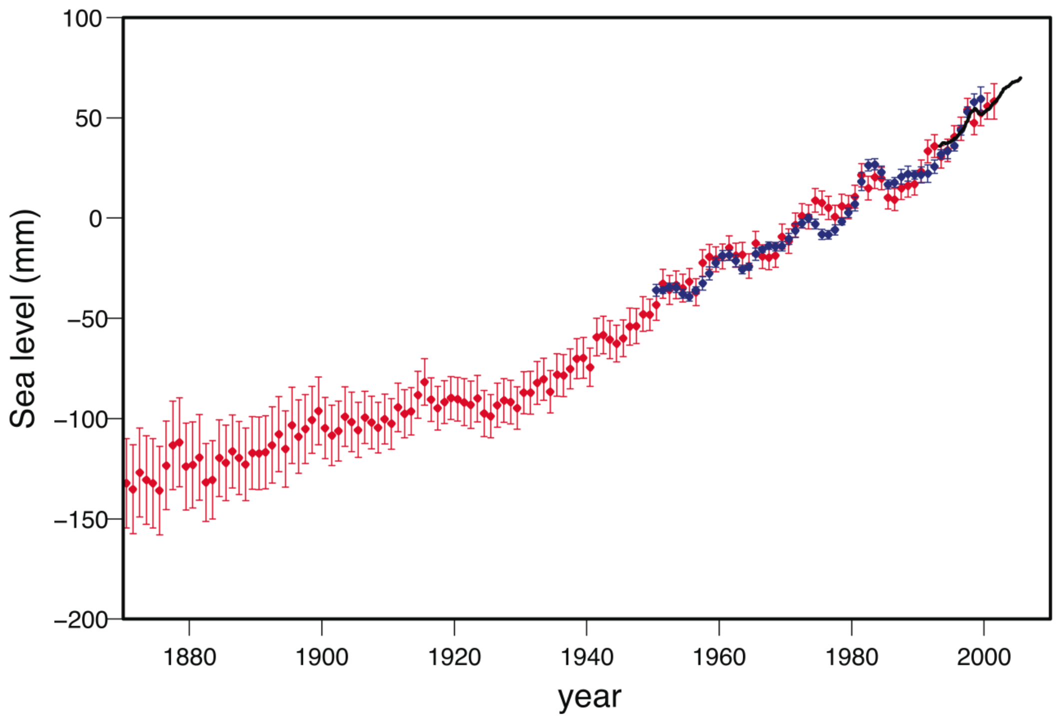

Figure 2.2: Annually-averaged global mean sea level (mm). The red curve shows reconstructed sea level fields since 1870 (*Church and White* 2006), updated by *Bindoff et al.* (2007). The blue curve shows coastal tide gauge measurements since 1950 (*Holgate and Woodworth* 2004). Both the red and blue curves represent anomalies from the 1961 to 1990 average. The black curve is derived from satellite altimetry, and represents the deviation from the average red curve for the period 1993 to 2001 (*Leuliette et al.* 2004). Error bars show 90% confidence intervals. Figure from *Bindoff et al.* (2007).

et al. 2007). There is significant spatial variability in the rates of this rise, which is likely due to non-uniform changes in temperature, salinity, and ocean circulation (*Bindoff et al.* 2007).

2.2.2 Physical Impacts

Global increases in sea level can work in combination with local changes due to other factors to create problems for communities, though it is not always possible to quantify their relative importance (*Rosenzweig et al.* 2007). Of primary consequence is alteration of the local geomorphology through coastal erosion. Erosion is exacerbated by rising sea levels both during storms and in the background, though alterations of other factors such as wave energy, sediment supply, land subsidence, sea ice cover, permafrost melting, human development, sand and coral mining, and mangrove destruction are also influential (*Rosenzweig et al.* 2007). For example, *Mimura and Nunn* (1998) found that sea level rise in combination with mangrove clearing has caused coastal erosion in Fiji from the 1960s onward. In addition to erosion, storm surges can become more damaging as sea level rises, as is observed on the U.S. east coast by *Zhang et al.* (2000). This implies that overall rising temperatures (contributing to more intense cyclone activity) will compound problems along coastlines experiencing rising sea levels and/or enhanced erosion, leading to ever more damaging storms. Immobile human infrastructure is vulnerable to changing weather patterns and encroaching seas, but natural systems are somewhat more adaptable. Coastal wetlands generally have the capacity to adapt to sea level rise, provided there is space to expand in to or if sedimentation keeps up with erosion (presently occurring in France and in parts of the UK) (*Haslett et al.* 2003, *van der Wal and Pye* 2004), but wetlands are lost if human development limits expansion or if other factors are at play (*Wolters et al.* 2005) e.g., channel dredging in New York City (*Hartig et al.* 2002), embankment build-up and bioturbation the UK (*van der Wal and Pye* 2004, *Wolters et al.* 2005, respectively).

2.2.3 Mechanisms of Change

Thermal expansion is the biggest contributor to global sea level rise. Between 1993 and 2003, the upper 3,000 m are estimated to have expanded 1.6±0.5 mm yr^{-1} (*Bindoff et al.* 2007), see Figure 2.3. This number reflects a significant acceleration, as estimates of a steric contribution between 1961 to 2003 are only 0.42±0.12 mm yr^{-1} (*Bindoff et al.* 2007). It is interesting to note that the uncertainty in the estimate of thermal expansion is greater for the 1993 to 2003 period than it is for 1961 to 2003. This might be due to the shorter modern time-series or the increasing influence of poorly understood eustatic contributors. Of the potential sources of eustatic sea

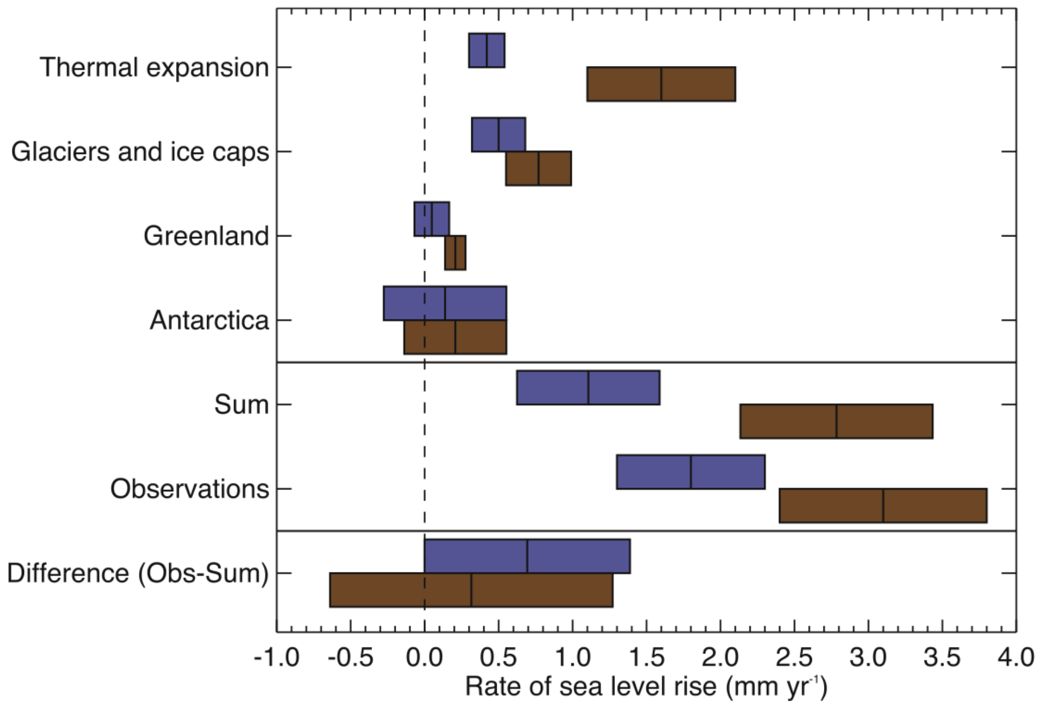

Figure 2.3: Estimated contributions to the budget of global mean sea level change (top four plots), the sum of these contributions and the observed change (middle plots), and the difference between observed and estimated change (bottom plot). Blue represents 1961 to 2003, brown is 1993 to 2003. Bars represent the 90% error range. Error for the sum is calculated as the square root of the sum of squared errors of the contributions. The difference error was calculated by combining errors of the sum and observed rate. Figure from *Bindoff et al.* (2007).

level change, the atmosphere is the least important, storing only about 35 mm of global mean sea level equivalent (*Bindoff et al.* 2007). Recent observations show only about 0.04 mm yr^{-1} trend in the atmospheric capacity, negligible relative to land-based reservoirs (*Bindoff et al.* 2007). Land ice is the largest reservoir, with glaciers and ice caps contributing 0.77±0.22 mm yr^{-1}, the Greenland Ice Sheet contributing 0.21±0.07 mm yr^{-1}, and the Antarctic Ice Sheet contributing 0.21±0.35 mm yr^{-1} from 1993 to 2003 (*Bindoff et al.* 2007). The large uncertainty in the last estimate is due to an incomplete understanding of the relevant processes and a lack of data; a discussion of the current understanding of Antarctic ice sheet dynamics can be found in Section 6.1.3.

Quantifying the contributions of other land sources (rivers and lakes, ground water, soil water, and snowpack) is difficult due to their small size and wide distribution (*Bindoff et al.* 2007). These reservoirs must be estimated using hydrological models forced with observations and general circulation models (GCMs) (*Bindoff et al.* 2007). These sources typically have large inter-annual and decadal variability which generally exceeds the sea level trend of 0.12 mm yr^{-1} (*Milly et al.* 2003). Anthropogenic alteration of these reservoirs is even more difficult to quantify; *Bindoff et al.* (2007) provides a good summary of what is known about human impacts. Generally, groundwater pumping disrupts the balance typically found in unaltered systems, and moves more water into the surface and atmospheric reservoirs, eventually leading to sea level rise. Wetland destruction also contributes to sea level as that water is no longer held *in situ*. Similarly, the loss of forested land removes water storage capacity, leading to more water becoming surface runoff which makes its way to the sea. Even irrigation in arid regions with continentally-isolated drainage basins can increase local evaporation, thereby leading to a net loss of water to the oceans. Dams, on the other hand, store water on land and can recharge groundwater stores, thereby having a negative influence on global sea level.

To what extent dams influence global mean sea level is open to debate; a recent paper by *Chao et al.* (2008) calls into question the observed acceleration of sea level rise over the 20th century, as well as the overall budgeting of reservoir contributions. By performing a careful accounting of the global water volume captured in reservoirs over the past century, *Chao et al.* (2008) claim global sea level would have risen steadily at 2.46 mm yr^{-1}, had a significant portion of the land runoff not been held back by dams. Furthermore, they estimate reservoirs have impounded an average of -0.55 mm yr^{-1} over the past century (more than previously estimated), which implies other sources of sea level rise are undervalued (*Chao et al.* 2008).

Highly variable, temporally brief datasets and widely distributed natural reservoirs under difficult-to-quantify human pressures, all in a large and complex system have led the IPCC's Fourth Assessment Report, to qualify their estimates of the global sea level budget as having so much uncertainty that it "has not yet been closed satisfactorily" (*Bindoff et al.* 2007). The Antarctic Ice Sheet is so poorly understood that models and remote observations are not in agreement of the *sign* of its eustatic sea level contribution, much less the quantity. When summarizing the contributions of Antarctic and Greenland ice sheets to sea level rise over the past century, the IPCC AR4 published a range from a small negative contribution to a large positive one (*Lemke et al.* 2007), which highlights the difficulties of accurately measuring these tremendous physical features. Anthropogenic influence on terrestrial reservoirs is even omitted from their final sea level contribution accounting due to the lack of information. The great difficulty (large spatial/temporal variability, spatial bias) of building a reliable dataset using tide gauges inhibit detection of global and long-term trends. The accuracy of these measurements themselves are called into question because calculations of decadal thermosteric contributions imply unlikely episodic and large contributions from land ice (*Bindoff et al.* 2007). From 1961 to 2003, thermal expansion is believed to have contributed about one-fourth of the observed global rise, while melting of land ice accounts for less than half (*Bindoff et al.* 2007). This leaves over one-fourth of the observed change in sea level over this period unexplained, which means either land sources are contributing more than previously thought, or that observed sea level rise is overestimated. This problem might be partly related to the significant North American bias in the data, especially since *Cabanes et al.* (2001) recently showed global mean sea levels are heavily impacted by changes in the Southern Ocean. Recent estimates are much better owing to our improving observational capabilities, and from 1993 to 2003 thermal expansion and land ice each contributed about half of the observed sea level rise (*Bindoff et al.*

2007). Whether tide gauges are overestimating variability (*Bindoff et al.* 2007) or mass contributors are underestimated or both, for the purposes of our study we elect to calibrate our reservoirs to the best estimates in the IPCC TAR and AR4, under the notion that these are the most robust estimates available.

2.3 Ocean Acidification

2.3.1 Observed Changes

Oceans are slightly alkaline, due to the minerals dissolved within them (*Raven et al.* 2005). Because CO_2 is slightly acidic, oceans take up the gas readily, playing an important role as a carbon sink. The rate of exchange between the atmosphere and the oceans is largely determined by the gradient in the partial pressure of carbon dioxide (pCO_2) between the two reservoirs, though other factors such as wind speed, precipitation, sea ice, heat flux and surfactants also determine carbon uptake (*Denman et al.* 2007). Ocean surface pCO_2 has increased alongside atmospheric CO_2 in recent decades, at a rate between 1.6 and 1.9 μatm yr^{-1} (atmospheric carbon has increased between 1.5 and 1.9 μatm yr^{-1}, basically equivalent given present uncertainty) (*Bindoff et al.* 2007), see Figure 2.4. The ocean-atmosphere pCO_2 gradient has also been increasing in recent decades; the annual flux of CO_2 gained 0.1 to 0.6 Gt yr^{-1} between the 1980s and 1990s (*Bindoff et al.* 2007). The exact capacity of the oceans to take up atmospheric carbon is unknown, but ever increasing concentrations will have corresponding decreases in buffering ability, and consequent decreases in pH. While currently no ill effects have been documented from a declining pH, globally oceans have decreased 0.1 units from the average acidity in 1750 (*Bindoff et al.* 2007,*Raven et al.* 2005). This rapid decline has important implications for life which has evolved in a slightly alkaline and relatively stable chemical environment. With the exception of rare events such as bolide impacts or methane hydrate degassing, pH has varied little over the past 300 million years and has never dropped more than 0.6 units below the pre-industrial value (*Caldeira and Wickett* 2003). Long time scales are important moderators of global mean pH; equilibration between the ocean surface and the atmosphere occurs quickly, in about 1 year (*Denman et al.* 2007), but downward migration via downwelling, occurs much more slowly. Global equilibration throughout the water column can take thousands to millions of years, depending upon the nature of the change (*Caldeira and Wickett* 2003). Of the estimated 118±19 GtC dissolved inorganic carbon (DIC) which has been added to the global oceans since 1750, almost half is still held within the upper 400 m (*Bindoff et al.* 2007).

2.3.2 Physical Impacts

Ocean acidification occurs when increasing concentrations of CO_2 in the atmosphere are accompanied by increasing concentrations in the oceans, where the CO_2 interacts with water and calcium carbonate ($CaCO_3$) to form bicarbonate (HCO_3^-), thereby lowering seawater pH and removing valuable carbonate (aragonite and calcite) from the ecosystem, (Equations 2.1 and 2.2).

$$CO_2 + H_2O \rightarrow H^+ + HCO_3^- \rightarrow 2H^+ + CO_3^{2-} \tag{2.1}$$

$$CO_2 + H_2O + CO_3^{2-} \rightarrow HCO_3^- + H^+ + CO_3^{2-} \rightarrow 2HCO_3^- \tag{2.2}$$

The dearth of evidence of physical impacts should not outweigh the potential for severe damage. Reduced carbonate concentration can affect the aragonite saturation state (*Raven et al.* 2005), and reduce calcification rates of calcifying organisms (*Raven et al.* 2005), (e.g. *Guinotte et al.* 2003). Planktonic and benthic calcifying organisms, and organisms using aragonite in their shells play an important role in marine food webs; increasing acidity and deficits in aragonite threaten these organisms and the species which depend on them (*Raven et al.* 2005).

Effects on calcifying organisms are fairly straightforward and replicated in the laboratory (e.g. *Ohde and Hossain* 2004); the interplay between other factors such

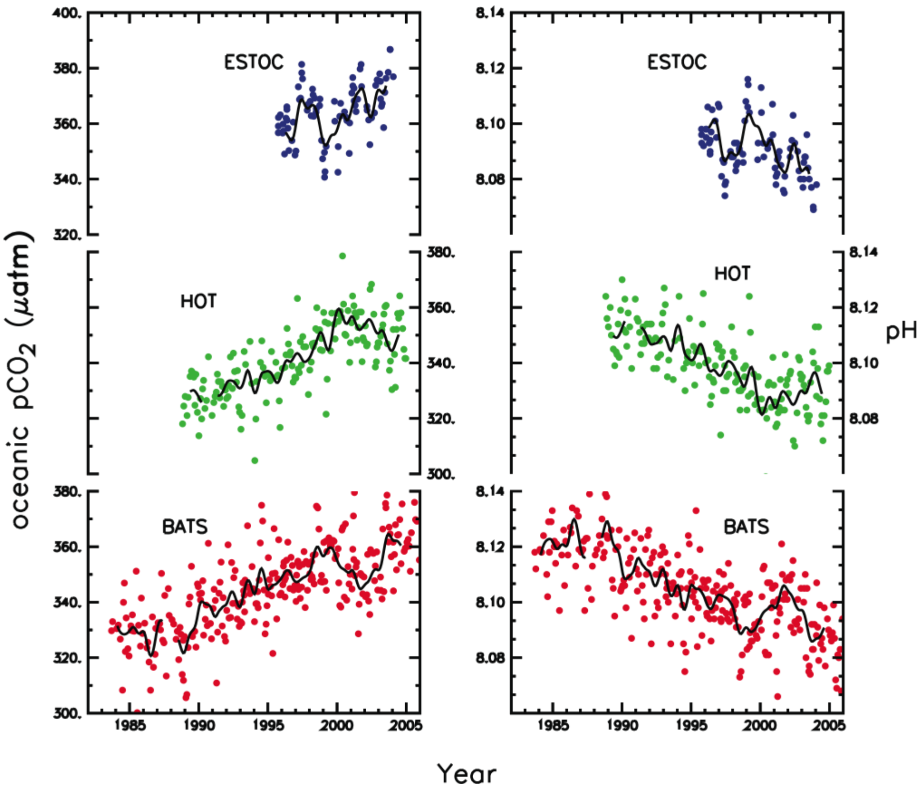

Figure 2.4: Changes in surface oceanic pCO_2, in μatm (left plot) and pH (right plot). Blue, green and red datasets are from European Station for Time-series in the Ocean (ESTOC, 29 °N, 15 °W; *Gonzalez-Davila et al.* (2003)), Hawaii Ocean Time-series (HOT, 23 °N, 158 °W; *Dore et al.* (2003)), Bermuda Atlantic Time-series Study (BATS, 31/32 °N, 64 °W; *Bates et al.* (2002), *Gruber et al.* (2002)), respectively. Values for both plots were calculated from dissolved inorganic carbon (DIC) and alkalinity at HOT and BATS; at ESTOC pH was measured directly and pCO_2 was calculated from pH and alkalinity. The mean seasonal cycle is removed from all data, and the black line is smoothed to remove variability over less than a 6 month period. Figure from *Bindoff et al.* (2007).

as nutrient settling and the carbon pump is poorly understood (*Raven et al.* 2005). Ocean acidification might enhance the dissolution of nutrients and carbonate minerals in sediments, which could act as a buffer (though only in the sediments along the sea floor) (*Andersson et al.* 2003, *Raven et al.* 2005). Other, less obvious impacts are also possible in an acidifying ocean. Water with a lower pH generally contains a greater proportion of freely dissolved forms of toxic metals, and while there is no evidence of ocean acidification yielding toxic speciation, it is theoretically possible

(*Raven et al.* 2005). Decreasing pH could also help to release iron into more soluble forms, providing a key limiting nutrient to calcifying organisms (*Raven et al.* 2005).

2.3.3 Mechanisms of Change

In addition to physical dissolution and mixing of CO_2, there are three carbon "pumps" in the ocean, which influence atmospheric concentrations (*Denman et al.* 2007), see Figure 2.5. The 'solubility pump' absorbs or releases CO_2 depending on the solubility of the gas (*Denman et al.* 2007). Along with downward mixing, this is the mechanism which dominates the uptake of anthropogenic carbon, as the rate of uptake is governed by the rate water is downwelled (*Denman et al.* 2007). The 'organic carbon pump' is limited by the availability of light and nutrients, and involves the fixation of carbon to particulate organic carbon (POC) via photosynthesis in the surface mixed layer, where after the particles descend downward (*Denman et al.* 2007). The POC is typically re-dissolved by bacteria before reaching 1,000 m depth (*Denman et al.* 2007). The 'calcium carbonate counter-pump' releases CO_2 in the surface mixed layer as a byproduct of the formation of calcium carbonate shells by phytoplankton (*Denman et al.* 2007). Calcium carbonate often sinks farther than POC before dissolving, and oceans are typically under-saturated with carbonate at depths below the mixed layer (*Denman et al.* 2007). All carbon entering the lower depths is either deposited as sediment or dissolved back into the water column (*Denman et al.* 2007). The dissolution of metastable carbonate minerals in sediments may act as a buffer in undersaturated bottom water, though there is no evidence this effect is felt in the water column above (*Andersson et al.* 2003). Upwelling brings the dissolved carbon back to the surface, where it outgasses to the atmosphere or is reused in biological processes (*Denman et al.* 2007). The organic carbon pump and carbonate counter-pumps play a secondary role in the uptake of anthropogenic carbon (*Denman et al.* 2007).

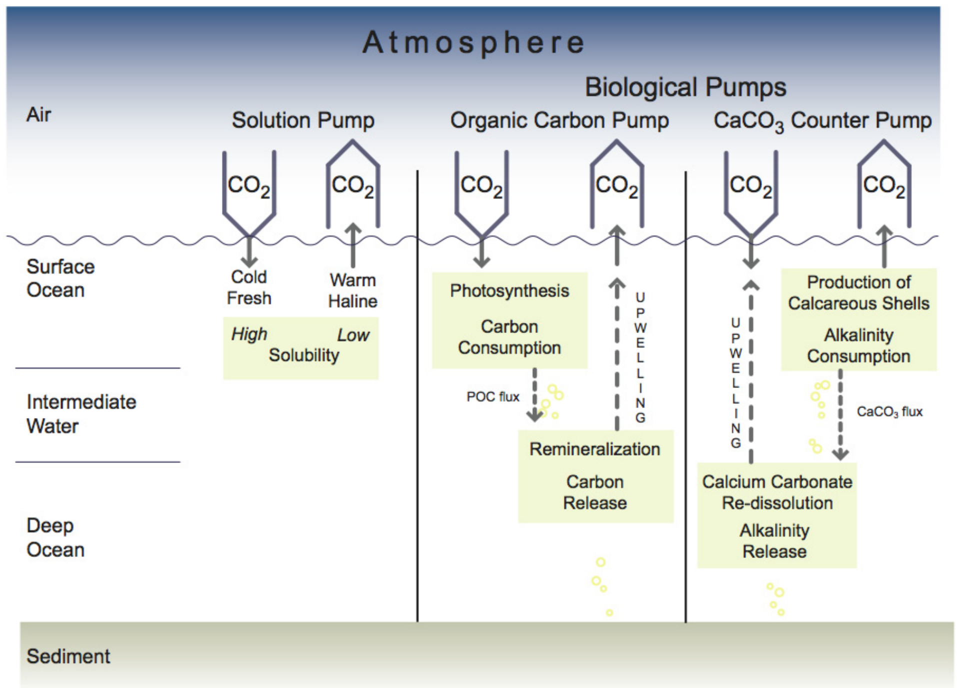

Figure 2.5: The three main oceanic regulatory carbon pumps that govern natural changes in atmospheric CO_2: the solubility, organic carbon and calcium carbonate 'counter' pumps. Oceanic uptake of anthropogenic CO_2 is dominated by inorganic carbon uptake at the surface and physical transport of the carbon to deeper layers. The biological pumps are not affected in the first order because they are regulated more by nutrient cycling, provided ocean circulation remains constant. If ocean circulation slows, anthropogenic carbon uptake is still dominated by the solubility pump and a positive feedback is established where slower sinking causes slower surface uptake, but carbon particles are able to reach greater depths before dissolving, causing a negative feedback in the biological pumps where more carbon is able to reach the ocean floor and be removed from the cycle. This negative feedback is not expected to be greater than the positive one, leading to reduced ability for the ocean to take up carbon over time. Figure from *Denman et al.* (2007) and adapted from *Heinze et al.* (1991).

Chapter 3

Projected Changes in the Marine Climate: Impacts on Humans and the Environment

Present climatic trends are expected to continue and even accelerate in coming decades. Experiments by a variety of general circulation models with a range of complexity are what projected changes in climate are based upon. The United Nations World Climate Research Programme (WCRP) has coordinated efforts between modelling groups through use of a standardized series of greenhouse gas (GHG) emissions pathways (the SRES scenarios[1]) in order to create more standardized projections, as well as to better understand uncertainties in the field (*Meehl et al.* 2007). Of the suite of models synthesized in the IPCC AR4, general agreement exists for rising air and ocean temperatures driven by anthropogenic forcing, continued melting of land-based ice with a net increase in sea level, and a declining pH globally (*Meehl et al.* 2007). How humans will be affected by and respond to these changes is difficult to forecast, so it is more useful to examine key vulnerabilities in human systems with the understanding that more vulnerable systems would be the first to weaken and the easiest to destabilize given altered climatic pressures. Limits to the degree of change

[1]The IPCC Special Report on Emissions Scenarios (*Nakicenovic and Swart* 2000) establishes several futuristic emissions pathways to the year 2100 for use in modeling climatic change. Each storyline represents different demographic, social, economic, technological and environmental developments (*Nakicenovic and Swart* 2000).

which would be acceptable to the global society have been set by the WBGU (German Council on Global Change), in an effort to stimulate discussion about regional and global vulnerability and social justice issues surrounding the changing marine environment.

3.1 Human Vulnerability to Marine Change

The effects of climate change on marine and human systems are and will remain highly variable with respect to location and socio-economic situation. Coastal zones (within 100 km of the coasts) are particularly vulnerable to climate change, as are the humans living within this band (at a density triple the global average). This vulnerability is expected to grow regardless of climate change; coastal zones are currently inhabited by one-quarter of the global population, and that figure is expected to rise to half by 2030 (*Small and Nicholls* 2003). Developing coastal nations are at a particular disadvantage when faced with climate change, as their economies are typically based more upon natural resources and agriculture (*Wilbanks et al.* 2007), and their populations face large socio-political and economic pressures.

The marine environment provides many goods and services upon which humans depend. Fisheries, energy, recreation and tourism, carbon sequestration and climate moderation, organic and non-organic waste removal and decomposition, coastal protection and many more benefits are derived from processes within marine ecosystems (*Fischlin et al.* 2007). These goods and services are sensitive to climate and are affected by changing conditions. For example, hurricane Katrina in 2005 polluted the U.S. Gulf Coast with a slurry of toxic chemicals, suffocated important oyster beds with mud, and put 4800 fishermen out of work (*Appel* 2005). Even non-marine human infrastructures can be adversely affected by changes to the marine climate. Transportation and energy supply infrastructure can be damaged by extreme events such as storms or flooding (*Wilbanks et al.* 2007); this damage can be exacerbated by rising sea levels and environmental degradation of natural buffers. Other infrastructure, such as municipal water supplies, can be stressed by increasing demand due to warmer temperatures and a growing population. Rapid depletion of groundwater resources can magnify saltwater intrusion and cause local subsidence, leaving a population more vulnerable to storm surges. Social systems can be disrupted by extreme weather events which shake up social networks, damage livelihoods and destroy homes and businesses (*Wilbanks et al.* 2007). Stresses on human systems, such as poverty or overpopulation, can be compounded by climatic change (*Wilbanks et al.* 2007). For example, extreme events such as flooding from hurricanes can lead to increased exposure of a population to other health risks, such as water pollution or disease (*Wilbanks et al.* 2007, e.g. *Appel* 2005). Damage from these events can be compounded by inadequate disaster response or a lack of recovery investment (*Wilbanks et al.* 2007).

Given our strong dependence upon the oceans, it is difficult to place economic value on their relative health. Ecosystem goods and services may be considered part of global capital assets, but tracking relative benefits and costs can be challenging in traditional economic frameworks, as environmental losses might overwhelm actual economic gains (such as extensive watershed pollution from a lucrative mining operation) and as agriculture and industry are inextricably linked to their surroundings (*Fischlin et al.* 2007). Economic losses worldwide due to natural disasters have climbed in recent decades, from 75.5 billion USD in the 1960s to 659.9 billion USD in the 1990s (UNDP). If socio-economic factors such as increasing per capita wealth and population growth in exposed areas are considered, loss trends are not so dramatic, but still present. *Wood et al.* (2006) demonstrated a 2% increase per year in economic losses due to catastrophes (cyclones, thunderstorms, hail, fire, flooding, etc.), though these data are biased towards large losses by hurricanes in the US and Caribbean between 2004 and 2005, and by the substantially greater wealth of the US compared to India (*Rosenzweig et al.* 2007).

3.1.1 Global Mean Temperature

AOGCMs project increasing anthropogenic influence on the climate system in coming years. Global mean surface temperatures could rise between 0.64 and 0.69°C above the mean 1980 to 1999 temperature by the time period 2011 to 2030, regardless of SRES scenario (*Meehl et al.* 2007), see Figure 3.1. Half of this warming has already been committed to (*Meehl et al.* 2007). As the century progresses, the amount of warming commitment made today will decrease in importance relative to the future emissions scenario pathway chosen, with global mean temperatures climbing around 1.3 to 1.8°C by the time period 2046 to 2065, depending upon the SRES scenario followed (*Meehl et al.* 2007). By the time period 2090 to 2099, global temperatures are quite different between SRES scenarios, and the current climate change commitment only comprises 20% of the future temperature (*Meehl et al.* 2007). Temperatures by the time period 2090 to 2099 could be between 2.8 and 4.0°C higher than the 1980 to 1999 mean, depending upon SRES scenario (*Meehl et al.* 2007).

Increasing global mean surface air temperatures could have profound effects globally. The corresponding thermal change in marine systems will also have profound effects on coral ecosystems, ocean stratification, and sea-ice ecosystems. As coral bleaching incidents are projected to increase in frequency and severity, this has dramatic implications for the 2-5% of the world fisheries harvest that reefs supply (*Pauly et al.* 2005). In coastal areas and ocean margins, increasing thermal stratification can lead to oxygen depletion, which causes a loss of habitats, biodiversity and species distribution (*Rabalais et al.* 2002). The reduction in sea ice biome area in polar waters by 42% and 17% in Northern and Southern regions by 2050 will likely result in large losses in net primary production, which could destabilize the entire sea-ice ecosystem and which would have consequences for both non-commercial and harvested species (*Fischlin et al.* 2007). Global net primary productivity is also likely to decrease be-

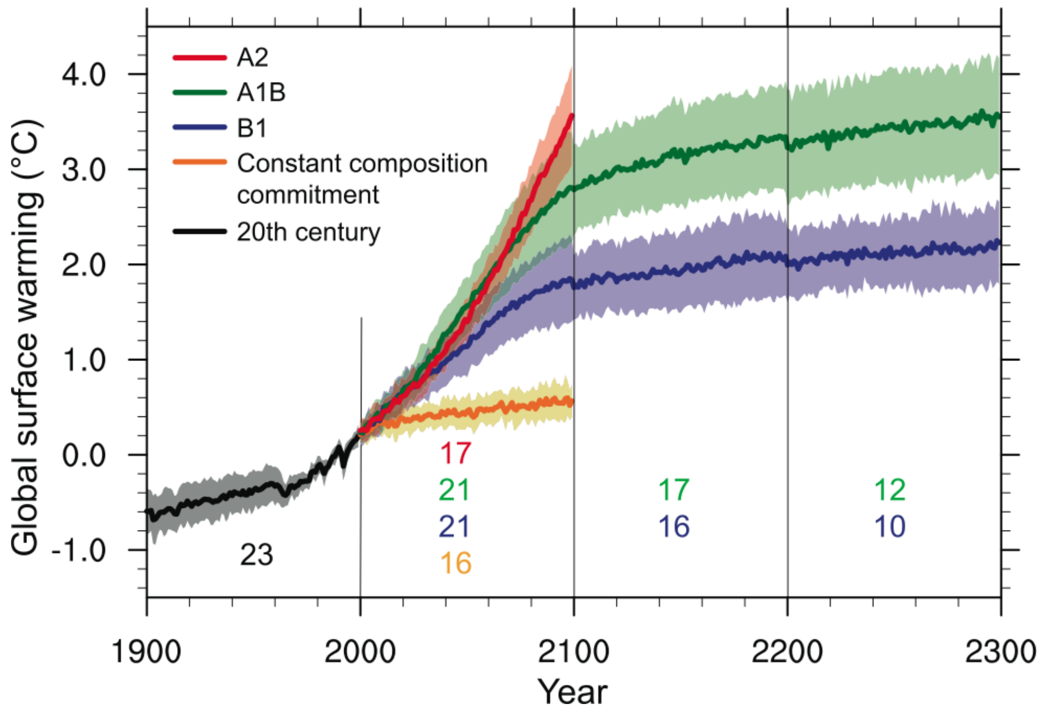

Figure 3.1: Projected multi-model mean surface warming relative to 1980 to 1999 for several SRES scenarios. Values beyond 2100 are for stabilization scenarios where emissions are held constant after 2100. Lines represent the mean, shading represents the ±1 standard deviation for individual models. Colored numbers denote the number of models run for each scenario. Figure from *Meehl et al.* (2007).

tween 0.7 and 8.1% by the mid-century, due to expansion of the sub-tropical gyre biome (4% in the Northern Hemisphere and 9.4% in the Southern Hemisphere), and the sub-polar gyre biome (16% in the Northern Hemisphere and 7% in the Southern Hemisphere), areas which typically have much lower productivity rates (*Fischlin et al.* 2007). Global drops in overall productivity are expected to result from lower primary productivity rates.

3.1.2 Sea Level Rise

Future projections of sea level rise suggest rates will continue to accelerate into the 21st century, with thermal expansion the dominant contributor but with land ice sources becoming increasingly productive (*Bindoff et al.* 2007), see Figure 3.2. How

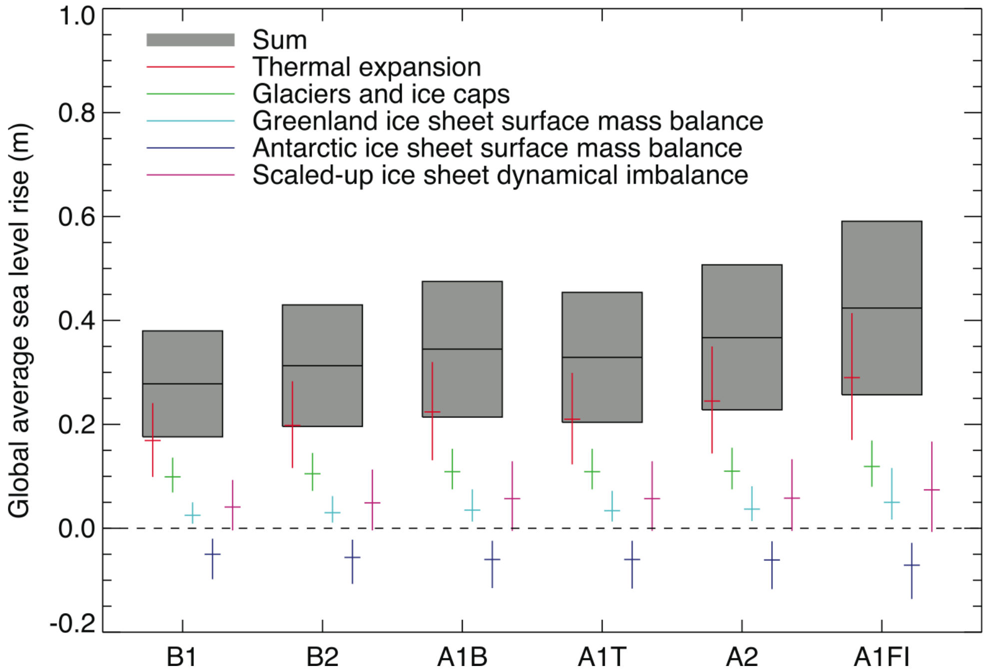

Figure 3.2: Projections of global mean sea level rise (shaded boxes) and its components (colored hatches) relative to the 1980 to 1999 mean. Shading denotes uncertainty (5 to 95% range). It is assumed that present observed ice mass flow acceleration will continue unchanged. Antarctic ice mass balance sensitivity is assumed negative (purple hatches), though for comparison increasing positive contributions are included (pink hatches). Figure from *Meehl et al.* (2007).

ice sheets, a potentially major contributor, will behave in the coming decades and centuries is only partly understood, so when and how they will alter global sea levels remains an open question. In Figure 3.2, the IPCC displays three alternative scenarios for ice sheet sensitivity; one where the ice sheet system becomes more balanced, one where the imbalance worsens, and one where the present observed imbalance does not change. It is unknown which scenario is most likely to occur, and in all cases sea level contributions will be greater than projected if ice discharge accelerates. Given an assumed persistent ice sheet sensitivity imbalance and depending upon SRES scenario, seas could rise between 0.18 to 0.59 m relative to the 1980 to 1999 time period over the next century (*Meehl et al.* 2007). The rate of rise also varies with scenario, but will very likely exceed the rate currently experienced (*Meehl et al.* 2007). Adaptability of human and natural systems to sea level rise is dictated more by the rate of rise than an absolute figure. Global sea levels rose 1.7$\pm$0.5 mm y^{-1} through the 20th century (*Bindoff et al.* 2007) and this rate may increase by a factor of 2.4 in the 21st (*Nicholls et al.* 2007).

Sea level rise is a consequence of climate change which, relative to more pressing effects such as drought or storm intensification, has been easier for decision makers to ignore due to its relevance on long timescales. Sea level rise taken alone is also relatively easy to adapt to for those who can afford to pay- infrastructure could be moved or modified and life would go on. The slow progression of the rise, relative to heat waves or wildfire or glacial melting, and the predictability of its rate in the near-term, means it lacks the compelling uncertainty of other global warming impacts. However, if sea level rise is examined on longer timescales (decades and longer) and in combination with the impacts from associated factors such as the rate of sea level rise, saltwater intrusion, increased storm surge heights, altered ocean circulation, etc., it becomes one of the most potentially problematic climatic consequences for future generations. For both human and natural systems, these are what ultimately limit our ability to adapt.

Future consequences from rising sea level depend heavily upon the SRES pathway followed, as environmental attitudes and socio-economics determine the adaptability of society more than actual sea level rise (*Nicholls* 2004, *Nicholls and Tol* 2006). *Nicholls and Tol* (2006) examined several SRES scenarios and found that in all scenarios the population exposed to sea level rise-induced flooding increases in the 21st century, and mitigation alone is insufficient to avoid impacts. A 40 cm rise in mean sea level by the 2080s could flood 100 million people per year for all SRES scenarios assuming no additional flood defenses are put in place (*Nicholls et al.* 2007).

Widespread flood protection would be a cost-effective response, and used in combination with mitigation could be an effective adaptation policy (*Nicholls and Tol* 2006). In general, small islands and low-lying deltas will be the most vulnerable to both flooding and wetland destruction due to future sea level rise (*Nicholls and Tol* 2006).

3.1.3 Ocean Acidification

As atmospheric concentrations of CO_2 are projected to increase into the future, global mean pH will continue to decrease; the IPCC projects between 0.14 and 0.35 additional units at the end of the next century (on top of the 0.1 decrease since 1750), depending upon SRES scenario (*Meehl et al.* 2007), see Figure 3.3. *Caldeira and Wickett* (2003) give a more pessimistic estimate, where they state that based upon current rates of change, we could see as much as a 0.5 unit drop in pH by 2100. These pH declines are of an order which might not have occurred for 300 million years (with the possible exception of reductions due to bolide impacts or methane hydrate eruptions) (*Caldeira and Wickett* 2003), and the rate of this change is possibly one hundred times faster than has been felt over that time (Raven et al.).

There is a great deal of uncertainty regarding effects as oceans continue to acidify. Both the physical and biological uptake of CO_2 by the oceans is dependent upon their density stratification and large scale circulation, so poor understanding of how these processes will change in a warming climate contributes to a poor understanding of the oceans as future carbon sinks (*Denman et al.* 2007). How ocean biota will react to a warmer, more acidic environment is also poorly understood, limiting our understanding of their future role in the carbon cycle (*Denman et al.* 2007). That being said, there is plenty of speculation based upon laboratory experiments and known vulnerabilities regarding how ecosystems *could* react to acidification. The regions which will be most effected are the Southern Ocean, which will experience calcium carbonate undersaturation during the latter half of the century for almost

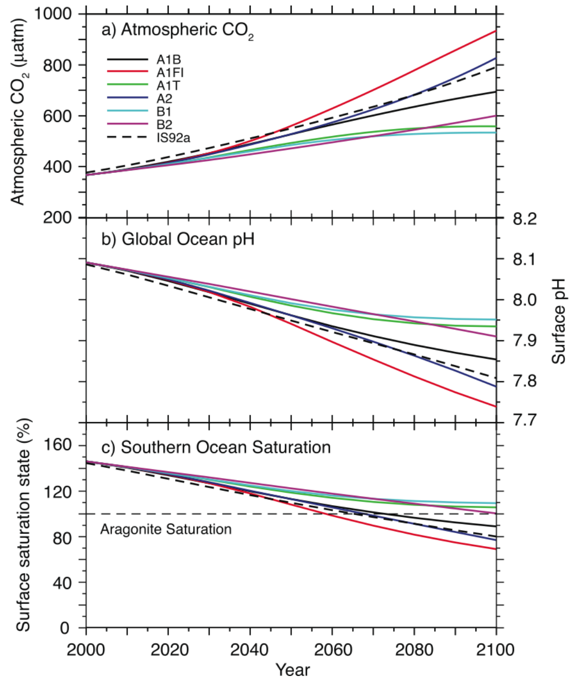

Figure 3.3: Changes in the global average surface pH and saturation state in the Southern Ocean under various SRES scenarios. Time-series are (a) atmospheric CO_2 concentrations for six SRES scenarios, (b) projected globally averaged surface pH, and (c) the projected average saturation state in the Southern Ocean with respect to aragonite. Figure from *Meehl et al.* (2007), and modified from the original in *Orr et al.* (2005).

all SRES scenarios, lower latitudes, and the deep ocean (*Meehl et al.* 2007), Figure 3.3.

Coral reefs in the lower latitudes are particularly susceptible to negative impacts from a decreasing aragonite saturation state. A reduction in their ability to build mass will reduce their ability to withstand erosion and compete for space, potentially decreasing their niche diversity and consequently decreasing the diversity in species which depend on them (*Guinotte et al.* 2003).

A lower saturation state will add another stress to coral communities already pressured by other factors such as pollution or warmer temperatures, pushing more into a marginal existence (*Guinotte et al.* 2003, *Raven et al.* 2005). Long-term changes in ocean acidity will affect coral growth on the same timescales, and could slow carbonate accumulation and lithification beyond the definition of what constitutes coral reefs (*Guinotte et al.* 2003). These changes can be considered permanent on human scales, as it would take tens of thousands of years for the carbon cycle to return to its pre-industrial state (*Raven et al.* 2005). How dim the future is for coral communities largely depends on their ability to adapt; fortunately, corals have proven extremely adaptable through geologic time, and may be able to accommodate drastic change, provided the rate is gradual (*Guinotte et al.* 2003).

Larger invertebrates and fish will also likely experience adverse effects from more acidic oceans. These animals use gills to respire, and have lower levels of CO_2 in their bodies than land-dwelling animals, which makes them relatively more sensitive to changes in CO_2 concentration (*Raven et al.* 2005). Acidic water causes their blood and tissues to become more acidic, which decreases the ability of their blood to carry oxygen and secrete excess ions (*Raven et al.* 2005). This state, called hypercapnia, has a rapid onset of a few hours (*Raven et al.* 2005). Hypercapnia is associated with a decrease in respiratory activity and reduced protein synthesis, which affects all aspects of the animals' lives (*Raven et al.* 2005). In general, widespread mortality or drastic reproductive changes are associated with pH levels outside the realistic range for the next century, so more detailed studies are needed regarding the effects of small acidity changes on fish and invertebrate populations (*Raven et al.* 2005).

The importance of avoiding widespread ocean acidification cannot be overestimated. While the direct effects on fish are largely uncertain, known adverse effects on coral reefs and calcifying organism populations could severely impact the food web upon which fish species depend (*Raven et al.* 2005). Coral reefs contain 25% of marine species (*Buddemeier et al.* 2004) and supply 2 to 5% of the annual global fisheries harvest (*Fischlin et al.* 2007), mostly in developing nations (*Pauly et al.* 2005). More than 2.8 billion people worldwide depend upon fish for 20% of their per capita annual animal protein intake (FAO 2006). Global fish production for food is projected to grow until the year 2020, but the demand for fish products will grow faster than supply (*Easterling et al.* 2007). While aquaculture is forecast to increase its market share relative to wild capture fishing (FAO 2006), even this production technique is vulnerable to climate damage due to its reliance on wild-caught seafood used in raising fish and Crustacea (*Easterling et al.* 2007). Industries such as tourism and fishing bring in millions of dollars annually to coastal nations, so maintaining coral reef health is crucial to national economies. The World Resources Institute estimates that in 2000, Caribbean coral reefs provided 3.1 to 4.6 billion USD in benefits to the global economy, and that by 2015 the loss of income might run into the hundreds of millions of dollars per year (*Burke and Maidens* 2004).

3.2 WBGU Guardrails

In light of growing concern about the present and future ocean state, the *WBGU* (2006) published a series of marine guardrails, or recommended boundaries on acceptable levels of anthropogenic alteration of the ocean system, for the purpose of giving decision-makers quantitative guidelines for sustainable development. These guardrails were calculated based on assessment of the science regarding ecological and societal impacts on marine and human systems from climate change, where crossing the guardrail would result in either immediate or future "intolerable consequences so significant that even major utility gains in other fields could not compensate for [the] damage" (*WBGU* 2006). The choice of using a negative guardrail (i.e., a threshold between acceptable and intolerable) stems from the difficulty in selecting a universally positive one (i.e., a specific optimal environmental condition). It is important to note that while respecting the WBGU guardrails will likely avoid the unacceptable changes addressed, it will not prevent all damage, and negative impacts will occur as conditions approach the guardrail. Furthermore, it should be noted that not all guardrails would be crossed simultaneously in a warming world. The complete set of guardrails recommended by the WBGU is as follows:

(i) Climate protection: The mean global rise in near-surface air temperature must be limited to a maximum of 2℃ relative to the pre-industrial value while also limiting the rate of temperature change to a maximum of 0.2℃ per decade. The impacts of climatic changes that would arise if these limits are exceeded would also be intolerable for reasons of marine conservation.

(ii) Marine ecosystems: At least 20-30% of the area of marine ecosystems should be designated for inclusion in an ecologically representative and effectively managed system of protected areas.

(iii) Sea level rise: Absolute sea level rise should not exceed 1 m in the long-term, and the rate should remain below 5 cm per decade at all times. Otherwise there is a high probability that human society and natural ecosystems will suffer non-tolerable damage and loss.

(iv) Ocean acidification: In order to prevent disruption of calcification of marine organisms and the resultant risk of fundamentally altering food webs, the following guardrail should be obeyed: the pH of near-surface water should not drop more than 0.2 units below the pre-industrial average value in any larger ocean region (nor in the global mean).

Of the four guardrails, all but one lends itself to the integrated assessment modeling described within these pages. Surface air temperature and sea level rise and rates of rise, and ocean pH guardrails are all easily incorporated into the model described in later chapters, but the percentage of protected marine ecosystems guardrail is ignored in our work because ACC2 cannot resolve ecosystems.

The temperature rise and rate of rise guardrails are based upon a plethora of potential adverse consequences for human and natural systems, and consider both gradual and non-linear impacts on human health, biodiversity, the displacement of ecosystems and their abilities to adapt, food production, water resources, and economic development (*WBGU* 2003). Large-scale singular events such as shutdown of the thermohaline circulation, instigating a runaway greenhouse effect, dramatic alteration of the Asian monsoon, disintegration of the West Antarctic ice sheet, and melting of the Greenland ice sheet were also thresholds considered in assigning this guardrail (*WBGU* 2003).

The WBGU recommendation that global mean sea level rise not exceed 1 m in the long term is based upon potentially severe and unavoidable consequences for humanity and natural coastal ecosystems (*WBGU* 2006). The absolute guardrail is more applicable to permanent structures like cities or world cultural heritage sites, while the rate guardrail applies to dynamic systems such as coral reefs or coastal wetlands (*WBGU* 2006). Impacts of the two guardrails are not independent; a rapid (slow) rate might cause less (more) tolerance for a long-term rise (*WBGU* 2006). Even with a slow rate of rise, however, a 1 m guardrail is still deemed by the WBGU to be maximal, and exceeding it would create significant flooding problems for coastal megacities such as New York City, Lagos and Kinshasa, and for densely populated mega-deltas (*WBGU* 2006). Smaller but culturally-significant cities such as St. Petersburg and Venice would also suffer from flooding and storm damage given a 1 m rise (*WBGU* 2006). At this level, some 900,000 people on small islands in the Pacific and Caribbean would also be subjected to larger and more destructive storm surges, and lose a significant proportion of their land (*WBGU* 2006), causing increased losses from storms and widespread social upheaval. The religious sites of Itsukushima in Japan and the Shore Temple in India are two cultural heritage landmarks which are threatened if sea level rises above 1 m (*WBGU* 2006). While moving the sites might be possible, it would subtract from their significance and cultural value (*WBGU* 2006). Natural world heritage sites would also be threatened by sea level rise exceeding this guardrail, such as Kakadu National Park in Australia and Sundarbans National Park in Bangladesh and India (*WBGU* 2006).

The WBGU sea level rate guardrail of 5 cm per decade is based upon vertical growth rates of coral reefs and mangrove forests (*WBGU* 2006). Corals grow vertically in optimal conditions at about 10 cm per decade, but mangroves have been modelled to lose habitat at a rate half of that (*WBGU* 2006). Even if this guardrail is respected, reefs and mangroves could have difficulty adapting to rising water levels if growing conditions are degraded by pressures from pollution, decreasing seawater acidity, habitat destruction, changes in temperature or other factors (*WBGU* 2006).

A lack of scientific understanding and the irreversible nature of ocean acidification led the (*WBGU* 2006) to invoke the precautionary principle[2] when assigning the pH guardrail. Their reasons are that past fluctuations in pH over the past 23 million years were little more than 0.1 units (*IMBER* 2005) and little is known regarding the impacts a larger variation might have on global oceans. Also of great concern is that a decrease of 0.25 pH could lead to parts of the Southern Ocean becoming undersaturated with respect to aragonite, which could have profound implications for global ocean carbon uptake and fisheries (*WBGU* 2006).

[2]This principle states that if the outcome of an action is potentially harmful to an unknown degree, the action should not be taken.

Chapter 4

A Historical Perspective on Climate Change Policy

Though the importance of carbon dioxide in regulating climate was recognized in the mid-19th century, it was not until the 1950s, when evidence from laboratory experiments, isotopic breakthroughs, and a greater understanding of geophysical processes coalesced in a political climate stirred by nuclear concerns, that a suspicion of problematic global warming arose in the scientific community (*Weart* 1997). Early research suggested that the oceans could take up carbon as fast as it was emitted and that atmospheric CO_2 and water vapor were opaque to infrared radiation, but work by Roger Revelle and Gilbert Plass in the mid-1950s showed that oceans are much slower sinks, and that gases in the upper atmosphere are less opaque than previously thought (*Weart* 1997). By 1960, Charles Keeling had released two years of careful measurements of carbon dioxide concentrations showing noticeable increases, which prompted calls for action by concerned scientists and official groups (*Weart* 1997). General environmental degradation began to attract more attention in the 1960s and 1970s, and climate change was swept into the broader category, often overshadowed by seemingly more urgent issues such as ozone depletion, acid rain, and nuclear disarmament. Since the establishment of coordinated efforts to address broad humanitarian and environmental international issues in the 1970s, climate change has assumed an increasingly important presence in global dialog. The United Nations has taken a proactive approach to dealing with the subject by establishing the Intergovernmental Panel on Climate Change (IPCC), which has served as the clearinghouse for the growing body of scientific knowledge and as the prime communicator of this knowledge to policymakers.

4.1 Concern About Carbon Dioxide

Comprehensive analysis of human impacts on the environment began in earnest in 1972, with the UN Conference on the Human Environment, which established assessment and management frameworks for environmental monitoring, education, research, and the free exchange of information. While climate change was not a primary concern of the 1972 conference, it was addressed in a publication prepared for the conference, the "Report of the Study of Man's Impact on Climate" (*SMIC* 1971). The Report called for greater monitoring of climate indicators, further study of past climates and increased modeling of climate dynamics, as well as more research into economic activities likely to influence climatic stability (*SMIC* 1971). The Report also included a section outlining the possible economic and social outcomes of changing climate and global pollution, as well as recommendations for dealing with such issues (*SMIC* 1971).

The 1971 Report and 1972 Conference may be considered the beginning of international dialog regarding climate change and global impacts of anthropogenic pollution. These efforts resulted in an assessment framework which laid the foundation of the IPCC, and established unprecedented international scientific and technological cooperation on complex socio-environmental issues.

4.2 Climate Stabilization and Limiting Emissions

As concern about carbon emissions and climate change grew, so too did calls to address the problem. Crossing a threshold of climate danger was a concept first addressed by *Schneider and Mesirow* (1976). The possibility of avoiding irreversible damage to the global climate was also posed by a United States government report "Energy and Climate" in 1977 (National Research Council NRC), as was the question of whether CO_2 emissions policy could be structured to achieve an "optimal" global climate (*Oppenheimer and Petsonk* 2005).

Climate change was not the only atmospheric issue of the late 1970s; concerns over pollution from supersonic aircraft, CFCs, and general interest in greenhouse gases spurred studies of climate-specific variation and change, and formed the basis for later international negotiations (*Oppenheimer and Petsonk* 2005). William Nordhaus, the developer of the economic model DICE which we use in our study, was one of the first to address questions of carbon emission policy optimization, and the economics of avoiding irreversible climate consequences and limiting CO_2 emissions (*Oppenheimer and Petsonk* 2005). He suggested that concentrations be kept within the "normal" range of variation over the Holocene, or that temperatures not be allowed to increase beyond 2℃ relative to pre-industrial (*Nordhaus* 1979).

In 1981, the White House Council on Environmental Quality (CEQ) issued two reports projecting a doubling of pre-industrial atmospheric CO_2 concentrations by the mid-2000s, which they predicted would have "marked" consequences for agricultural productivity, coastlines, and ecosystems (CEQ (a,b)). They also studied several fossil-fuel use scenarios based on limiting concentrations to 1.5, 2.0 and 3.0 times that of pre-industrial levels, and concluded that acceleration of fossil-fuel consumption would necessitate more dramatic decreases in the future to avoid crossing a CO_2 concentration ceiling (CEQ (b)). Stabilization of concentrations was ignored in the US, but four years later the UN Environment Programme, the World Meteorological Organization, and the International Council of Scientific Unions convened the International Conference on the Assessment of the Role of Carbon Dioxide and Other Greenhouse Gases. Their report included a series of emissions scenarios which stabilized CO_2 concentrations, and formed a committee to establish a framework convention (*Bolin et al.* 1986).

4.3 Setting Climate Targets

There are two main approaches to environmental policy which have influenced international environmental negotiation; one is based on environmental objectives, the other on political and economic feasibility (*Oppenheimer and Petsonk* 2005). As they relate to climate change, adopting an environmental objective approach would involve ceilings set for CO_2 *concentrations* and corresponding climate indicators such as temperature or sea level rise, whereas a politico-economic approach would adopt *emissions* targets. The US Clean Air Act is an example of regulation by environmental objective, where standards are set based upon their impacts on human health. The phase-out of ozone-depleting gases by the Montreal Protocol 1987 is an oft-cited example of a successful economic approach, which mandated (and achieved) reductions of the production and consumption of these gases.

In the wake of the Montreal Protocol, workshops resulted in a WMO (1988) report which called for a climate target of a "tolerable rate" of warming of no more than one-tenth of a degree Celsius per decade, and for no more than one or two degrees warming total relative to the pre-industrial temperature (*Rijsberman and Swart* 1990). These targets were based upon estimated impacts on natural systems and their ability to adjust (*Oppenheimer and Petsonk* 2005). When environmental targets were used in these early negotiations, language was sometimes added providing for economic preservation (e.g. Noordwijk Declaration). Also in 1988, a target based on political and economic considerations was introduced at a conference in Toronto, which called for a 20% reduction in industrialized countries' emissions from 1988 levels by 2005 (WCCA). While this approach focused on near-future emissions targets, it did recognize the longer-term necessity of stabilizing atmospheric concentrations, and recognized further reductions in global emissions would be necessary to meet this goal (WCCA).

The IPCC was established in 1988, and the Response Strategies Working Group (RSWG) addressed both atmospheric concentration and emission regulation approaches beginning with the first in a series of assessment reports in 1990 (IPCC RSWG). These assessment reports have become pivotal in international climate negotiation, and synthesize the growing body of work regarding relevant physical processes, social and economic impacts, and adaptability. The 1990 report did not make recommendations for policy action, but instead recommended a framework convention to develop protocol (IPCC RSWG). Before the framework convention was organized, the Second World Climate Conference (*Jager and Ferguson* 1990) issued a declaration that "the ultimate global objective should be to stabilize greenhouse gas concentrations at a level that would prevent dangerous anthropogenic interference with climate", and stated stabilization of emissions would be a first step towards stabilization of concentrations (*Oppenheimer and Petsonk* 2005). This declaration laid the foundation for Article 2 of the United Nation Framework Convention on Climate Change, which occurred in 1992 and which states:

> " The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow

> ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner." (*UNFCCC* 1992)

Agreement on the UNFCCC offered the strongest framework yet for international climate policy, and adopted the "safe corridor" concept, naming a set of emissions trajectories which would preserve options for stabilization of long-term concentrations at acceptable amounts (*Oppenheimer and Petsonk* 2005). This "safe corridor" was used in the Kyoto Protocol, which was the first legally binding GHG emissions budget, though the corridors were based more on feasibility factors and only indirectly on environmental consequences (*Oppenheimer and Petsonk* 2005). Agreement on the UNFCCC also activated the scientific and economic communities to construct a basis for interpreting Article 2, which so far has been done mostly under the direction of the IPCC (*Oppenheimer and Petsonk* 2005).

Chapter 5

Integrated Assessment and Decision-making Frameworks

Defining the 'danger' described by Article 2 of the UNFCCC is the cornerstone of international climate policy debate. Placing such a qualitative limit on a quantitative problem poses challenges, especially because decisions require coordinated international efforts over a highly subjective and politically sensitive matter. The science and theory of objectively assessing such complex problems has seen rapid growth in recent years, though these methods too are not altogether unbiased.

5.1 Interpreting Article 2 - what is dangerous interference?

Implementation of Article 2 first requires specific interpretation of its stated objective to "prevent dangerous anthropogenic interference with the climate system". Three indicators guide, but do not define, this dangerous interference:

(i) assuring that ecosystems can adapt,

(ii) food production is not threatened, and

(iii) economic development proceeds in a sustainable manner (*UNFCCC* 1992).

There is no universally accepted methodology for determining what level of climate change may be considered dangerous, and by whom, but that has not prevented experts from suggesting thresholds which they personally hold to be unacceptable

Table 5.1: Examples of dangerous climate change benchmarks proposed by researchers. All of these are 'external' definitions, or those which are created by acknowledged experts in related fields and which are based upon physical or social indicators. Adapted from *Dessai et al.* (2004).

	Danger measured in thresholds of physical vulnerability
1.	Large-scale eradication of coral reef systems (*O'Neill and Oppenheimer* 2002)
2.	Disintegration of the West Antarctic Ice Sheet (*Vaugh and Spouge* 2002)
3.	Breakdown of the thermohaline circulation (*Rahmstorf* 2000)
4.	Qualitative modification of crucial climate-system patterns such as ENSO and NAO (*Timmermann et al.* 1999)
5.	Climate change exceeding the rate at which biomes can migrate (*Markham* 2000)
	Danger measured in thresholds of social vulnerability
6.	Irrigation demand exceeding 50% of annual seasonal water usage for agriculture in northern Victoria, Australia (*Jones* 2000)
7.	Depopulation of sovereign atoll countries (*Barnett and Adger* 2003)
8.	Additional millions of people at risk from water shortage, malaria, hunger and coastal flooding (*Parry et al.* 2001)
9.	Destabilization of international order by environmental refugees and emergence of conflicts (*Homer-Dixon* 1991; *Barnett* 2003)
10.	World impacts exceeding a threshold percentage of GDP (*Fankhauser* 1995); (*Nordhaus and Boyer* 2000))

(*Dessai et al.* 2004). These suggested thresholds include local-to-global singular and accelerating effects, and involve both direct geophysical change, environmental and socio-economic responses (Table 5.1). These thresholds are not equally constraining; for example large-scale destruction of coral reefs will likely occur long before loss of the Atlantic Thermohaline circulation (*Nicholls et al.* 2007, *Schneider et al.* 2007).

A question regarding interpretation of Article 2 is at what spatial scale danger should be defined (*Yamin et al.* 2006). As an international document, is it constrained to global impacts, or should the smaller-scale be considered, and to what level? The broader and more immediate the negative impacts, the more likely it is that a phenomenon would be considered dangerous (*Oppenheimer and Petsonk* 2005). At the same time, if only global-scale impacts are considered, smaller-scale regional impacts might be neglected which could eventually have global consequences (loss of Arctic ecosystems, for example) (*Yamin et al.* 2006). It is likely that using a finer scale for interpreting Article 2 (say, at a provincial or state level) would lead to lower thresholds for acceptable change (*Yamin et al.* 2006). Accordingly, international consensus would become more difficult as more thresholds are permitted into the negotiation process (*Yamin et al.* 2006).

Because dangerous change is so hard to define, other approaches are used to address Article 2 which avoid definitions entirely. The European Climate Forum (ECF), came up with three "concepts of danger". These three concepts are:

(i) **Determinative dangers**, which are dangers that stand out as events having global and unprecedented consequences, such as extinction of iconic species or loss of entire ecosystems, loss of human cultures, water resource threats, or substantially increasing mortality levels.

(ii) **Early warning dangers**, or dangers already present in certain areas which are likely to spread or worsen with increasing warming. Examples of these include Arctic sea ice retreat, boreal forest fires, or increased incidences of drought.

(iii) **Regional dangers**, which are too regional to be considered determinative, but which still significantly impact food security, water resources, infrastructure or ecosystems.

These three concepts are meant to stimulate further discussion and dialog in the policy community, and were assembled as a response by scientists to requests from policymakers for assistance in framing climate impacts in the context of Article 2 (ECF 2004). The three criteria listed in Article 2 are implicit in these concepts, if it is assumed the global society shares similar beliefs regarding food production, ecosystems, and economic development. The absence of specific definitions leaves some subjectivity, particularly in the case of regional danger, where what might be considered determinative for one population (i.e., widespread drought in Australia) is inconsequential to another.

Similar to the ECF, the IPCC has adopted an alternative to specific definitions of dangerous thresholds in the form of assessments of key vulnerabilities (*Schneider et al.* 2007). They chose to do this with the perspective that scientists should only be descriptive, whereas proscriptions are outside their role and are the responsibility of politicians. Key vulnerabilities are the product of the exposure of systems and populations to climate change, the sensitivity of those systems and populations to such influences, and their capacity for adapting to them. Modifications in any of these criteria may affect the systems' or populations' vulnerability (*Schneider and Lane* 2006). Six objective and subjective criteria are suggested for assessing and defining key vulnerabilities: (i) Magnitude, (ii) Timing, (iii) Persistence and reversibility, (iv) Likelihood and confidence, (v) Potential for adaptation, and (vi) Importance of the vulnerable system. Key vulnerabilities may either be systemic (natural) thresholds, say shutdown of the Thermohaline circulation or loss of sea ice touching land where indigenous people depend on it for hunting (*Schneider and Lane* 2006). Key vulnerabilities may also be normative (social) thresholds, such as sea level rising beyond an acceptable level for those living on small islands (*Schneider and Lane* 2006). The use of criteria holds an advantage over the concept approach used by the ECF in that they are a tool which can be used to assess impacts as they arise, whereas the criteria behind the ECF concepts might not be clear enough for consistent assessments. Also, some (but not all) of the criteria are quantifiable, which aids in comparison between impacts in terms of relative danger, as well as assessment of impacts with respect to the guidelines in Article 2. Thresholds are also more easily applied to impacts which have been assigned some degree of consistent rating.

Within the efforts to define dangerous interference, two distinct paradigms dominate (Figure 5.1) (*Dessai et al.* 2004). The first is a "top-down" paradigm, which starts with scenarios for future socio-economic changes and uses them in hierarchical models, quantifying physical indicators of vulnerability such as water availability

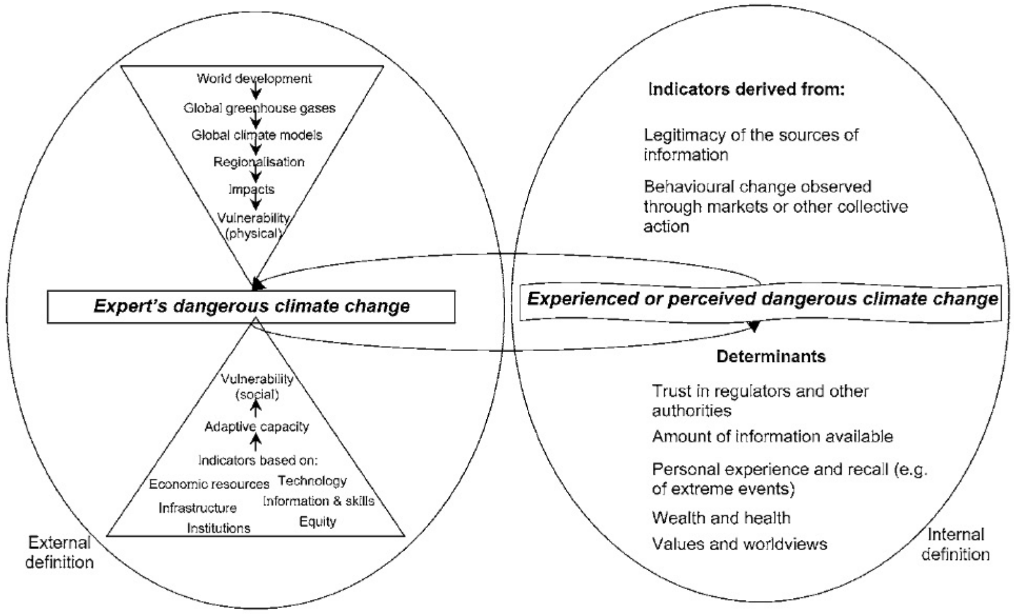

Figure 5.1: External versus internal definitions of dangerous climate change. Most integrated assessments use external definitions as they are more easily quantified and assimilated at a global scale. The exclusive use of external definitions, however, risks marginalizing minority opinions and has negative implications for human rights and social justice issues. Figure from *Dessai et al.* (2004).

or affected crop yields (*Dessai et al.* 2004). These types of assessments quantify danger in terms of the ability of the natural world to function, or in terms of people at risk or reduction in economic welfare, and often do not include adaptation strategies (*Dessai et al.* 2004). Article 2, the ECF concepts of danger, and most of the IPCC key vulnerabilities all fit this model. The "bottom-up" approach examines social vulnerability to present climate and future change by testing hypotheses on the determinants of vulnerability regionally and between social groups (*Dessai et al.* 2004). This approach focuses on the social indicators of vulnerability such as poverty, lack of education, access to health care, or levels of empowerment (*Dessai et al.* 2004). Adaptation potential as an IPCC key vulnerability fits within this category. The bottom-up paradigm addresses adaptive capacity implicitly, in contrast to the top-down paradigm (*Dessai et al.* 2004). Both methods, however, are "external" definitions of danger, as they are determined by experts according to normative criteria based upon descriptive theories of human behavior and decision-making (*Dessai et al.* 2004). "Internal" definitions, or those based on psychological, social, moral, or institutional processes which influence personal perceptions of danger and tolerable change should also be considered when formulating a universal definition of dangerous interference (*Dessai et al.* 2004). Internal definitions are determined by personal experiences, values and trust, and vary widely among social groups (*Dessai et al.* 2004). Internal and external definitions are not independent; individual perceptions of climate change vulnerability, for example, are largely based on the individuals' perceptions of the trustworthiness of informational sources (*Dessai et al.* 2004). Conversely, climate researchers' questions are often shaped by societal notions of unacceptable risk and intolerable consequences, whether through personal research interests or funding (*Dessai et al.* 2004).

The risk of relying exclusively on external definitions of danger is that in doing so, the interests of politically weaker socio-economic groups may be overlooked in favor of the interests of more powerful majorities (*Dessai et al.* 2004). For example, changing ocean chemistry and increasing ocean temperatures have already started to impact coral reefs, and episodic bleaching will likely become more frequent and severe. The economic consequences of coral reef destruction will likely be restricted primarily to developing nations and select tourist destinations, which will not garner the political force to achieve "dangerous interference" status in the international arena (*Oppenheimer and Petsonk* 2005). Additionally, loss of Arctic sea ice has already started to affect minority groups used to subsistence lifestyles, and even though present changes may already be considered dangerous by their members, little is being done by the international community to protect what they value. From an equity perspective, any climate change which has a greater impact on those who contributed the least to the problem is less just and potentially more dangerous in that it may destabilize political or economic systems (*Schneider and Lane* 2006). Utilizing both internal and external frameworks for defining dangerous climate change offers a means of maximizing democratic and just decision making (*Dessai et al.* 2004).

Establishing international consensus on what events and ongoing issues constitute "danger" will likely be one of the great diplomatic challenges of creating global climate policy, as climate change will be spatially and temporally heterogeneous and impacts will vary accordingly. Ultimately, any definition of danger will be up to politicians, as this will require value judgments, which are outside the role of the scientific community (*Schneider and Lane* 2006). In order to fill the gap between science and policy, some governments have commissioned organizations such as the German Advisory Council on Global Change, whose role is to recommend policy action based on sound science. Their guardrails, described in Chapter 3, are based upon a degree of climate change that the Council considers to have severe and irreversible implications for society, given the available scientific evidence. Their guardrails were defined with Article 2 in mind, and while the IPCC key vulnerabilities had not been published at the time the WBGU set its guardrails, their rationale behind the selection of guardrails closely follows these criteria. Also, the guardrails are global, but fit into all three ECF concepts because the WBGU seeks to avoid all determinative dangers and takes a precautionary approach to early warning and regional dangers, i.e. the pH guardrail seeks to avoid undersaturation of the Southern Ocean and the sea level rate guardrail seeks to preserve coastal mangrove and other highly vulnerable communities.

5.2 Implementing Article 2- decision making frameworks

Integrated assessments are studies which examine many facets (social, environmental, economic) of a particular complex problem. These studies have been used extensively to address climate change, and might offer a pure economic assessment of impacts (e.g. *Bosello et al.* 2007, *Tol* 2005), or examine strategies to achieve a particular goal. Achieving compliance with Article 2 in the near and long-terms is one such goal which has been applied in integrated assessment studies.

Implementation of Article 2 requires the conversion of environmental objectives into hypothetical GHG emissions pathways (*Oppenheimer and Petsonk* 2005). Such analyses often adopt an inverse approach, where boundaries on tolerable climate change are defined first, and then pathways are found which respect them. These pathways might be inferred from physical climate indicators such as global temperature, or limits on atmospheric carbon concentrations (*Oppenheimer and Petsonk* 2005). Either the physical indicators themselves or environmental or social impacts, such as keystone species loss or cultural damages, might be used as the starting point for finding these pathways (*Oppenheimer and Petsonk* 2005). Trade-offs between possible objectives require a means of weighing the relative costs and benefits of both climate change and climate damages (*Oppenheimer and Petsonk* 2005). Such analyses may be complicated when several criteria are used to judge emissions pathways, for while one pathway might respect one environmental objective, it does not necessarily respect another, say the long-term global temperature threshold is respected by several pathways but the rate of warming and the long-term goal are respected by a smaller subset. Several methodologies have been applied to this problem and are drawn from economics.

5.2.1 Cost-benefit analysis

Cost-benefit analysis (CBA) is one means of comparing emissions pathways, and its application to climate change was pioneered by William Nordhaus and colleagues (e.g. *Nordhaus* 1994, *Nordhaus and Boyer* 2000, *Keller et al.* 2000, *Nicholls and Tol* 2006, *Tol* 2003). Emissions reductions should occur only if the benefits of doing so exceed the costs, which opens CBA to criticism. Assigning monetary value to human life and then weighing this value against global economic output has troubling ethical implications. Depending on the criteria used to assign this value, not all human groups are likely to be valued equally, and those individuals who contribute less economically risk marginalization. In a similar vein, irreversible damages such as the loss of biodiversity simply cannot be easily monetized (*Corfee-Morlot and Hohne* 2003). Also, because climate impacts are aggregated globally, spatially heterogeneous degrees of severity are not accounted for. Another criticism is that low-probability but high-risk events such as collapse of the THC are not adequately addressed (*Azar and Lindgren* 2003, *Manne et al.* 1995). Also, positive secondary benefits to emissions reductions, such as improved air or water quality, are not considered (*Oppenheimer and Petsonk* 2005). Similarly, secondary negative effects from climate damage such as political instability are not adequately treated with CBA (*Oppenheimer and Petsonk* 2005). Lastly, cost-benefit analysis cannot represent the real human response to climate change because it is more likely that we will follow a strategy of learning and reacting (*Azar and Lindgren* 2003), whereas implementing a cost-benefit strategy assumes the ground rules will not change.

5.2.2 Cost-effectiveness analysis

A cousin of CBA is cost-effectiveness analysis (CEA), which seeks to maximize utility provided certain constraints on environmental variables (e.g. *Bruckner and Zickfeld* in press, *Keller et al.* 2000, 2005, *Nordhaus* 1994). This approach draws upon both economic optimization and sustainability frameworks (*Oppenheimer and Petsonk* 2005), and is useful for examining catastrophic thresholds. *Bruckner and Zickfeld* (in press), and *Keller et al.* (2000) use CEA to define maximal GHG emissions pathways which avoid serious weakening of the Atlantic THC. *Keller et al.* (2005) examine mass coral bleaching and melting of the West Antarctic Ice Sheet under this framework. Cost-effectiveness delays mitigation for the long-term future because this period is valued less than the present and near-future (*Hammitt* 1999). A weakness of this form of analysis lies in that deviation from the most effective pathway could lead to violation of a guardrail; if the guardrail concerns a high-stakes or irreversible consequence, the precautionary principle is violated.

5.2.3 Tolerable Windows

The Tolerable Windows Approach (TWA) is one methodology for simultaneously applying several criteria to limit the choice of emissions pathways (e.g. *Bruckner et al.* 2003, *Cameron et al.* 1997, *Petschel-Held and Schellnhuber* 1997, *Petschel-Held et al.* 1999, *Toth et al.* 2003a). Instead of trying to minimize the costs of mitigation and respect climate guardrails (as is done with CEA), the TWA tries to minimize climate change and respect mitigation (economic) guardrails. The approach creates a more objective range of solutions in order to satisfy a spectrum of political inclinations. Both population-based (e.g. *Kleinen and Petschel-Held* 2007, *Parry et al.* 2001) and sustainability approach (e.g. *Bruckner and Zickfeld* in press, *O'Neill and Oppenheimer* 2002, *Toth et al.* 2003b, *Wright and Erickson* 2003) versions have been applied to climate change (*Oppenheimer and Petsonk* 2005). The population based approach has been used to examine the changes in populations at risk for water shortages, hunger, malaria (*Parry et al.* 2001) and coastal flooding (*Kleinen and Petschel-Held* 2007).

There are strengths and weaknesses in both population and sustainability approaches. Adaptive capacity may be explicit in the population approach, which can be useful, but a drawback is that there is still no implicit definition of what is "dangerous", versus "really bad", so value judgments are still required. The sustainability approach is useful for defining danger as it relates to threats to unique systems and singular events by focusing on impacts which are so broadly negative few would disagree with their definition as dangerous (*Oppenheimer and Petsonk* 2005) (the ECF determinative concept of danger). Examples of these thresholds include disintegration of the WAIS, shutdown of the THC, or mass bleaching of coral reefs. *Bruckner and Zickfeld* (in press) investigate the stability of the Atlantic THC and use the TWA to find GHG emissions corridors which avoid not only systemic shutdown but also unacceptable economic hardship from mitigation. *Toth et al.* (2003b) examine pathways which avoid large changes in vegetation in protected areas. Uncertainty in the timing and scope of these thresholds can confound attempts at identifying distinct climate danger zones (*Oppenheimer and Petsonk* 2005), but invoking the precautionary principle and targeting the lowest plausible change value for temperature or concentration might aid decision makers (*Montgomery and Smith* 2000, *O'Neill and Oppenheimer* 2002).

5.2.4 Other frameworks

An emerging form of integrated assessment utilizes probability distributions (often in combination with CBA, CEA or TWA) to assess emissions pathways avoiding dangerous climate change, (e.g. *Kriegler* 2005, *Mastrandrea and Schneider* 2004, *Rahmstorf and Zickfeld* 2005, *Schneider and Mastrandrea* 2005, *Tol* 2005). Classical probability theory is difficult to use for describing problems with large amounts of uncertainty, so alternatives have been developed which offer ranges of probability as solutions rather than fixed values, (e.g. *Kriegler* 2005, *Rahmstorf and Zickfeld* 2005). *Mastrandrea and Schneider* (2004) look for ways to reduce the probability of reaching the extreme degrees of the IPCC TAR 'Reasons for Concern' (the predecessor to IPCC AR4 key vulnerabilities). *Rahmstorf and Zickfeld* (2005) calculate emissions corridors which safeguard the thermohaline circulation to within a certain degree of probability. Incorporating uncertainty implicitly is useful for assessing risk and for application of the precautionary principle. This method also addresses the weakness of the above frameworks in that it can also capture high-risk, low probability, nonlinear climate impacts in an economically meaningful manner.

Non-quantitative and non-utilitarian frameworks have also been proposed to address humanitarian issues such as equity, justice and human rights (*Oppenheimer and Petsonk* 2005), (e.g. *Brown* 2003, *Gardiner* 2004, *Tonn* 2003). *Tonn* (2003) proposes that an equity-first approach be used where each individual on the planet is allowed an equal share of GHG emissions. These emissions rations would be progressively reduced in order to manage three categories of risk (substantial regional and global environmental or social impacts, and extinction of humans) in a socially-accepted way. *Brown* (2003), and *Gardiner* (2004) both suggest an open discussion of ethics and justice is lacking in the current study of climate change, and these important issues risk being overlooked if not given explicit treatment in international dialog and research. They do not, however, offer means of evaluating various ethical viewpoints or suggest ways of facilitating consensus. These more subjective approaches rely on personal and group perceptions of unacceptable risk and are therefore less conducive to international deliberations, though may be useful given further development.

5.2.5 General criticisms

There are several common complaints made about integrated assessments conducted in the frameworks mentioned above, many of which are focused on (but not limited to) the DICE model used in our study. Aside from the criticisms mentioned in previous sections, the value selected for the time discounting rate is one of the more contentious issues; this rate refers to the discount on future 'utility', or welfare, and measures the importance of the welfare of future generations relative to the present one (*Nordhaus* 2007). A discount rate of zero means the welfare of all generations is considered equal, while a positive rate weights the present generation's well-being as more important to that of those in the future (*Nordhaus* 2007). Market data suggest this rate to be about 0.03 yr^{-1}, though not all analyses use the market rate (for example, recently *Stern* (2007) used a rate of 0.001 yr^{-1}). The use of empirically-based discount rates generally suggests limited mitigation in the near-term, with larger mitigation efforts in the distant future. This is a problem because while human behavior reflects a thought process based in human lifetimes, it does not account for the millennial scales of drastic climate alteration, and could therefore lead to policies which bring us dangerously close to causing effectively irreversible and catastrophic environmental damage. The use of discount rates determined based upon ethical standards or a strong desire to avoid catastrophic climate damage may lead to very different GHG emissions pathways, so how this value is determined also decides the results of the assessment.

Another common simplifying assumption in integrated assessment models is one of exogenous technological change, where the technologies used to improve energy efficiency or transition to alternative fuels are developed with money set aside for research and development (R&D) of these technologies. This separate, external funding makes mitigation prohibitively expensive compared to adaptation. Using endogenous technological change (the idea of learning-by-doing, where technological progress occurs regardless of changing conditions) can significantly lower estimates for mitigation costs (e.g. *Edenhofer et al.* 2005, *Grubb et al.* 1995, *Janssen and De Vries* 2000, *Schwoon and Tol* 2006), and it also differentiates various mitigation techniques in terms of importance (*Edenhofer et al.* 2005). Endogenous technological change makes improving energy efficiency less desirable than moving away from fossil fuel use altogether, because with the ability to learn-by-doing it is possible to implement new technology in increasingly cost-effective ways (*Edenhofer et al.* 2005). Evidence from the real world energy market suggests that the industry operates with a combination of exo/endogenous development; (*Grubb et al.* 1995) cite Japan as an example of a country which experienced rapid growth in R&D in the 1970s and 1980s as a reaction to the oil shocks of 1973. While the government provided some of the investment funds, it was a pittance compared to other developed nations. The drive for greater energy efficiency inspired research into all aspects of technology, making Japan one of the most technologically advanced societies by the late 1980s (*Grubb et al.* 1995).

Part II

New Work

Chapter 6

Model Description

Aggregated climate/economy models have been used to investigate optimal carbon emissions pathways which avoid dangerous climate thresholds in thermohaline circulation strength (e.g. *Bruckner and Zickfeld* in press, *Keller et al.* 2000), sea level rise (e.g. *Bosello et al.* 2007), global temperature (e.g. *Keller et al.* 2005), and coastal flooding (e.g. *Kleinen and Petschel-Held* 2007). To our knowledge, this is the first application of this type of coupled model to a comprehensive trio of marine climate indicators (global mean temperature, sea level rise, and pH), and the first use of global mean pH change in cost-effectiveness and tolerable windows analysis. The models used are the Aggregated Carbon Cycle, Atmospheric Chemistry and Climate Model (ACC2 - *Tanaka and Kriegler* 2007) and the Dynamic Integrated Climate-Economy Model (DICE - *Nordhaus* 1994). The former model is the latest version (3.0) and is a descendant of the ICLIPS Climate Model (ICM) developed by *Bruckner et al.* (2003). DICE is a global aggregated economic model developed by William Nordhaus (*Nordhaus* 1994, *Nordhaus and Boyer* 2000). Both models have a history of use in integrated assessments, though have not been coupled to each other previously. Both ACC2 and DICE are written in the language and programming environment GAMS (General Algebraic Modelling System), a platform useful for solving optimization problems (*Brooke et al.* 1992).

6.1 ACC2

Optimization problems require large computational resources which balloon with long time-series. The simplicity of ACC2 provides a useful alternative to more complex models, making it ideal for multi-scenario, long-term runs. It was selected for this study both for its efficiency as well as the ease of coupling it to DICE, and because it is a relatively new model, improved beyond it's predecessor ICM. A complete description can be found in *Tanaka and Kriegler* (2007), but the basic elements are shown in Figure 6.1 and are described as follows: it is a reduced carbon cycle climate model which uses impulse-response functions (IRFs) [1] to describe the behavior of state variables. Multi-gas chemistry is included in ACC2 and includes radiative forcing for CO_2, CH_4, N_2O, 29 halocarbons, SF_6, SO_2, tropospheric and stratospheric ozone, direct effects of sulfate and carbonaceous aerosols, indirect effects of all aerosols, stratospheric H_2O, OH, NO_x, CO and VOC. This is an improvement over ICM, which contains less chemistry. Like ICM, ACC2 is a globally-aggregated model with an annual iteration. It contains separate spin-up (1750 to 2000) and forward (2000 onward) modes, which for our study we run from 2000 to 2100. ACC2 assumes an equilibrium state prior to 1750. While this follows the lead of larger GCMs, it may not be accurate given a constantly changing earth system (*Tanaka and Kriegler* 2007). It is important to note, therefore, that the pre-industrial condition must be considered quasi-steady state.

The spin-up mode utilizes an inverse approach[2] to calculate starting points in

[1]Impulse Response Functions are the measured temporal response of a state variable calculated from the perturbation of the control run of a more complex model (in this case, the European Centre Hamburg Model 3-Large Scale Model (ECHAM3-LSG))(for a detailed description of IRFs, see *Hooss et al.* (2001)). IRFs are calculated using empirical orthogonal function analysis (EOFs), where spatial patterns in state variables relative to global mean temperature are extracted from a GCM and superimposed on the simpler model. The advantage of using IRFs is that by "tuning" the output from the simple model to the output of the more complex one, it is possible to achieve the results of the complex model more cheaply and with greater agility. The IRF approach has a history of use in integrated assessments, and is the basis of ACC2 as well as ICM (*Bruckner et al.* 2003).

[2]The inverse calculation scheme in the ACC2 spin-up mode estimates uncertain properties in

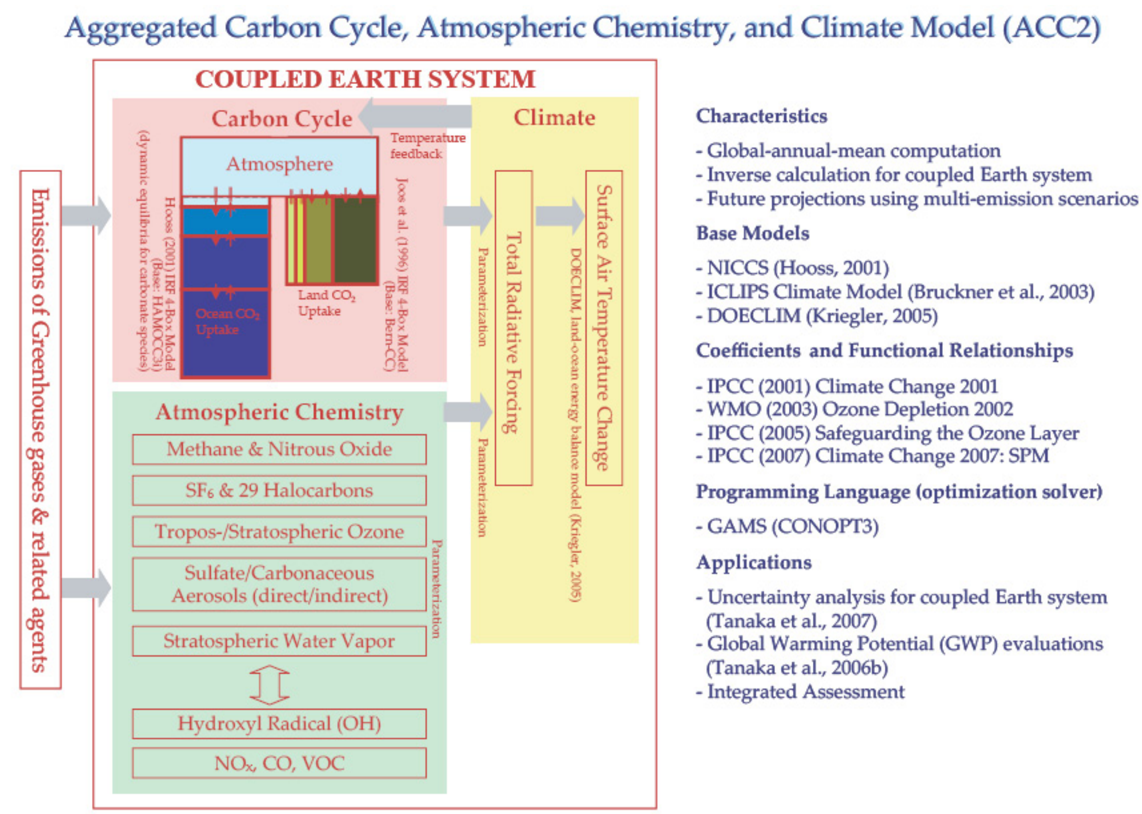

Figure 6.1: Schematic of ACC2. Figure from *Tanaka and Kriegler* (2007).

the year 2000. The forward mode uses SRES scenarios for anthropogenic radiative forcing by GHGs until the year 2100, and then holds GHG emissions other than CO_2 and SO_2 constant. CO_2 and SO_2 emissions were originally calculated like the other GHGs in the model, but we have modified ACC2 to allow DICE to calculate emissions as a function of economic welfare. ACC2 makes a distinction between CO_2 emissions from land use change (anthropogenic afforestation, deforestation, agriculture) and those from fossil fuel combustion (consumption, production, gas flaring, cement production). Coefficients and functional relationships in ACC2 reflect *IPCC TAR WG1*, *Joos et al.* (2001), *WMO* (2003), and *IPCC* (2005). The most recent IPCC assessment report (*IPCC AR4 WG1*) reflects no change in these coefficients and functional relationships from the previous report, and so the model is in accord

the Earth system using various measurements in the spin-up mode, parameters, and functional relationships, which are then used to re-calibrate the model as additions are made to the structure. This inverse calculation is what determines the model state for the future mode.

with most recent published findings.

6.1.1 DOECLIM

In addition to the physical interpretation of IRFs, ACC2 improves upon the surface temperature calculation in ICM by including an alternative: a land-ocean Energy Balance Model (EBM), the Diffusion Ocean Energy balance CLImate Model (DOECLIM). DOECLIM calculates the surface air temperature explicitly from the radiative forcing, thereby providing greater capability for exploring secondary climate variables like sea level rise. DOECLIM is calibrated using seasonal data to estimate coefficients, a constant mixed layer depth from the AOGCM MAGICC, and CO_2-doubling experiments from the AOGCM CLIMBER-2. The two modelling approaches (IRF vs. DOECLIM) are selectively activated with a switchboard file, allowing the user to choose a setting which maximizes computational efficiency while expanding flexibility in the carbon cycle box models.

The structure of ACC2 is simple, but there is a great deal of flexibility in the calculation of individual parameters. Overall, the climate sensitivity can either be calculated using the inversion scheme, or set manually. In the atmosphere, CO_2 concentration is determined by anthropogenic emissions and fluxes into the ocean and land boxes. In the past mode anthropogenic emissions are parameterized with the inversion scheme, and in the forward mode they are prescribed from SRES scenarios. Solar forcing may either be included in future radiative forcing or neglected. Net terrestrial carbon storage change (change in physiological processes such as photosynthesis and respiration) is calculated as carbon uptake, and can either be held at a pre-industrial constant (calculated by the inverse mode) or be made dependent on global temperature. Emissions of CO_2 due to soil erosion, changes in nutrient availability and the water cycle are not explicitly modeled due to large uncertainties. Perturbation of NPP due to CO_2 fertilization is parameterized using set factors for respiration, decay and decomposition, and compared to IRFs for the inversion scheme. Like terrestrial carbon storage, NPP can be held constant or calculated explicitly in the forward mode. Ocean CO_2 uptake parameters are also calculated using IRFs, and have the option of explicit calculation of some dependent factors. Explicit calculation of the thermodynamic equilibria is one such option within DOECLIM. Ocean carbon uptake is limited to a simplified solubility pump (without geologic-scale dissolution and precipitation) and a first-order approximation of the carbonate pump (via thermodynamics); soft-tissue and full carbonate interactions are ignored. Vertical diffusivity of heat downwards into the ocean can either be set as a parameter of the inverse calculation, or prescribed by the user. Carbon exchange between reservoirs is assumed constant before year 1750, whereupon the inverse scheme is used to calculate exchange rates for the spin-up mode. Pre-industrial fluxes may either be included or left out of the carbon cycle.

In addition to direct calculations, uncertainty within the carbon cycle is also flexible within ACC2. Both 'best-guess' and precautionary estimates are available to the user for the past mode uncertainty ranges in CO_2 emissions from land use change, post-1959 atmospheric CO_2 concentrations, and other GHG emissions and concentrations. Setting the uncertainty regarding the degree of influence of ENSO on past atmospheric CO_2 concentrations and global temperature is also an option.

6.1.2 Modifications to ACC2

We have modified ACC2 for the purposes of our study. We updated the sea level calculation to solve a problem with contributions from glaciers and small ice caps which limited the length of runs (*Tanaka and Kriegler* 2007), and to explicitly calculate thermal expansion as described in *IPCC TAR WG1*, Appendix 11.1. In all versions of ACC2, contributors to sea level rise are the continuous and past loss of mass from Greenland and Antarctic ice sheets (GIS and AIS, respectively), thermal expansion, the loss of mass from glaciers and small ice caps, runoff from thawing permafrost, and sediment deposition on the sea floor. The contribution g, from glaciers and small ice caps, was previously calculated in ACC2 using the parameterization from *IPCC TAR WG1*, Appendix 11.1, where g_u is the loss of mass with respect to the glacier steady-state without consideration of area contraction and is derived from an integration of global temperature with respect to time.

$$g(t) = 0.934 g_u(t) - 1.165 g_u^2(t) \tag{6.1}$$

This is an empirical relationship taken from a quadratic fit to the AOGCM scenario IS92a (*IPCC TAR WG1*, Chapter 11). This relationship holds until around 2160, whereupon the second term grows larger than the first and glaciers and small ice caps show net growth, an unphysical result (see blue line in Figure 6.2). Tanaka (unpublished) since modified the calculation to use Equation 6.1 until the year 2100, whereupon further melting stopped and glacier and small ice cap contribution remained constant at 2100 levels (see pink line, Figure 6.2). This provides a quick fix and allows for the extension of the model, but makes glacial sea level equivalent dependent upon emission pathway. To solve this dilemma, we implemented a smoothing function after a critical level of sea level rise ($g_{critical}$, with a corresponding temperature $T_{critical}$) where contribution to sea level rise from glaciers and small ice caps follows an exponential curve to a prescribed maximum. This smoothing function is displayed in Figure 6.2 as the black line, and also as Equation 6.2, where g_{smooth} is the difference between the prescribed maximum sea level rise and $g_{critical}$, and s_{init} is the slope of the function immediately before $g_{critical}$.

$$g(T) = g_{critical} + g_{smooth}(1 - e^{\frac{s_{init}}{-g_{smooth}}(T - T_{critical})}) \tag{6.2}$$

IPCC AR4 WG1 estimates the total potential sea level contribution from glaciers and small ice caps to be between 0.15 and 0.37 m. We selected the values of $g_{critical}$ (0.28 m relative to pre-industrial equilibrium, of which 0.03 m had already occurred

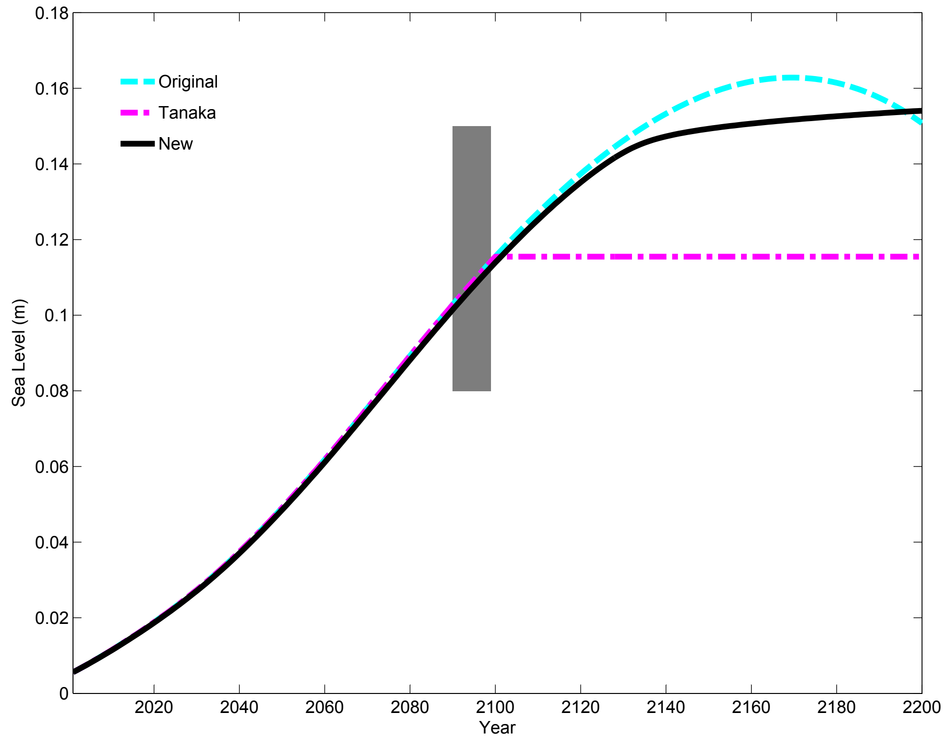

Figure 6.2: Contribution to global mean sea level by glaciers and land ice other than ice sheets. The first version of ACC2 used a parameterization from *IPCC TAR WG1*, which was only applicable until around year 2160 (denoted blue line). Tanaka (unpublished) updated the calculation to stop contributing at year 2100 (denoted pink line). We altered the calculation with a smoothing function to cause glaciers to slow their annual contribution until reaching a finite total amount (denoted black line). All curves are plotted using the A1B scenario for non-CO_2 GHGs. The gray bar denotes the *Meehl et al.* (2007) 90% confidence interval estimate of glacier contribution to sea level rise for the A1B scenario, averaged between 2090 and 2099, relative to the 1980 to 1999 mean.

by 2000 in ACC2) and g_{smooth} (0.07 m) based upon these estimates, so that total glacial contribution would not exceed 0.35 m for any scenario. In this new method, Equation 6.1 calculates glacier contribution to sea level rise up until the $g_{critical}$ value is reached, whereupon it is replaced by Equation 6.2. Having a continuous sea level contribution for glaciers and small ice caps is a more realistic parameterization than previous attempts and allows us to set a guardrail for use in DICE.

Another modification we made to ACC2 is to update the calculation of thermal expansion, which was based upon surface temperature IRFs. Calculating thermal expansion from the ocean thermal profile was called for by *Tanaka and Kriegler* (2007), as one of the next logical steps to improving ACC2. We used the parameterization in *IPCC TAR WG1*, Appendix 11.1, where sea level rise due to thermal expansion is relative to that in year 1990. In order to calculate thermal expansion explicitly, we first found the interior ocean temperature as a function of depth and time (T_o). Using a pure diffusion model without upwelling, where heat diffusion is described by:

$$\text{For} \quad 0 < z < z_B : \frac{\partial}{\partial t} T_o(z,t) = \kappa_v \frac{\partial^2}{\partial z^2} T_o(z,t) \tag{6.3}$$

$$\text{B.C.:} \quad T_o(0,t) = T_s(t), \frac{\partial}{\partial z} T_o(z_B,t) = 0 \tag{6.4}$$

$$\text{I.C.:} \quad T_o(z,0) = 0 \tag{6.5}$$

In this case, the upper boundary ($z = 0$) to the mixed layer has the same temperature as the mixed layer T_s, and the heat flux into the ocean floor at $z = z_B$ vanishes. The solution for T_o is solved analytically by *Kriegler* (2005, Appendix B):

$$\begin{aligned} T_o(z,t) = {} & T_s(t) - \int_0^t \dot{T}_s(t') Erf(\frac{z}{2\sqrt{\kappa_v (t-t')}}) dt' \\ & + \sum_{n=1}^{+\infty} (-1)^n \int_0^t \dot{T}_s(t') (\text{Erf}(\frac{2nz_B - z}{2\sqrt{\kappa_v (t-t')}}) - \text{Erf}(\frac{2nz_B + z}{2\sqrt{\kappa_v (t-t')}}))) dt' \end{aligned} \tag{6.6}$$

Where T_s is ocean surface temperature, z is ocean depth, κ_v is the vertical diffusivity with a value of 0.55 $cm^2 s^{-1}$, n is a bottom correction term, and Erf is the error function defined as

$$\text{Erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x -t^2 dt \tag{6.7}$$

The series in Equation 6.6 converges quickly, so the only terms of importance are that of the zeroth order term describing the behavior of an infinitely deep ocean and one to three next order bottom correction terms. We found that inclusion of the bottom correction terms in Equation 6.6 are not necessary for the length of time we run the model, and only make a small difference in the thermal profile (roughly 9mm by 2200, Figure 6.3). Once the thermal profile was calculated, T_o was plugged in to the Linearized Equation of State:

$$\rho(z,t) = \rho_0(z)[1 - \alpha(T_o(z,t) - T_0(z)) + \beta(S(z,t) - S_0(z))] \tag{6.8}$$

In Equation 6.8, ρ is density, α is a coefficient of thermal expansion (1.7exp-4 K^{-1}), β is the coefficient of saline contraction, and S is salinity. For simplification we assumed constant salinity, and the last term dropped out. Rearranging Equation 6.8 to isolate both ρ terms on one side gives a ratio of change for each time step in each depth. Multiplying this ratio by the layer thickness at each depth, and summing over z we obtained the thermal expansion in meters.

This explicit calculation adds the capability of tracking the evolution of interior ocean temperature and density profiles, an improvement over the IRF approach. The estimate of thermal expansion produced using the updated equation is lower than that produced by the IRF while still being within the range estimated by *IPCC AR4 WG1* (see Figure 6.3).

Figure 6.4 shows the evolution of the interior temperature profile from 1750 to 2200. Sea surface temperatures show a net positive anomaly over the time-series, though a short-term decrease associated with a Little Ice Age minima starting in 1789 and lasting until 1852 causes a negative anomaly for years 1810-1852 in the upper 500 meters. The negative thermal profile anomaly appears to be reflecting two periods of increased volcanic radiative forcing, the first focused around 1810 and the second 1832. Future profiles are calculated using the A1B scenario. The steady profile near the bottom confirms the assertion by *Kriegler* (2005) that bottom correction

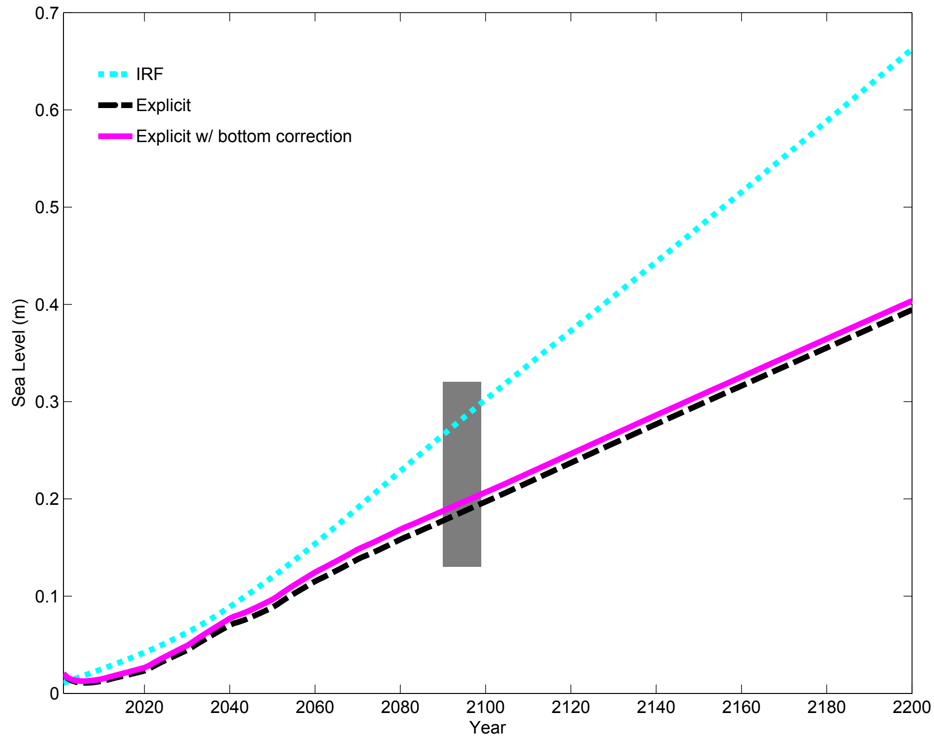

Figure 6.3: Comparison of the original IRF (cyan) and updated explicit (black, dashed) calculation of thermal expansion for SRES scenario A1B. The pink line denotes the inclusion of the bottom correction terms in Equation 6.6. The grey shading denotes the range in estimated thermal expansion estimate published in *IPCC AR4 WG1* (90% confidence interval).

terms in Equation 6.6 are unnecessary for our time scale.

6.1.3 Validation of Model Set-up

For our experiment, we elect to use the standard settings for the spin-up and forward modes, run with DOECLIM. In the spin-up mode, the inverse scheme is activated to calculate parameters with optimal agreement to data. Carbon dioxide emission by fossil fuel consumption and land use change is calculated in the inverse scheme, starting with assumed equilibrium in 1750. Carbon uptake by oceans and land are also calculated in the inversion, though biological sensitivities to temperature which affect carbon uptake are prescribed. Natural and anthropogenic emissions of other

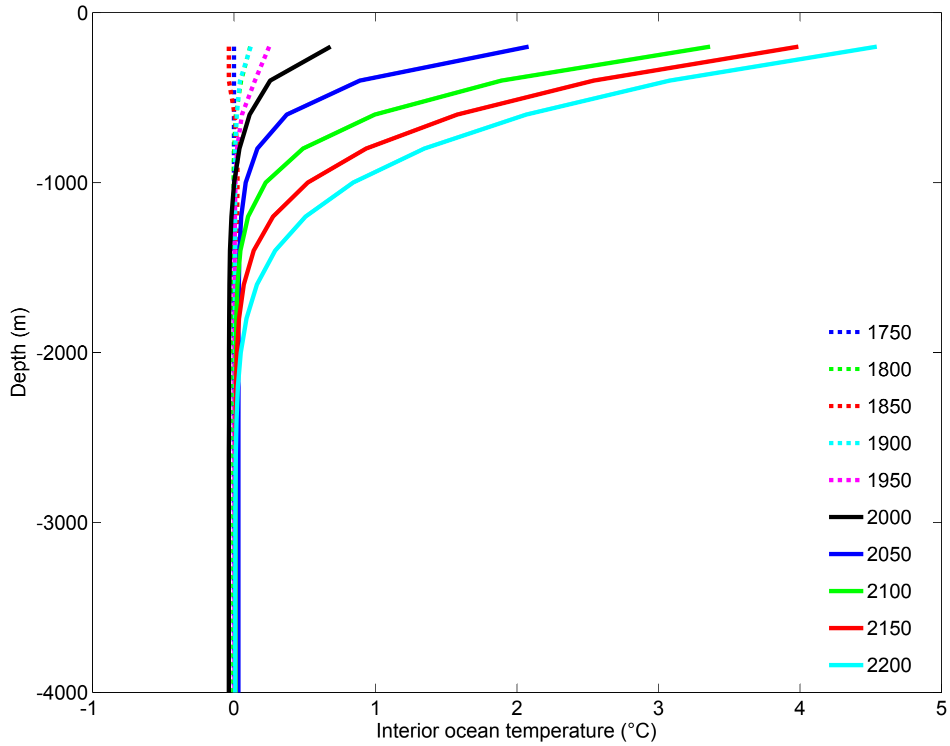

Figure 6.4: Thermal expansion below the mixed layer at 50-year intervals for the duration of spin-up and forward runs. Forward runs use the A1B scenario.

GHGs CH_4 and N_2O are calculated in the inversion between 1750 and 2000, though NO_x, CO, VOC and SO_2 emissions are prescribed. We use conservative estimates of larger uncertainty ranges in sensitivities than what are found in the literature. The effect of ENSO on atmospheric carbon concentrations and global temperature is factored in after year 1960. In the future mode, solar forcing is included in the total radiative budget, parameters are held constant and the inverse scheme is deactivated.

Climate Sensitivity

All of the model parameters in DOECLIM are dependent on only two free variables, climate sensitivity and ocean vertical diffusivity (*Tanaka and Kriegler* 2007). Equilibrium climate sensitivity can be prescribed or inversely calculated in the spin-up mode of ACC2. Prescribed parameters are estimated as a function of either sensitivity or diffusivity based upon empirical data and runs of more complex climate models (*Tanaka and Kriegler* 2007). This assembled dataset, in combination with set parameters in ACC2, produce a 4.0℃ equilibrium sensitivity for a doubling of atmospheric CO_2 concentration. This value is somewhat higher than that found in *Meehl et al.* (2007), who reports the most likely value is about 3℃, with a range between 2 and 4.5℃. This higher sensitivity is indicative of the weakness of the climate carbon-cycle feedback in ACC2, where for a doubled atmospheric CO_2 concentration, less CO_2 is taken up by the earth system, forcing the global temperature higher.

Ice Mass Balance Sensitivity

Ice mass balance sensitivities of the Antarctic and Greenland ice sheets are also adjustable in ACC2, and because there is a large amount of uncertainty regarding long-term ice sheet response to climate change (particularly for the AIS, see Section 3), we have elected to use a range of AIS sensitivities in our analysis. *Meehl et al.* (2007) give a best-guess sensitivity for Greenland as 0.11±0.09 mm $yr^{-1}℃^{-1}$ and for Antarctica as -0.29±0.18 mm $yr^{-1}℃^{-1}$. These sensitivities are based upon a global warming of 3℃ relative to the pre-industrial temperature.

Using these sensitivities in ACC2 give us a good approximation of IPCC projections to 2100 (see the 90% confidence interval for 2090 to 2099 for sea level rise components, relative to 1980 to 1999, in Table 6.1 and GIS and AIS projections in Figure 6.5), but there is some concern that the IPCC projections are not realistic, particularly in the long term behavior of the AIS. Recent observations (over the past 20 years) of the AIS mass balance are not consistent with the models, and have not detected the predicted warming and net accumulation of precipitation over the ice sheet as a whole, though some warming and precipitation increase has been observed over the Antarctic peninsula (*Meehl et al.* 2007). Furthermore, ice loss has accelerated in recent years in parts of East and West Antarctica and the Antarctic Peninsula (*Lemke et al.* 2007).

While continued warming might lead to increased accumulation over parts of the AIS, extrapolating from present observations (i.e., a net loss) lends one to think that large increases in temperature could not spur net growth continent-wide. What the sensitivity of the mass balance is to changes in global mean temperature is anyone's guess, but it is likely that the AIS will eventually become a large positive contributor to sea level. Whether this occurs before or after a 3°C global increase is unknown. Recent observations of estimated sea level contribution by Antarctica (roughly 0.2 mm y^{-1}) divided by the estimated global warming rate (0.045°C yr^{-1}) and averaged over the period 1993 to 2003 (*Bindoff et al.* 2007, *Trenberth et al.* 2007) yield a crude sensitivity of 4.4 mm yr^{-1}°C^{-1}. Such a large response to recent warming might be transient, or provide only a taste of what is to come.

The choice of mass balance sensitivity makes a large difference in global sea level contribution by the AIS; by 2100, there exists a difference between upper and lower estimates exceeding 1 m for scenario A1B (Figure 6.5). This difference grows to over 3 m by 2200. Large AIS contributions based on 4.4 mm yr^{-1}°C^{-1} are well beyond those predicted from other sources and would make the AIS the primary factor in what would be extremely rapid sea level rise.

Dramatic AIS destabilization brought on by a large (4.4 mm yr^{-1}°C^{-1}) ice mass balance sensitivity would quickly overrun the WBGU-recommended sea level guardrail of 1 m. Because ice sheet sensitivity is so poorly constrained, it warrants special treatment beyond the scope of this thesis. We focus on the two other ice mass balance sensitivities for the AIS in our model runs: the IPCC-recommended value listed above (-0.29 mm yr^{-1}°C^{-1}, referred to as 'IPCC'), and a positive value of 0.11 mm yr^{-1}°C^{-1}, where Antarctica has the same sensitivity as Greenland (referred to as 'GIS').

ACC2 and IPCC Comparison

A comparison of ACC2 model output to historical conditions and GCM results found in *IPCC AR4 WG1* suggests ACC2 does a reasonable job representing climatic pro-

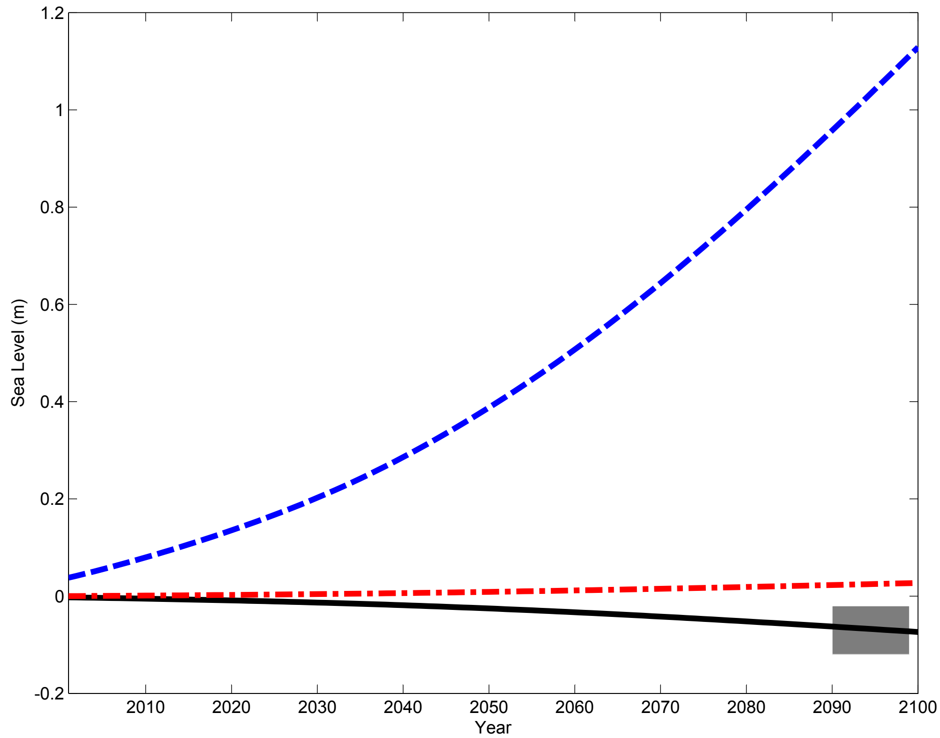

Figure 6.5: Sea level rise using different AIS mass balance sensitivities for scenario A1B. The black line denotes the modeled sensitivity suggested by *Meehl et al.* (2007)(-0.29 mm yr^{-1}°C^{-1}). This value produces net continental accumulation in ACC2 consistent within the 90% confidence interval of *IPCC AR4 WG1* estimates, denoted gray band. A higher sensitivity (red line) equivalent to that of Greenland (0.11 mm yr^{-1}°C^{-1}) is also used. A large positive sensitivity of 0.44 mm yr^{-1}°C^{-1} (blue line) is based upon a crude calculation of recent observed AIS mass balance sensitivity.

cesses using an equilibrium climate sensitivity of 4.0°C. Comparison of state variables in the spin-up mode is not useful as the inverse scheme calculates values based on fit to observational data. Additionally, with the exception of thermal expansion, sea level contributors are not implemented until year 1990, making comparison of these variables in the spin-up to observed rates difficult.

Bias within ACC2 is apparent in the forward mode, where atmospheric concentrations are projected lower by about 100 ppm in the year 2100 for higher and mid-range scenarios A1FI, A2, IS92a, and A1B relative to IPCC published estimates (compare Figures 3.3, p. 27, and 6.6). Low-range scenarios B2, A1T and B1 have less bias between ACC2 and IPCC projections, though are still roughly 50 ppm lower than estimates in *Meehl et al.* (2007). All CO_2 concentrations are initialized at the observed concentration of 370 ppm in 2000. The increasing disparity between IPCC and ACC2 CO_2 concentrations over time suggests that estimates will be increasingly biased with longer runs, especially for high-emission scenarios. Presumably, this low bias in atmospheric concentration can be attributed to model parameterization of the carbon cycle and could be corrected in future studies.

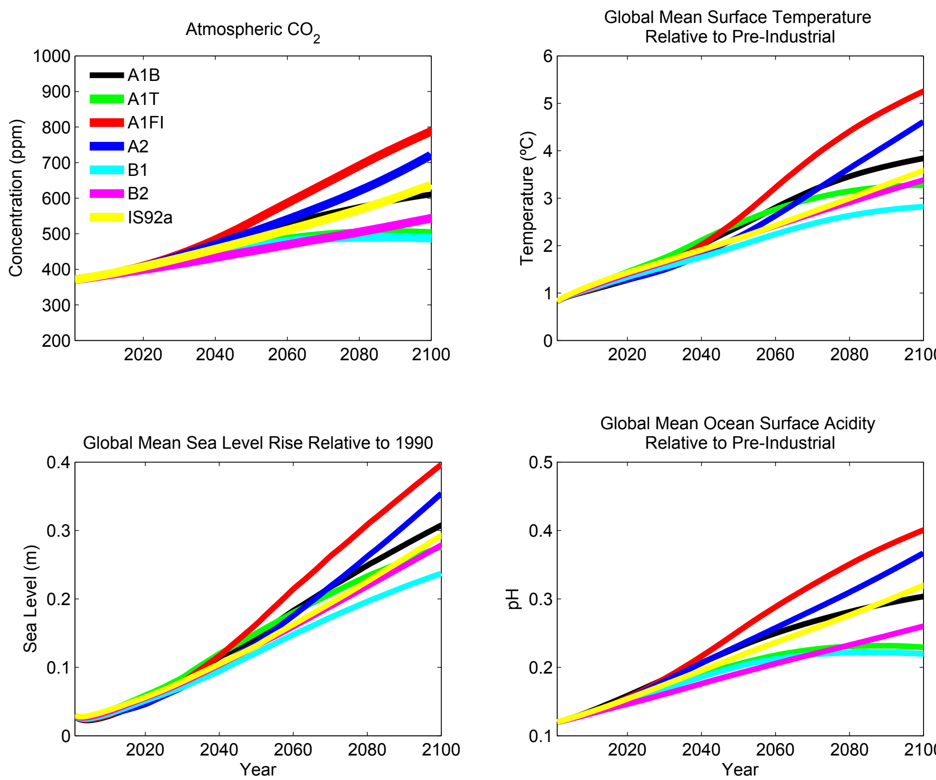

Figure 6.6: Time-series of ACC2 variables using SRES scenarios with a climate sensitivity of 4.0℃.

Global mean temperature estimates in ACC2 are on the high side of the IPCC-estimated range. Temperature time-series are shown in Figure 6.6 for SRES scenarios and can be compared to Figure 3.1, p. 23. For example, intermediate scenario A1B projects a temperature of 3.84℃ for year 2100, while the IPCC-estimated range is 1.7

to 4.4℃. These and other ranges (for sea level rise and ocean pH) are published as global averages over the 2090 to 2099 time period, relative to the 1980 to 1999 mean. In Figure 6.6, the global temperature is plotted relative to the value in 1990, so the comparison is not directly equivalent but is very close. The high bias in global mean temperature projections are a product of the higher climate sensitivity in ACC2 than what is used in AOGCMs cited by *IPCC AR4 WG1*.

In ACC2, total sea level rise (and cryospheric contributors) are initialized at year 1990 using *IPCC TAR WG1* estimates of change relative to year 1910. A short spin-up for these components is acceptable due to their exclusive dependence upon mean temperature and ice mass balance sensitivity in the model. Thermal expansion is calculated from 1750 onward in order to capture thermal trends throughout the water column. Like CO_2 concentrations, global mean sea level rise exhibits a low bias, though projections are still well within the range published by *IPCC AR4 WG1* for year 2100 (see Figure 6.7 and Table 6.1). For example, scenario A1B projects a 0.31 m rise in total sea level by 2100, compared to a range of 0.21 to 0.48 m (*Meehl et al.* 2007). The two sea level components which create the low bias are the GIS contribution and thermal expansion. The slight low bias in global sea level could affect the economic analyses with the coupled ACC2-DICE model, though since ACC2 produces results within IPCC estimates, this is not a large concern.

Table 6.1: Components of sea level rise by SRES Scenario, in meters. ACC2 rise is averaged from years 2090-2099, relative to years 1990-1999. IPCC rise is averaged from years 2090-2099, relative to years 1980-1999. The IPCC columns show the 5-95% confidence range in AOGCM estimates (*Meehl et al.* 2007).

SRES Scenario	**Therm Exp**		**Glaciers**		**GIS**		**AIS**		**Total**	
	ACC2	IPCC	ACC2	IPCC	ACC2	IPCC	ACC2	IPCC	ACC2	IPCC
A1B	0.20	0.13 0.32	0.11	0.08 0.15	0.03	0.01 0.08	-0.07	-0.12 -0.02	0.31	0.21 0.48
A1T	0.17	0.12 0.30	0.11	0.08 0.15	0.03	0.01 0.07	-0.07	-0.12 -0.02	0.28	0.20 0.45
A1FI	0.28	0.17 0.41	0.13	0.08 0.17	0.03	0.02 0.12	-0.09	-0.14 -0.03	0.40	0.26 0.59
A2	0.24	0.14 0.35	0.11	0.08 0.16	0.03	0.01 0.08	-0.07	-0.12 -0.03	0.35	0.23 0.51
B1	0.13	0.10 0.24	0.10	0.07 0.14	0.02	0.01 0.05	-0.06	-0.10 -0.02	0.24	0.18 0.38
B2	0.17	0.12 0.28	0.11	0.07 0.15	0.03	0.01 0.06	-0.07	-0.11 -0.02	0.28	0.20 0.43

Thermal expansion is the one major variable calculated in the ACC2 spin-up

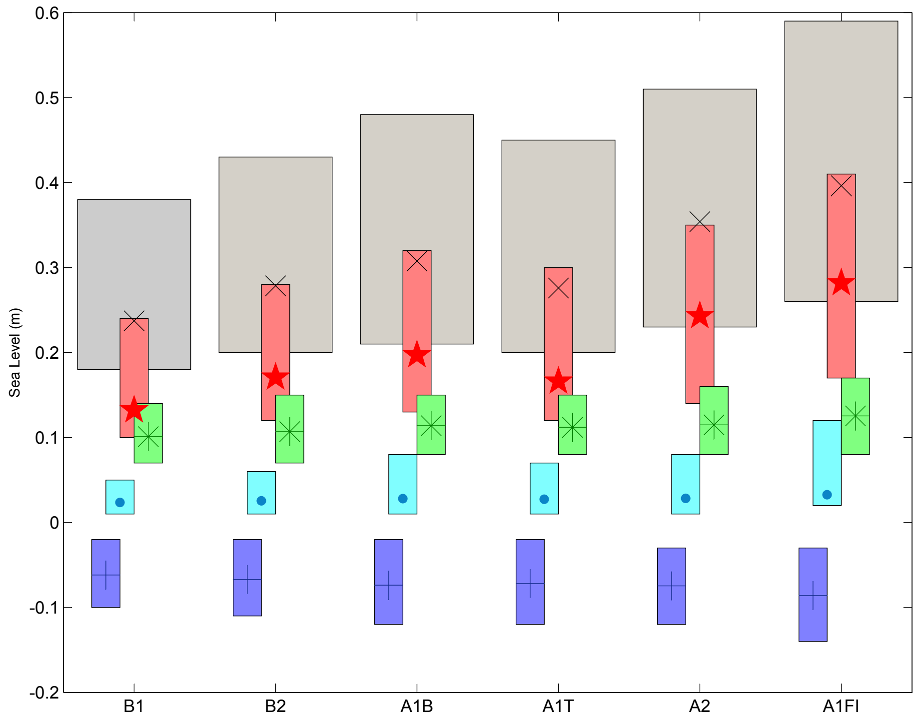

Figure 6.7: Sea level rise at year 2100 broken down by contributor. The Antarctic contribution is modelled using the IPCC-recommended ice mass balance sensitivity. This plot is a re-creation of Figure 3.2, where IPCC 90% confidence intervals for the time period 2090-2099 relative to 1980-1999 are denoted by boxes, and markers represent ACC2 model output relative to 1990. Total sea level rise is denoted by the gray box (x), thermal expansion by pink (five-point star), glaciers and small ice caps by green (multi-point star), GIS by light blue (dot), and AIS by blue (plus).

suited to comparison with historical data. *Bindoff et al.* (2007) estimate an average rate of thermal expansion in the upper 3000 m between 1961 to 2003 as 0.42±0.12 mm/y. As is apparent in Figure 6.8, thermal expansion is highly variable on an annual basis, making a linear interpolation more amenable for comparison than a raw time-series. The trend in thermal expansion produced by ACC2 over the same time period (1961-2003) is 1.2 mm/y, almost triple the central IPCC estimate! As shown in Figure 6.7, this extraordinary high trend does not carry into the forward mode.

Finally, ACC2 projections of global surface pH agree reasonably well with IPCC

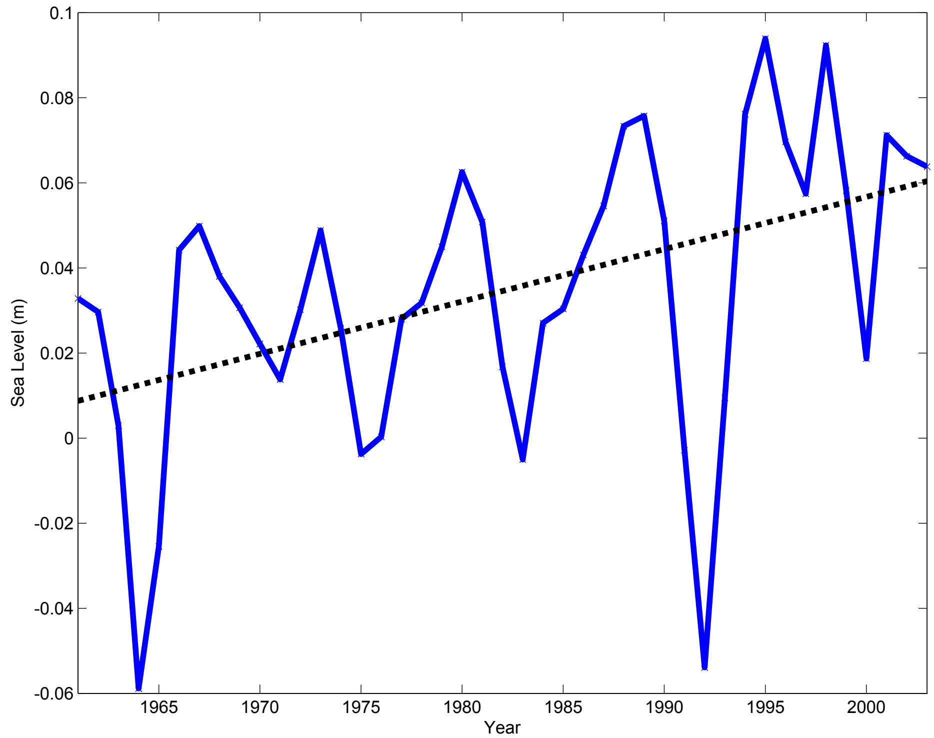

Figure 6.8: Time-series of thermal expansion using a climate sensitivity of 4.0℃, calculated in the spin-up mode of ACC2. The blue line denotes the period 1961-2003. The black dotted line represents the linear trend over this same time period (1.2 mm/y).

estimates. The 0.1 unit drop since pre-industrial levels reported by *Bindoff et al.* (2007) is slightly less than that calculated in ACC2 (decline of 0.12), but the projections for 2100 are solidly within the range estimated by *Meehl et al.* (2007) (see Figures 6.6 and 3.3). For example, scenario IS92a projects a drop of 0.32 units, compared to a range of 0.1 to 0.4 units by 2100 (*Meehl et al.* 2007).

Though ACC2 reasonably approximates IPCC projections for changes in ocean surface acidity, it is important to note some of the limitations of ACC2 for modelling atmosphere-to-ocean carbon uptake. The H+ concentration is calculated from global mean temperature change using thermodynamic equilibria and does not consider regional changes such as sub-polar thermohaline circulation or ocean overturning, or changes to coastal biological productivity, all of which could have profound impacts on the rate of carbon uptake in the future. Of all the simplifications to carbon uptake by oceans in ACC2, these are the most potentially inaccurate assumptions for our time scale. *Bruckner and Zickfeld* (in press) examine thermohaline circulation thresholds using a model easily incorporated into ACC2, though changes to the circulation in their study do not reflect explicit changes in ocean carbon uptake. A lesser omission is a lack of buffering by $CaCO_3$ in the mixed layer, where constant alkalinity is assumed. For the time scale of our model run, this assumption should only result in a few percent change in the carbon flux (*Tanaka and Kriegler* 2007). Lastly, the soft-tissue (organic carbon) pump which transports particulate organic material downward operates on a millennial scale, and while it is treated implicitly within ACC2 (via calibration with GCMs), it is not calculated explicitly.

6.2 DICE

For the economic component of our model, we use the globally aggregated model DICE. We selected it from a number of other economic models because it is computationally efficient, written in GAMS and has a history of use in similar integrated assessments (e.g. *Bruckner and Zickfeld* in press, *Keller et al.* 2000, *Mastrandrea and Schneider* 2004). A complete description of DICE can be found in *Nordhaus and Boyer* (2000). Briefly, DICE is a Ramsey-type optimal growth model which contains endogenous variables that represent the fundamental global economic structure. A Cobb-Douglas production function (Box 6.9) captures the investment and capital accumulation cycle using exogenous technological change (A) and labor (L) factors; endogenous capital (K) and damage from carbon emissions mitigation (Ω) variables determine output (Q). The elasticity of output with respect to capital is γ.

$$Q(t) = \Omega(t)A(t)K(t)^{\gamma}L(t)^{1-\gamma} \tag{6.9}$$

$$Q(t) = C(t) + I(t) \tag{6.10}$$

$$K(t) = (1 - \delta_k)K(t-1) + I(t-1) \tag{6.11}$$

Output includes both per capita consumption (C) and investment (I). Capital depreciates with a rate of δ_k but is increased through investment. For the purposes of this study we aim to maximize utility, or welfare (U) given specified constraints (the WBGU guardrails), where U is a function of per capita consumption and labor, and q is a social time preference discount factor.

$$max \sum_{t} U[C(t), L(t)](1+q)^{-t} \tag{6.12}$$

$$U[C(t), L(t)] = L(t)(\log[C(t)]) \tag{6.13}$$

Annual global carbon emissions, E, are calculated by

$$E(t) = [1 - \mu(t)]\sigma(t)Q(t) \tag{6.14}$$

Where μ is a prescribed annual emissions control level percentage which may be set to zero for the purposes of examining a business-as-usual (BAU) emissions trajectory, and σ is a prescribed carbon intensity factor.

6.2.1 Coupling ACC2 and DICE

ACC2 and DICE are coupled differently depending upon the type of economic analysis being implemented. For cost-effectiveness analysis, the models are coupled via Equation 6.14, where CO_2 emissions are calculated in DICE and used in ACC2 to compute a new temperature. For cost-benefit analysis, a climate damage (Ω) function

Ramsey Optimal Growth Models

Ramsey models follow an optimal growth framework where the accumulation of capital per worker (i.e., investment) over time is equal to the amount of output per worker minus the consumption per worker and the rate of depreciation of that capital. So whatever capital is not consumed depreciates steadily. The discount rate on goods is derived from a combination of time discounting, the elasticity of marginal utility, and growth in consumption (*Nordhaus* 1994). Time discounting is the observed phenomenon that society values the real incomes of different generations unequally; that is, to present society, the wealth of future generations matters less than that of the present generation. The more removed the future generation, the less their wealth matters today. The elasticity of marginal utility refers to the variable relative worth of an additional unit of consumption, which declines with increasing consumption.

is included as well, which is computed in DICE:

$$\Omega(t) = (1 - b_1\mu(t)^{b2})/[1 + \theta_1 T(t)^{\theta_2}] \tag{6.15}$$

This equation forms the direct link between temperature (T), calculated in ACC2, and climate damage Ω. Climate damage enters the function for output (Q) in Equation 6.9. The parameters θ_1 and θ_2 represent the scale and non-linearity of the damage function, and the coefficients b_1 and b_2 represent the scale and non-linearity of the cost function. The cost function is what is optimized in the coupled model runs. Explicit climate damage is not required in cost-effectiveness analysis because guardrails are used instead, but it is required in analyses which address economic damages specifically (such as cost-benefit analysis).

Because DICE operates on a 5-year iteration and ACC2 annually, a linkage file was constructed to linearly interpolate emissions output from DICE for use in ACC2. A schematic of the coupling of ACC2 and DICE is shown in Figure 6.9.

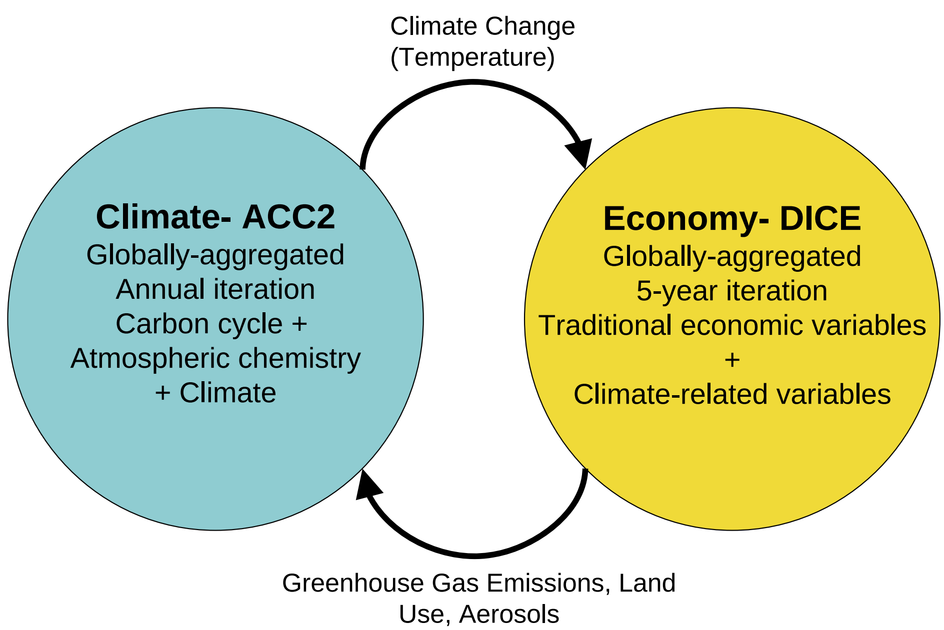

Figure 6.9: ACC2/DICE schematic.

Chapter 7

Results

Before stepping in to the economic analysis of the coupled ACC2/DICE results, it is important to understand that the SRES scenarios do not respond equally when WBGU ocean guardrails are applied. Our economic analysis finds optimal CO_2 emission pathways, but GHG emissions other than CO_2 are prescribed as following the SRES scenarios. Higher non-CO_2 emissions pathways (higher SRES scenarios) yield larger changes in temperature, sea level, and ocean pH, and therefore are more difficult to maintain below the guardrails than lower emissions pathways. Altering the equilibrium climate sensitivity and ice mass balance sensitivities also affects our results, where increasing sensitivity yields corresponding decreasing ability to limit ocean change. In order to succinctly summarize the range of SRES scenarios (for non-CO_2 GHGs), three representative high, moderate and low scenarios (A2, A1B, B1, respectively) will be used for the economic analysis.

7.1 Cost-effectiveness Analysis

Cost-effectiveness analysis calculates CO_2 emissions in DICE which maximize economic utility given climate guardrails prescribed in ACC2. This section analyzes the series of WBGU-recommended marine guardrails using various equilibrium climate and ice mass balance sensitivities.

Included in some of the cost-effectiveness analysis plots are results of business-as-usual (BAU) runs, where utility is still optimized but climate damage is assumed to have no influence on the economy and the emissions reduction rate (μ) is zero. This configuration represents an economically-optimistic viewpoint and the "best" economic conditions the model could produce given prescribed economic restrictions and no climate guardrails.

7.1.1 Global Mean Temperature

Whether the WBGU-recommended temperature guardrails can be respected by optimized CO_2 emissions pathways depends upon the equilibrium climate sensitivity used. Figure 7.1 shows optimized pathways for several physical and economic variables using a range of climate sensitivities, where global mean temperature is restricted to rise less than 2℃ by 2200, at a rate not to exceed 0.2℃ per decade. Non-CO_2 GHGs are prescribed following the A1B scenario. Only the first 100 years of the run are shown because of end-point effects from the optimization [1]. For the highest climate sensitivity shown, 3.5℃, it appears that the rate of change is more constraining (at least for the first 50 years) than the absolute temperature. Changes in sea level which correspond to the restricted temperature pathway are far below the WBGU-recommended guardrail (1 m rise), which indicates temperature guardrails are more restrictive than that of sea level rise. Likewise, ocean pH pathways corresponding to a restricted global temperature fall below the WBGU-recommended guardrail of 0.2 unit decline for climate sensitivities greater than 2℃, indicating temperature guardrails are more restrictive than the pH guardrail. The 2℃ scenario shows a greater response in terms of pH because acidity is directly calculated from CO_2 concentration, which is allowed to climb higher with a relatively smaller change in temperature compared to other climate sensitivities.

The economic variables reflect the physical results in that climate sensitivities

[1] ACC2/DICE calculates an optimal path between fixed beginning and end points, and the last few years of the model runs often contain rapid slope changes to adjust the pathway to the end point. These abrupt changes can be safely ignored.

which result in lower temperatures also have higher allowable emissions, with correspondingly lower emissions reductions, and lower costs. Note that the least-sensitive pathway, 2℃, exhibits an emission pathway that peaks just above 8 GtC per year, which is several GtC less than the ACC2-calculated BAU path (denoted by the thin dotted lines), and only half the annual emissions laid out by *Meehl et al.* (2007) for the A1B scenario. The actual climate sensitivity is likely closer to the middle of the IPCC-estimated range (of 2 to 4.5℃), which means carbon emissions must likely depart even more substantially from business-as-usual behavior in order to respect temperature guardrails. For a climate sensitivity of 3.5℃, CO_2 emissions would need to drop to zero before 2050 in order to respect the guardrail (a 100% emission reduction), and annual costs would climb from 4 to almost 6% of the Gross World Product (GWP) once emissions are cut. To put such large losses into perspective, Canada lost 43% of her gross domestic product between Great Depression years 1929 and 1933, an average of almost 11% per year (Government of Canada).

Figure 7.1 only contains pathways for climate sensitivities 2 to 3.5℃, even though *Meehl et al.* (2007) suggests a likely range of 2 to 4.5℃. This is because higher sensitivities yield 'infeasible' results, or pathways which cannot respect the climate guardrails, even with severe reductions in carbon emissions. Such results hold dire implications, should true climate sensitivity lie on the high end of the IPCC-estimated range. It should be noted, however, that ACC2/DICE does not consider carbon sequestration, which would reduce CO_2 concentrations and could increase the range of feasible results.

7.1.2 Sea Level Rise

The WBGU-recommended sea level guardrails are a great deal less restrictive than those for global mean temperature. Figure 7.2 contains cost-effective pathways for a range of equilibrium climate sensitivities, all using non-CO_2 GHG emissions prescribed following scenario A1B. Sea level rise is so unrestrictive that all settings follow

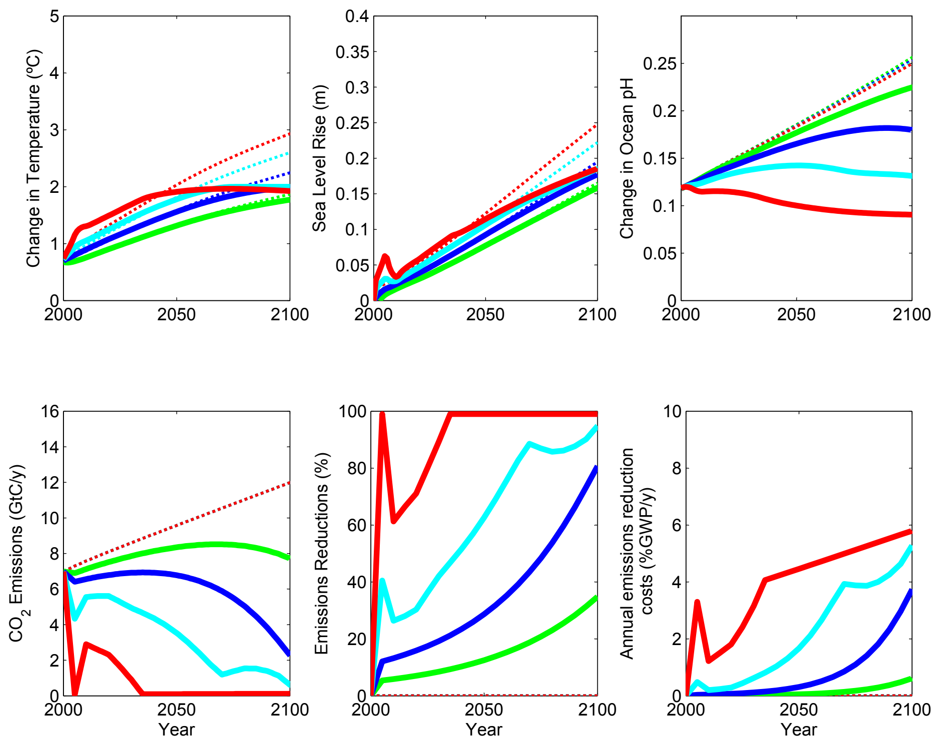

Figure 7.1: Cost-effective pathways for WBGU temperature guardrails (2℃ and 0.2℃ per decade), using various equilibrium climate sensitivities. All runs use prescribed non-CO_2 emissions for the A1B scenario. Colors denote sensitivities of 2.0℃ (green), 2.5℃ (blue), 3.0℃ (cyan), and 3.5℃ (red). The business-as-usual (BAU) paths are denoted by thin dotted lines. Higher sensitivities do not respect the temperature guardrails.

the BAU pathway. The BAU pathway varies for the physical variables because of different temperature responses by the climate to emissions. The BAU pathways are identical in the economic variables because the economy is presumed immune to climatic effects by definition for BAU.

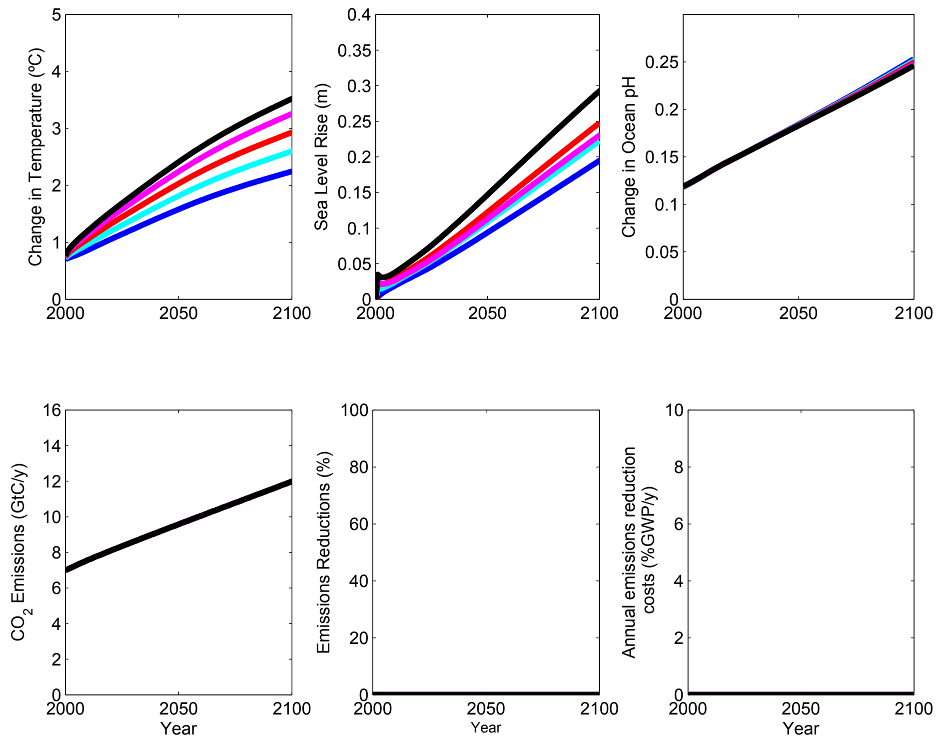

Figure 7.2: Cost-effective pathways for WBGU-recommended sea level rise guardrails (1 m absolute and 5 cm/decade rate). Equilibrium climate sensitivities are denoted by colors; 2.5°C (blue), 3.0°C (cyan), 3.5°C (red), 4.0°C (pink), and 4.5°C (black). All runs use non-CO_2 GHG emissions from scenario A1B. This case uses the IPCC-recommended Antarctic sensitivity (a negative value).

Though Figure 7.2 suggests violating the WBGU sea level guardrails is unlikely in the next couple of centuries, extrapolation of the sea level trend does suggest the WBGU-recommended guardrails might eventually be violated, if emissions trajectories are not reduced. These guardrails are intended to apply to very long-term change, so a longer model run would be more appropriate for calculating these emission pathways. Furthermore, the use of a negative Antarctic ice mass balance sensitivity in this plot could be an overly optimistic assumption. The next section examines how changing this assumption affects the analysis.

Antarctic sensitivity

Even with the use of a higher sensitivity for Antarctica (set at a value equal to that of Greenland ice mass balance), WBGU-recommended sea level guardrails are generally still unrestrictive enough that pathways follow the BAU trend (see Figure 7.3). In this figure, a series of sea level rise rates and the WBGU-recommended absolute guardrail have been applied to scenarios run using positive and negative ice mass balance sensitivities. All runs use a 4℃ equilibrium climate sensitivity. Non-CO_2 GHGs are prescribed following three SRES scenarios (A1B, B1, and A2).

In addition to the A2 path using the IPCC-recommended sensitivity for Antarctica (a negative sensitivity), the configurations which deviate from the BAU path using a GIS sensitivity are sea level rise rate of 3 cm/decade in the A2, A1B, and B1 scenarios, and a rate of 4 cm/decade for the A2 scenario. The model is particularly sensitive to rates; a 1 cm/decade change in guardrail can make a 40% difference in emissions reductions by 2090 for A2, as well as in the general shape of the emissions pathways. The results also show that should Antarctic sensitivity to increasing temperatures be higher than what is currently predicted, emissions policy will have to be dramatically different; for the A2 scenario, this equates to a difference in emissions reduction of 100% by about 2030. Such rapid de-carbonization would cost around 4% GWP per year, a serious (but necessary) economic sacrifice. Lower non-CO_2 emission scenarios A1B and B1 exhibit smaller differences between Antarctic sensitivities (40% emission reduction by 2050 for A1B, 5% emission reduction by 2050 for B1, with higher reductions in the long-term). Bear in mind that the positive ice cap sensitivity used here is far less than what recent observations support. With so much uncertainty surrounding Antarctic ice mass sensitivity, the possibility of large economic costs in the future warrants caution.

In addition to the importance of Antarctic ice sheet sensitivity, another critical point can be made from Figure 7.3. Non-CO_2 GHG emissions can have a large influence on optimal CO_2 pathways. For example, using A2 versus A1B non-CO_2 emissions results in a decrease in allowable annual carbon emissions of over 5 GtC/y by 2050 for a rate guardrail of 3 cm/decade. This corresponds to 60% more emissions reductions if A2 is used, and 3% additional GWP spent. Since non-CO_2 GHGs show influence over carbon policy, it can be argued that they should be regulated as well.

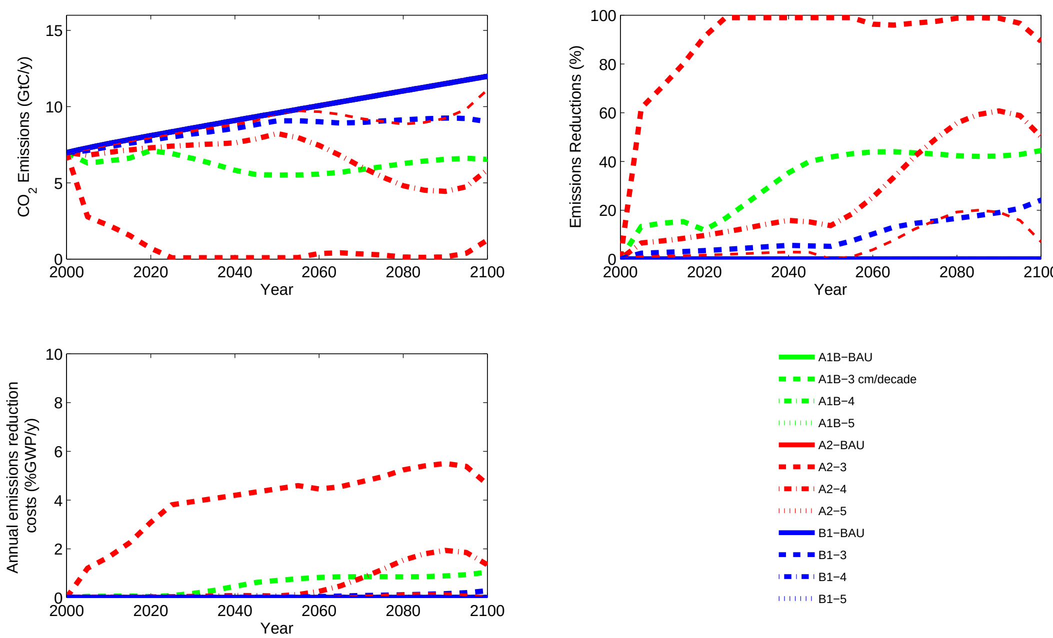

Figure 7.3: Cost-effective pathways for sea level rise using multiple Antarctic ice mass balance sensitivities. Colors denote scenario, with A1B (green), A2 (red) and B1 (blue). The line style denotes sea level guardrail combinations. Solid lines denote BAU pathways. Dashed lines indicate a sea level guardrail of 1 m rise at 3 cm/decade, dash-dot lines indicate 1 m rise at 4 cm/decade, and dotted lines denote the WBGU-recommended 1 m rise at 5 cm/decade. Thick lines denote GIS ice mass balance sensitivity used for Antarctic melting, while thin lines represent the IPCC-recommended negative Antarctic sensitivity. Dash-dot and dotted lines not visible on the plot follow the BAU pathway.

7.1.3 Ocean Acidification

Using ocean acidity as a guardrail for economic analysis was recently suggested to be critical but utterly lacking in the global climate policy debate (*Zeebe et al.* 2008). The restrictiveness of WBGU pH guardrails with cost-effectiveness analysis lies somewhere between that of temperature and sea level. Figure 7.4 shows the results of using the WBGU-recommended maximum drop in pH of 0.2 units relative to pre-industrial levels. All runs use the non-CO_2 GHG emissions of the A1B scenario. BAU paths are also shown for comparison. All runs use the IPCC-recommended negative Antarctic sensitivity, though this is irrelevant in our calculations. While the sensitivity of ice caps could affect the H+ concentration in the real world, it makes no difference in our assumed constant-volume ocean.

In order to respect the WBGU guardrail, all climate sensitivities require departure from the BAU pathway. Declines in CO_2 emissions begin at the very start of the run, and rapidly increase to greater than 60% (with a corresponding cost of 2% GWP) by 2100. There is relatively little variation between climate sensitivities because ocean pH is a function of CO_2 concentrations, not temperature. What small variation there is between sensitivities is likely due to thermal dependencies in the atmosphere-ocean carbon cycle.

Further examination of economic variables derived from the same analysis suggests that corresponding economic delays will be minor over the next century (given the magnitude of the required economic de-carbonization). Figure 7.5 compares the cost-effective and BAU pathways for several of these economic variables. Until the 2080s, consumption and investment (the sum of which equals output) deviate only slightly from the BAU path, suggesting the pH guardrail could be respected while BAU levels will be achieved only months later than would be without constraint. The BAU and cost-effective paths diverge in the later years of the run, with a lag in output levels of several years by 2100. This level of reduced economic growth is significant, and could be expected to worsen into the future.

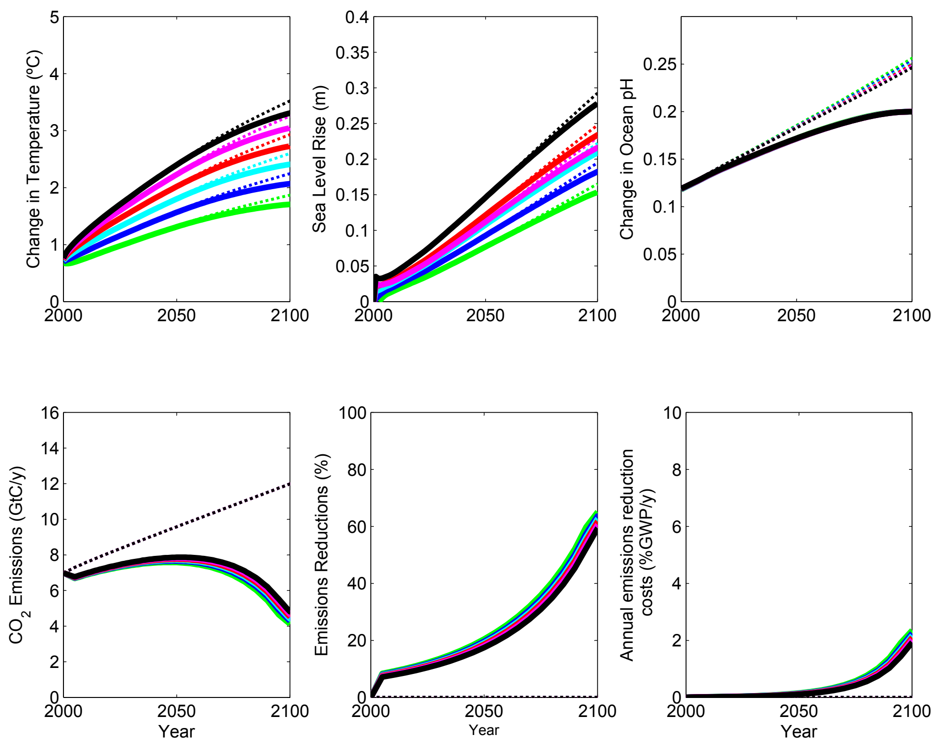

Figure 7.4: Cost-effective pathways for ocean acidification using a variety of equilibrium climate sensitivities. All paths use non-CO_2 GHG emissions following the A1B scenario. The BAU path for each respective sensitivity is shown as a thin dotted line. Climate sensitivities are denoted as follows; 2.0℃ (green), 2.5℃ (blue), 3.0℃ (cyan), 3.5℃ (red), 4.0℃ (pink), and 4.5℃ (black).

7.2 Tolerable Windows Approach

The tolerable windows approach combines elements of cost-effectiveness analysis (guardrails) but examines corridors, not pathways. ACC2 is iterated through the 200 year time-series, with CO_2 emissions maximized or minimized every ten years. These maximal/minimal values form the upper and lower boundaries of the "emissions corridor". This corridor provides greater policy maneuverability than a cost-effective pathway. The lower boundary is determined by economic guardrails (see *Bruckner and Zickfeld* in press for a good explanation). These guardrails constrain

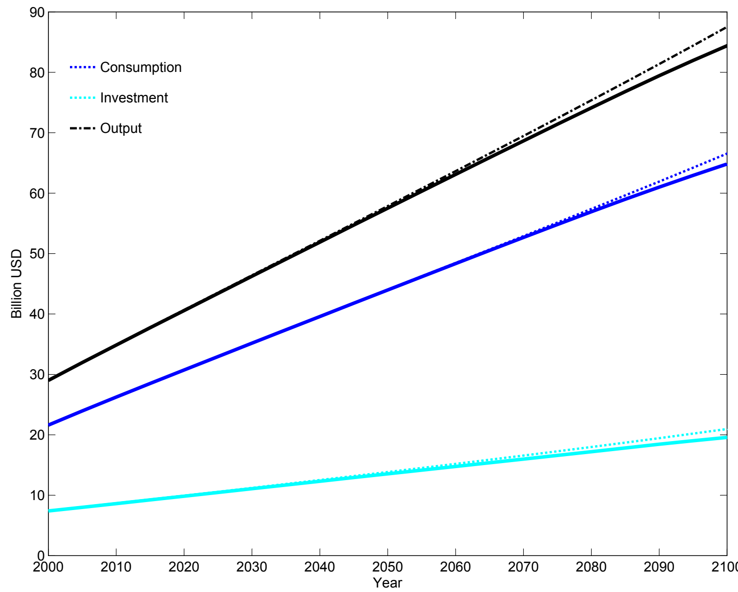

Figure 7.5: Optimal economic pathways respecting the ocean acidification guardrail using an equilibrium climate sensitivity of 4℃. All paths use non-CO_2 GHG emissions following the A1B scenario. The BAU path for each respective sensitivity is shown as a dotted line. Economic variables are denoted as follows; consumption (blue), investment (cyan), and output (black).

welfare losses and the rate of increase of emission reduction control (1.33% per year). The upper boundary is determined by the WBGU guardrails. Stepping outside this corridor would violate either economic or environmental restrictions. The converse is not necessarily true; not all conceivable pathways within the corridor are acceptable. The corridor is intended for finding a general range of acceptable pathways, and then using another type of analysis (cost-benefit, cost-effective, etc.) to further explore interesting paths.

7.2.1 All WBGU Ocean Guardrails

A representative emissions corridor is shown in Figure 7.6 for scenario A1B. WBGU-recommended guardrails constrain sea level rise and ocean pH. In this figure, several pathways which respect both upper and lower bounds represent a few of the runs used to construct the upper guardrail. Runs used to construct the lower bound follow the path of the lower bound and are not shown. Following any of the pathways in blue would respect environmental and economic guardrails, but deviation from these paths could cause guardrails to be violated, even if the path stays within the tolerable corridor. The uppermost red boundary is an aggregation of the peaks in the blue pathways, and follows a path from 7 to 16 GtC per year. This level is well above emissions levels calculated in cost-effectiveness analysis (see the black line in the figure), though low considering emissions averaged 7.2±0.3GtC per year between 2000 and 2005 and are increasing rapidly (*IPCC AR4 WG1*). Following the upper boundary is *not* an optimal solution.

The sample pathways in Figure 7.6 show that the guardrails allow high emissions briefly, but also require rapid change on either side of the peak and a mean value which is far lower. Any CO_2 emission pathway which would respect both upper and lower bounds is likely to be found in the lower reaches of the window, as the higher one is only briefly attainable. The spikes in emissions bias the graph visually, creating the appearance that higher emissions are permissible when in fact the bulk of emissions must be quite low. Obviously the tolerable window is meant only as a very rough guideline and not as a sustainable action plan. It must be thought of as a starting point, where factions can find a middle ground and begin their dialog.

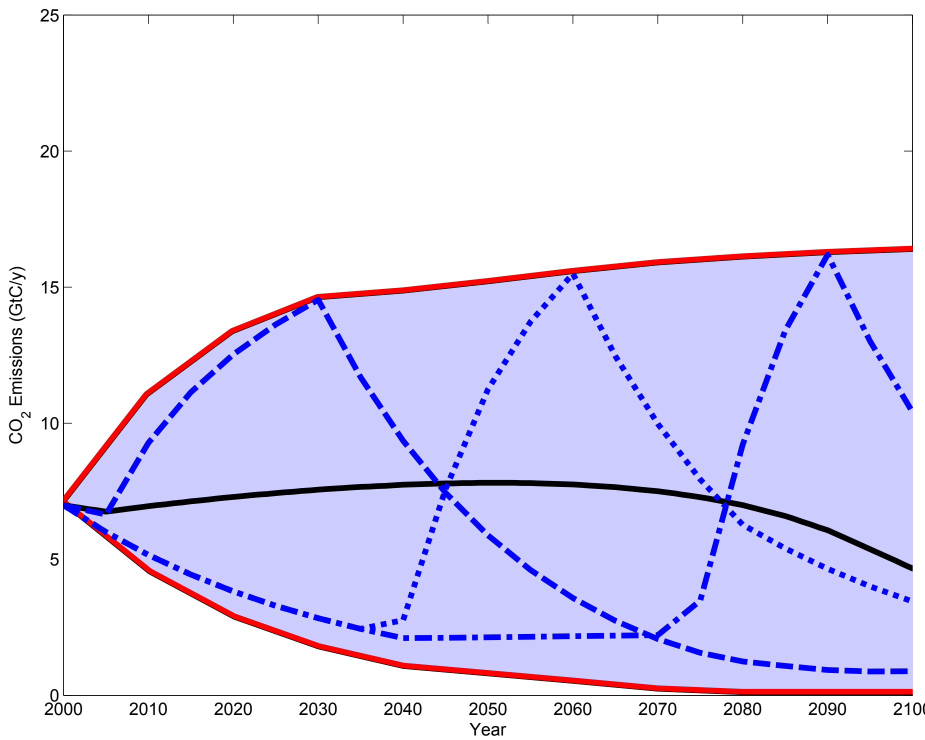

Figure 7.6: Emission corridor using all marine WBGU guardrails (excluding temperature) and non-CO_2 GHG emissions scenario A1B. Red lines denote the boundary between acceptable and unacceptable domains. Blue lines illustrate the algorithm used for the calculation of the upper corridor boundary. These blue lines maximize CO_2 emissions in years 2030 (dashed line), 2060 (dotted line) and 2090 (dash-dot line). The black line denotes the cost-effective emissions pathway under the same constraints.

Chapter 8

Conclusions

Recent observed and predicted changes to the global climate present troubling consequences for social and natural systems. These changes, brought on largely by anthropogenic emissions of greenhouse gases (GHGs), have the potential to disrupt the fabric of human society and push ecosystems to the brink of collapse. The ocean environment is at least as vulnerable as the terrestrial one, as rising temperatures and sea level, and increasing acidity pressure physical processes and biological populations already impacted by environmental degradation. Health of ocean systems and their relative stability matter not only to marine inhabitants, but also to the growing numbers of people who rely on them for sustenance and live along coasts. While global concern over general environmental degradation has increased steadily since the middle of last century, climate change is a relative latecomer to international negotiation. The Intergovernmental Panel on Climate Change formed in 1988 and has assumed an increasing profile in the global arena as awareness of the potential dangers of global warming spreads. In 1992, the drafting and ratification of the United Nations Framework Convention on Climate Change was a turning point for international recognition of the importance of avoiding dangerous anthropogenic interference with the climate system. Since ratification of this document, much time and money has been spent working out how to objectively define and address this dangerous interference. Officials seeking assistance in formulating policy have increasingly turned to integrated assessments which rationalize policy options in terms of economics.

Two forms of integrated assessments, cost-effectiveness analysis and the tolerable windows approach, are amenable to globally aggregated climate/economic modelling. These we apply to the newly coupled model ACC2/DICE, using climate guardrails laid out by the German Advisory Council on Global Change (WBGU). The extremely coarse resolution of ACC2/DICE limits its usefulness to drawing first-order (but nevertheless interesting) conclusions.

In our analysis of CO_2 *emissions pathways which respect WBGU guardrails, we find that guardrails set on marine indicators such as the rate and absolute limit of sea level rise and mean ocean pH are overshadowed by more restrictive (and therefore more difficult to achieve) global mean temperature limits.* This holds true with the range of equilibrium climate sensitivities tested (2 to 4.5℃). In all cases emissions pathways are required to deviate immediately and substantially from their business-as-usual pathways in order to respect the temperature guardrails of 2℃ and 0.2℃ per decade. In cases using climate sensitivities equal to or greater than 4℃, no solutions are possible, meaning respecting the guardrails is impossible without additional climate management measures (e.g., mitigation). For a climate sensitivity of 3.5℃, the rate of rise is more constraining than the absolute limit in the first half of the 21st century.

These results support the findings of *Rive et al.* (2007) who project that the feasibility of a 2℃ guardrail is highly dependent upon the value of the equilibrium climate sensitivity. It also supports their conclusion that delays in GHG regulation limit our ability to achieve the targets (*Rive et al.* 2007). These results also support the notion that WBGU temperature limits offer the most robust protection from unacceptable climatic change, a finding also supported by *Keller et al.* (2000), and

Toth et al. (2003b). Our results must be accompanied by the caveat that our model inversely calculates a high climate sensitivity (4°C), meaning that temperature change may be over-estimated. We addressed this by using a range of climate sensitivities for our analysis, and the effect of higher temperatures may partly serve to counter-act the under-estimated atmospheric concentrations of CO_2.

Alternative measures of climate danger focused on the marine indicators mentioned above are relatively less restrictive than temperature. According to our cost-effectiveness analysis, sea level rise and rates of sea level rise are sufficiently unrestrictive to be of little concern in coming centuries. This is likely true in spite of our model under-estimating thermal expansion and Greenland ice sheet contributions. Of course, the sensitivity of ice sheets to warming is highly uncertain, and sea level rise could exhibit rapid, non-linear behavior in the future which would render our model useless for projecting sea level rise. Recent observed Antarctic ice sheet destabilization exceeds rates predicted by ACC2, suggesting the model to be woefully unable to capture sea level dynamics. ACC2 also does not consider the sea level commitment beyond the course of the model run; *Plattner et al.* (2008) recently used a suite of GCMs to project a sea level commitment of 0.2 to 0.7 m additional rise beyond 2100 levels by 2300, due to GHG emissions over the 21st century. Such a commitment effected between 2000 and 2100 could easily exceed the WBGU guardrails. A longer model run (or incorporation of commitment) would be more useful for optimizing long-term change and economic stability, though longer runs would also likely run into the upper limits of the calibration of ACC2, thereby lessening the model's reliability.

Of more pressing concern is ocean acidification, which is likely to violate global mean guardrails this century, provided no emission management steps are taken. Fortunately, our analysis shows pH guardrails can be respected provided prompt, effective reductions in emissions. Emission pathways which respect pH guardrails are the most timely and unique as they had not been modelled explicitly prior to our study.

Even though pH guardrails are capable of being respected, this does not mean that coral reefs are safeguarded. Thermal bleaching is still a real danger; *Keller et al.* (2005) used cost-effective analysis in conjunction with guardrails applied to coral bleaching, and recommend large decreases in emissions by 2100 to avoid dangerous damage to the reefs.

General findings regarding our cost-effectiveness analysis include the importance of non-CO_2 GHGs in shaping optimal emissions pathways, which suggests regulation of a suite of gaseous pollutants to be prudent given the difficulty already faced with meeting temperature guardrails. Looking at the economics, costs of respecting WBGU guardrails range from 0% GWP annually for sea level rise to almost 6% GWP for temperature by 2100 for higher climate sensitivities. It is important to understand these costs do not include spending due to climate damages; this spending would be either legislated or voluntary for the specific purpose of meeting climate targets through de-carbonizing the economy. Whole percentage points of GWP may be considered significant; *Keller et al.* (2000) concluded that even a 1% reduction in GWP due to thermohaline slowdown warrants policy action. Delays in levels of consumption compared to business-as-usual range from months (in the first half of the next century), to years by 2100 for limiting ocean pH. This delay is expected to be even higher for the more stringent temperature guardrails.

Methodological criticisms from previous cost-effective analyses still hold for our research. The economically optimal pathways we calculate see the largest increases in spending after 2050. This delay is due to the positive discount rate used in DICE, discussed in Chapter 5. Future generations are valued less than the present one by the present generation, so economically it makes sense to burden the distant future with the cost of paying for de-carbonization. While empirically-based, this discount rate contributes to the mismatch between human and geologic time scales, a problem which dogs environmental efforts of all kinds. It does not allow for rational decision-making regarding abrupt climate change, because humans have no cultural memory, and hence no perspective, on risks. Using a negative discount rate, on the other hand, carries its own risks in that resultant policy decisions would not reflect the will of the people and could fail. Future tests of ACC2/DICE could include varying the discount rate to ascertain its impacts on optimal pathways.

The other contentious simplifying assumption in DICE which shapes our results is that of exogenous technological change, which produces higher costs than what would be the result of endogenous technological change (learning-by-doing) (*Edenhofer et al.* 2005). If DICE assumed that investments in research and development include improvements in energy efficiency, technology would become more carbon efficient and less carbon-intensive with increasing cost efficiency. The assumption of exogenous technological change does not match market data (*Grubb et al.* 1995), and therefore modifying DICE to accept learning-by-doing could substantially lower our estimates of cost.

The tolerable windows approach addresses another criticism of cost-effectiveness analysis in that instead of providing a stringent pathway which could easily be overshot, it calculates an optimal emissions corridor. Our analysis of WBGU marine guardrails (excluding temperature) using a climate sensitivity of 4℃ suggests emissions must stay within a corridor with an upper boundary which resembles present trends. The emission corridor boundaries represent the limit of intolerable climate change, so following the upper bound is not an acceptable option and would not respect the WBGU guardrails. The emissions corridor we calculate for preserving marine guardrails constrains emissions far below what GCM business-as-usual scenarios predict over the coming century. Even though we used a high climate sensitivity for this analysis, both sea level and pH guardrails showed a lack of dependence on the climate sensitivity value used, so these conclusions extend to lesser sensitivities as well. This tolerable corridor is similar in magnitude to one calculated by *Toth et al.* (2003b), using a limit of 40% of global protected ecosystems experiencing dramatic transformation.

Though this thesis represents over a year of investigation, there is more which could be done. Including a probability assessment of scientific as well as socio-economic parameters would increase understanding of the threats of economic and environmental degradation. Incorporating non-GHGs into the analysis by means of using CO_2-equivalent forcing would give a more complete picture of the costs of meeting climate guardrails. Using a regional model such as RICE (Regional Integrated model of Climate and the Economy, *Nordhaus and Yang* 1996) would highlight regional differences and could increase our understanding of differential affects. Application of a longer time-series would greatly enhance projections of sea level rise and the applicability of guardrails to long term goals. Adapting ACC2 to accept extremely high rates of ice sheet melting would enable the use of observed melting rates, which would also be very interesting as no integrated modelling studies presently take it into account. With respect to ocean acidification, inclusion of a dependency upon meltwater input from ice sheets would be interesting, even if limited to a first-order effect.

Bibliography

Andersson, A., F. Mackenzie, and L. Ver, Solution of shallow-water carbonates: An insignificant buffer against rising atmospheric CO2, *Geology*, *31*, 513–516, 2003.

Appel, A., After Katrina: tracking the toxic flood, *Nature*, *437*, 462, 2005.

Azar, C., and K. Lindgren, Catastrophic events and stochastic cost-benefit analysis of climate change, *Climatic Change*, *56*, 245–255, 2003.

Barras, J. A., Land area change in coastal Louisiana after the 2005 hurricanes- a series of three maps, U.S. Geological Survey Open-File Report 06-1274, http://pubs.usgs.gov/of/2006/1274/, 2006, accessed 26.06.08.

Bates, N., A. Pequignet, R. Johnson, and N. Gruber, A short-term sink for atmospheric CO_2 in subtropical mode water of the North Atlantic Ocean, *Nature*, *420*, 489–493, 2002.

Bindoff, N., et al., *Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, chap. Observations: Oceanic Climate Change and Sea Level, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2007.

Bolin et al., *The Greenhouse Effect, Climatic Change, and Ecosystems*, Wiley, Chichester, 1986.

Bosello, F., R. Roson, and R. S. J. Tol, Economy-wide estimates of the implications of climate change: Sea level rise, *Environmental & Resource Economics*, *37*, 549–571, 2007.

Brohan, P., J. Kennedy, I. Harris, S. Tett, and P. Jones, Uncertainty estimates in regional and global observed temperature changes: A new data set from 1850, *Journal of Geophysical Research (Atmospheres)*, *111*, 2006.

Brooke, A., D. Kendrick, and A. Meeraus, Gams: A user's guide, 1992.

Brown, D., The importance of expressly examining global warming policy issues through an ethical prism, *Global Environmental Change-Human and Policy Dimensions*, *13*, 229–234, 2003.

Bruckner, T., and K. Zickfeld, Low risk emissions corridors for safeguarding the Atlantic thermohaline circulation, *Mitigation and Adaptation Strategies of Global Change*, in press.

Bruckner, T., G. Petschel-Held, M. Leimbach, and F. Toth, Methodological aspects of the tolerable windows approach, *Climatic Change*, *56*, 73–89, 2003.

Buddemeier, R. W., J. A. Kleypas, and R. B. Aronson, *Coral reefs and global climate change: potential contributions of climate change to stresses on coral reef ecosystems*, Pew Center on Global Climate Change, Arlington, VA, 2004.

Burke, L., and J. Maidens, *Reefs at Risk- Analysis of Threats to Coral Reefs*, World Research Institute, Washington, DC, USA, 2004.

Cabanes, C., A. Cazenave, and C. Le Provost, Sea level change from Topex-Poseidon altimetry for 1993-999 and possible warming of the southern oceans, *Geophysical Research Letters*, *28*, 9–12, 2001.

Caldeira, K., and M. Wickett, Anthropogenic carbon and ocean pH, *Nature*, *425*, 365, 2003.

Cameron, O., K. Fukuwatari, and T. Morita (Eds.), *The Tolerable Windows Approach to Integrated Assessments*, IPCC, Tsukuba Japan, 1997.

CEQ, *To Breathe Clean Air*, Washington, DC, 1981a.

CEQ, *Global Energy Futures and the Carbon Dioxide Problem*, Washington, DC, 1981b.

Chao, B. F., Y. H. Wu, and Y. S. Li, Impact of artificial reservoir water impoundment on global sea level, *Science*, *320*, 212–214, 2008.

Church, J., and N. White, A 20th century acceleration in global sea-level rise, *Geophysical Research Letters*, *33*, 2006.

Corfee-Morlot, J., and N. Hohne, Climate change: long-term targets and short-term commitments, *Global Environmental Change - Human and Policy Dimensions*, *13*, 277–293, 2003.

Denman, K., et al., *Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, chap. Couplings Between Changes in the Climate System and Biogeochemistry, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2007.

Dessai, S., W. Adger, M. Hulme, J. Turnpenny, J. Kohler, and R. Warren, Defining and experiencing dangerous climate change - An editorial essay, *Climatic Change*, *64*, 11–25, 2004.

Dore, J., R. Lukas, D. Sadler, and D. Karl, Climate-driven changes to the atmospheric CO2 sink in the subtropical North Pacific Ocean, *Nature*, *424*, 754–757, 2003.

Easterling, W., et al., *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Inter-*

governmental Panel on Climate Change, chap. Food, fibre and forest products, pp. 273–313, Cambridge University Press, Cambridge, UK, 2007.

ECF, Report on the Beijing Symposium on Article 2, 2004, http://www.european-climate-forum.net/pdf/ECF_beijing_results.pdf.

Edenhofer, O., N. Bauer, and E. Kriegler, The impact of technological change on climate protection and welfare: Insights from the model MIND, *Ecological Economics*, *54*, 277–292, 2005.

Edwards, M., and A. Richardson, Impact of climate change on marine pelagic phenology and trophic mismatch, *Nature*, *430*, 881–884, 2004.

FAO, The state of world fisheries and aquaculture, ftp://ftp.fao.org/docrep/fao/009/a0699e/a0699e.pdf, Rome, Italy, 2006.

Fischlin, A., et al., *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, chap. Food, fibre and forest products, pp. 273–313, Cambridge University Press, Cambridge, UK, 2007.

Gardiner, S., Ethics and global climate change, *Ethics*, *114*, 555–600, 2004.

Gardner, T., I. Cote, J. Gill, A. Grant, and A. Watkinson, Hurricanes and Caribbean coral reefs: Impacts, recovery patterns, and role in long-term decline, *Ecology*, *86*, 174–184, 2005.

Gonzalez-Davila, M., J. Santana-Casiano, M. Rueda, O. Llinas, and E. Gonzalez-Davila, Seasonal and interannual variability of sea-surface carbon dioxide species at the European Station for Time Series in the Ocean at the Canary Islands (ESTOC) between 1996 and 2000, *Global Biogeochemical Cycles*, *17*, 2003.

Government of Canada, 1929-1939 - the great depression, http://www.canadianeconomy.gc.ca/English/economy/1929_39depression.html, 2007, accessed 01/11/2008.

Grebmeier, J., et al., A major ecosystem shift in the northern Bering Sea, *Science*, *311*, 1461–1464, 2006.

Grubb, M., T. Chapuis, and M. Duong, The Economics Of Changing Course - Implications of Adaptability and Inertia for Optimal Climate Policy, *Energy Policy*, *23*, 417–431, 1995.

Gruber, N., C. Keeling, and N. Bates, Interannual variability in the North Atlantic Ocean carbon sink, *Science*, *298*, 2374–2378, 2002.

Guinotte, J., R. Buddemeier, and J. Kleypas, Future coral reef habitat marginality: temporal and spatial effects of climate change in the Pacific basin, *Coral Reefs*, *22*, 551–558, 2003.

Hammitt, J., Evaluation endpoints and climate policy: Atmospheric stabilization, benefit-cost analysis, and near-term greenhouse-gas emissions, *Climatic Change*, *41*, 447–468, 1999.

Hansen, J., R. Ruedy, M. Sato, M. Imhoff, W. Lawrence, D. Easterling, T. Peterson, and T. Karl, A closer look at United States and global surface temperature change, *Journal of Geophysical Research (Atmospheres)*, *106*, 23,947–23,963, 2001.

Hartig, E., V. Gornitz, A. Kolker, F. Mushacke, and D. Fallon, Anthropogenic and climate-change impacts on salt marshes of Jamaica Bay, New York City, *Wetlands*, *22*, 71–89, 2002.

Haslett, S., A. Cundy, C. Davies, E. Powell, and I. Croudace, Salt marsh, sedimentation over the past 120 years along the West Cotentin Coast of Normandy (France):

Relationship to sea-level rise and sediment supply, *Journal of Coastal Research*, *19*, 609–620, 2003.

Hegerl, G., F. Zwiers, P. Braconnot, N. Gillett, Y. Luo, J. M. Orsini, N. Nicholls, H. Penner, and P. Stott, *Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, chap. Understanding and Attributing Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2007.

Holgate, S., and P. Woodworth, Evidence for enhanced coastal sea level rise during the 1990s, *Geophysical Research Letters*, *31*, 2004.

Hooss, G., R. Voss, K. Hasselmann, E. Maier-Reimer, and F. Joos, A nonlinear impulse response model of the coupled carbon cycle-climate system (NICCS), *Climate Dynamics*, *18*, 189–202, 2001.

IMBER, Science plan and implementation strategy, *IGBP Report 52*, IGBP Secretariat, Stockholm, 2005, `http://www.igbp.net/documents/resources/report-52.pdf`.

IPCC AR4 WG1, *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, 2007.

IPCC RSWG, *Climate Change: The IPCC Response Strategies*, Island Press, Washington, DC, 1990.

IPCC TAR WG1, *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge, United Kingdom and New York, NY, 2001.

Jager, J., and H. Ferguson (Eds.), *Climate Change: Science, Impacts and Policy-Proceedings of the Second World Climate Conference*, WMO, Cambridge University Press, 1990.

Janssen, M., and B. De Vries, Climate change policy targets and the role of technological change, *Climatic Change*, *46*, 1–28, 2000.

Joos, F., I. Prentice, S. Sitch, R. Meyer, G. Hooss, G. Plattner, S. Gerber, and K. Hasselmann, Global warming feedbacks on terrestrial carbon uptake under the Intergovernmental Panel on Climate Change (IPCC) emission scenarios, *Global Biogeochemical Cycles*, *15*, 891–907, 2001.

Keller, K., K. Tan, F. Morel, and D. Bradford, Preserving the ocean circulation: Implications for climate policy, *Climatic Change*, *47*, 17–43, 2000.

Keller, K., M. Hall, S. Kim, D. Bradford, and M. Oppenheimer, Avoiding dangerous anthropogenic interference with the climate system, *Climatic Change*, *73*, 227–238, 2005.

Kleinen, T., and G. Petschel-Held, Integrated assessment of changes in flooding probabilities due to climate change, *Climatic Change*, *81*, 283–312, 2007.

K.M. Lugina, e. a., *Trends: A Compendium of Data on Global Change*, chap. Monthly surface air temperature time series area-averaged over the 30-degree latitudinal belts of the globe, 1881-2004, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, TN, 2005, `http://cdiac.esd.ornl.gov/trends/temp/lugina/lugina.htm`.

Kriegler, E., *Imprecise Probability Analysis for Integrated Assessment of Climate Change*, Ph.D. thesis, University of Potsdam, 2005.

Lemke, P., et al., *Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, chap. Observations: Changes in Snow, Ice and Frozen Ground, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2007.

Leuliette, E. W., R. S. Nerem, and G. T. Mitchum, Calibration of TOPEX/Poseidon and Jason Altimeter data to construct a continuous record of mean sea level change, *Marine Geodesy*, *27*, 79–94, 2004.

Manne, A., R. Mendelsohn, and R. Richels, A Model for Evaluating the Regional and Global Effects of GHG Reduction Policies, *Energy Policy*, *23*, 17–34, 1995.

Mastrandrea, M., and S. Schneider, Probabilistic integrated assessment of "dangerous" climate change, *Science*, *304*, 571–575, 2004.

McWilliams, J., I. Cote, J. Gill, W. Sutherland, and A. Watkinson, Accelerating impacts of temperature-induced coral bleaching in the Caribbean, *Ecology*, *86*, 2055–2060, 2005.

Meehl, G., et al., *Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, chap. Global Climate Projections, Cambridge University Press, 2007.

Metz, B., et al. (Eds.), *IPCC Special Report on Safeguarding the Ozone Layer and the Global Climate System: Issues related to Hydrofluorocarbons and Perfluorocarbons*, Cambridge University Press, Cambridge, UK and New York, NY, 2005.

Milly, P., A. Cazenave, and M. Gennero, Contribution of climate-driven change in continental water storage to recent sea-level rise, *Proceedings of the National Academy of Sciences of the United States of America*, *100*, 13,158–13,161, 2003.

Mimura, N., and P. Nunn, Trends of beach erosion and shoreline protection in rural Fiji, *Journal of Coastal Research*, *14*, 37–46, 1998.

Montgomery, W., and A. Smith, Global climate change and the precautionary principle, *Human and Ecological Risk Assessment*, *6*, 399–412, 2000.

Nakicenovic, N., and R. Swart (Eds.), *Special Report on Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK, 2000.

National Research Council (NRC), *Energy and Climate*, Washington, DC, 1977.

Nicholls, R., Coastal flooding and wetland loss in the 21st century: changes under the SRES climate and socio-economic scenarios, *Global Environmental Change - Human and Policy Dimensions*, *14*, 69–86, 2004.

Nicholls, R., and R. Tol, Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over the twenty-first century, *Philosophical Transactions of the Royal Society A -Mathematical Physical and Engineering Sciences*, *364*, 1073–1095, 2006.

Nicholls, R., P. P. Wong, V. Burkett, J. Codignotto, J. Hay, R. McLean, S. Ragoonaden, and C. Woodroffe, *Climate Change 2007: Climate Change Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, chap. Coastal Systems and Low-Lying Areas, pp. 315–356, Cambridge University Press, Cambridge, UK, 2007.

NOAA, Billion dollar U.S. weather disasters, 1980-2007, `http://www.ncdc.noaa.gov/oa/reports/billionz.html`, 2007, accessed 26.06.08.

Noordwijk Declaration, Noordwijk declaration on atmospheric pollution and climate change, *International Environmental Reporter*, Vol. 12, p.624, 1989, reprinted December 13, 1989.

Nordhaus, W., *The Efficient Use of Energy Resources*, chap. Strategies for the control of carbon dioxide, Yale University Press, New Haven, 1979.

Nordhaus, W., *Managing the Global Commons*, MIT Press, 1994.

Nordhaus, W., Critical assumptions in the Stern review on climate change, *Science*, *317*, 201–202, 2007.

Nordhaus, W., and Boyer, *Warming the World: Economic Models of Global Warming*, MIT Press, Cambridge, MA, 2000.

Nordhaus, W., and Z. Yang, A regional dynamic general-equilibrium model of alternative climate-change strategies, *AMERICAN ECONOMIC REVIEW*, *86*, 741–765, 1996.

Ohde, S., and M. Hossain, Effect of CaCO3 (aragonite) saturation state of seawater on calcification of Porites coral, *Geochemical Journal*, *38*, 613–621, 2004.

O'Neill, B., and M. Oppenheimer, Climate change - Dangerous climate impacts and the Kyoto protocol, *Science*, *296*, 1971–1972, 2002.

Oppenheimer, M., and A. Petsonk, Article 2 of the UNFCCC: Historical origins, recent interpretations, *Climatic Change*, *73*, 195–226, 2005.

Parry, M., et al., Millions at risk: defining critical climate change threats and targets, *Global Environmental Change - Human and Policy Dimensions*, *11*, 181–183, 2001.

Pauly, D., R. Watson, and J. Alder, Global trends in world fisheries: impacts on marine ecosystems and food security, *Philosophical Transactions of the Royal Society B - Biological Sciences*, *360*, 5–12, 2005.

Petschel-Held, G., and H. Schellnhuber, *Cost-Benefit Analysis of Climate Change: The Broader Perspectives*, chap. The Tolerable Windows Approach to Climate Control: Optimization, Risks and Perspectives', Birkhauser, Switzerland, 1997.

Petschel-Held, G., H. Schellnhuber, T. Bruckner, F. Toth, and K. Hasselmann, The tolerable windows approach: Theoretical and methodological foundations, *Climatic Change*, *41*, 303–331, 1999.

Plattner, G. K., et al., Long-term climate commitments projected with climate-carbon cycle models, *JOURNAL OF CLIMATE*, *21*, 2721–2751, 2008.

Programme, U. N. E., Montreal protocol on substances that deplete the ozone layer, reprinted in 26 I.L.M. 1550, 1987, text available at `www.unep.org`.

Rabalais, N., R. Turner, and W. Wiseman, Gulf of Mexico hypoxia, aka "The dead zone", *Annual Review of Ecology and Systematics*, *33*, 235–263, 2002.

Rahmstorf, S., and K. Zickfeld, Thermohaline circulation changes: A question of risk assessment - An editorial review essay, *CLIMATIC CHANGE*, *68*, 241–247, 2005.

Raven et al., Ocean acidification due to increasing atmospheric carbon dioxide, 2005.

Rijsberman, F., and R. Swart (Eds.), *Targets and Indicators of Climate Change*, Stockholm Environment Institute, Stockholm, 1990.

Rive, N., A. Torvanger, T. Berntsen, and S. Kallbekken, To what extent can a long-term temperature target guide near-term climate change commitments?, *CLIMATIC CHANGE*, *82*, 373–391, 2007.

Rosenzweig, C., et al., *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, chap. Assessment of observed changes and responses in natural and managed systems, pp. 79–131, Cambridge University Press, Cambridge, UK, 2007.

Schneider, S., and J. Lane, *Avoiding Dangerous Climate Change*, chap. An Overview of 'Dangerous' Climate Change, pp. 81–91, Cambridge University Press, 2006.

Schneider, S., and M. Mastrandrea, Probabilistic assessment "dangerous" climate change and emissions pathways, *Proceedings of the National Academy of Sciences of the United States of America*, *102*, 15,728–15,735, 2005.

Schneider, S., and L. Mesirow, Genesis Strategy - Climate and Global Survival, *Futurist*, *10*, 192–197, 1976.

Schneider, S., et al., *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, chap. Assessing key vulnerabilities and the risk from climate change, pp. 779–810, Cambridge University Press, Cambridge, UK, 2007.

Schwoon, M., and R. S. J. Tol, Optimal CO2-abatement with socio-economic inertia and induced technological change, *Energy Journal*, *27*, 25–59, 2006.

Small, C., and R. Nicholls, A global analysis of human settlement in coastal zones, *Journal of Coastal Research*, *19*, 584–599, 2003.

SMIC, Inadvertent climate modification, in *The Study of Man's Impact on Climate (SMIC)*, edited by C. M. Wilson and W. H. Matthews, p. 308, MIT Press, Cambridge, MA, 1971.

Smith, T., and R. Reynolds, A global merged land-air-sea surface temperature reconstruction based on historical observations (1880-1997), *Journal of Climate*, *18*, 2021–2036, 2005.

Stern, N., *The Economics of Climate Change*, Cambridge University Press, 2007.

Tanaka, K., and E. Kriegler, *Aggregated Carbon Cycle, Atmospheric Chemistry, and Climate Model (ACC2): Description of the forward and inverse modes*, Max Planck Institute for Meteorology, 2007.

Tol, R., Is the uncertainty about climate change too large for expected cost-benefit analysis?, *Climatic Change*, *56*, 265–289, 2003.

Tol, R., The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties, *Energy Policy*, *33*, 2064–2074, 2005.

Tonn, B., An equity first, risk-based framework for managing global climate change, *Global Environmental Change - Human and Policy Dimensions*, *13*, 295–306, 2003.

Toth, F., T. Bruckner, H. Fussel, M. Leimbach, and G. Petschel-Held, Integrated assessment of long-term climate policies: part 1 - Model presentation, *Climatic Change*, *56*, 37–56, 2003a.

Toth, F., T. Bruckner, H. Fussel, M. Leimbach, and G. Petschel-Held, Integrated assessment of long-term climate policies: part 2 - Model results and uncertainty analysis, *Climatic Change*, *56*, 57–72, 2003b.

Trenberth, K., et al., *Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, chap. Observations: Surface and Atmospheric Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2007.

UNDP, Reducing disaster risk: A challenge for development, `http://www.undp.org/bcpr/disred/rdr.htm`, 2004.

UNFCCC, United nations framework convention on climate change, in *United Nations Framework Convention on Climate Change*, p. 25, United Nations, United Nations, 1992.

van der Wal, D., and K. Pye, Patterns, rates and possible causes of saltmarsh erosion in the Greater Thames area (UK), *Geomorphology*, *61*, 373–391, 2004.

Walther, G., E. Post, P. Convey, A. Menzel, C. Parmesan, T. Beebee, J. Fromentin, O. Hoegh-Guldberg, and F. Bairlein, Ecological responses to recent climate change, *Nature*, *416*, 389–395, 2002.

WBGU, *Climate Protection Strategies for the 21st Century: Kyoto and Beyond*, 2003a, `http://www.wbgu.de/wbgu_sn2003_engl.html`.

WBGU, *The Future Oceans- Warming Up, Rising High, Turning Sour* , 2006b.

WCCA, *Statement on Implications for Global Security*, World Conference on the Changing Atmosphere, 1988, reprinted as World Meteorological Organization and United Nations Environment Program WMO/OMM Doc.710(1989).

Weart, S., The discovery of the risk of global warming, *Physics Today*, *50*, 34–40, 1997.

Webster, P., G. Holland, J. Curry, and H. Chang, Changes in tropical cyclone number, duration, and intensity in a warming environment, *Science*, *309*, 1844–1846, 2005.

Wilbanks, T., P. R. Lankao, M. Bao, F. Berkhout, S. Cairncross, F.-P. Ceron, M. Kapshe, R. Muir-Wood, and R. Zapata-Marti, *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, chap. Food, fibre and forest products, pp. 357–390, Cambridge University Press, Cambridge, UK, 2007.

Wilkinson, J., *Status of Coral Reefs in the World*, Australian Institute of Marine Science, Townsville, Australia, 2004.

WMO, *Developing Policies for Responding to Climatic Change, A Summary of the Discussions and Recommendations of the Workshops Held in Villach (28 September- 2 October 1987) and Bellagio (9-13 November 1987)*, WMO/TD 225, Beijer Institute, Stockholm, Geneva, 1988.

WMO, Scientific assessment of ozone depletion: 2002, Global Ozone Research and Monitoring Project, *Report No. 47*, 2003.

Wolters, M., J. Bakker, M. Bertness, R. Jefferies, and I. Moller, Saltmarsh erosion and restoration in south-east England: squeezing the evidence requires realignment, *Journal of Applied Ecology*, *42*, 844–851, 2005.

Wood, R. M., S. Miller, and A. Boissonnade, The search for trends in a global catalogue of normalized weather-related catastrophe losses, in *Workshop on Climate Change and Disaster Losses: Understanding and Attributing Trends and Projections*, Hohenhammer, Munich, 2006.

Wright, E., and J. Erickson, Incorporating catastrophes into integrated assessment: Science, impacts, and adaptation, *Climatic Change*, *57*, 265–286, 2003.

Yamin, F., J. Smith, and I. Burton, *Avoiding Dangerous Climate Change*, chap. Perspectives on 'Dangerous Anthropogenic Interference'; or How to Operationalize Article 2 of the UN Framework Convention on Climate Change, pp. 81–91, Cambridge University Press, 2006.

Zeebe, R. E., J. C. Zachos, K. Caldeira, and T. Tyrrell, Oceans - Carbon emissions and acidification, *SCIENCE*, *321*, 51–52, 2008.

Zhang, K., B. Douglas, and S. Leatherman, Twentieth-century storm activity along the US east coast, *Journal of Climate*, *13*, 1748–1761, 2000.