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Lesson 8 - Projected Climate Changes, part 2

The links below provide an outline of the material for this lesson. Be sure to carefully read through the entire lesson before returning to Canvas to submit your assignments.

Introduction

About Lesson 8

We will now look at some of the more subtle, and indeed, less certain, future climate changes projected by climate models. These include changes in the cryosphere—that is glaciers, ice sheets, and sea ice; changes in sea level, which reflect an integration of a number of factors including melting ice and warming oceans; and changes in extreme weather events including tropical cyclones. While it is more difficult to accurately project changes in these attributes of the climate system, their profound potential impact on civilization and our environment necessitate their consideration.

What will we learn in Lesson 8?

By the end of Lesson 8, you should be able to:

- qualitatively assess the potential impacts of increasing greenhouse gas concentrations on the distribution of ice on the Earth's surface, global sea level, tropical storm activity, severe weather, and other relevant climatic and meteorological phenomena;
- discuss the potential importance of carbon cycle feedbacks; and
- discuss the concept of climate tipping points, and their potential impacts.

What will be due for Lesson 8?

Please refer to the Syllabus for specific time frames and due dates.

The following is an overview of the *required activities* for Lesson 8. Detailed directions and submission instructions are located within this lesson.

- Participate in Lesson 8 discussion forum: Climate Change Projections.
- Read:
  - IPCC Fifth Assessment Report, Working Group 1 [1]
  - Summary for Policy Makers [2], Future Global and Regional Climate Change
    - E.4 Ocean: p. 24
    - E.5 Cryosphere: p. 24-25
    - E.6 Sea Level: p. 25-26
    - E.7 Carbon and Other Biogeochemical Cycles: p. 26-27
  - Dire Predictions, v.2: p. 110-117

Questions?

If you have any questions, please post them to our *Questions?* discussion forum (not e-mail), located under the Home tab in Canvas. The instructor will check that discussion forum daily to respond. Also, please feel free to post your own responses if you can help with any of the posted questions.

Sea Ice, Glaciers, Ice Sheets

Critics often argue that climate scientists are alarmist and overstate projections of future climate change (if you have any doubt about this, just do a Google news search [3] on e.g., "warming" and "alarmist" and see what turns up—warning: the Internet is a wild frontier of information, misinformation, and outright disinformation—you should always question the objectivity and qualifications of any apparent news sources).

Ironically, in many cases, the climate science community has been overly cautious and conservative in their projections (see for example this review by Rahmstorf et al. in the journal *Science* [4]), perhaps, in part, out of fear of being labeled as alarmist by its detractors). One case in point is the decline in Arctic summer sea ice extent. The decline in minimum summer Arctic sea ice has outpaced even the most dramatic of the IPCC projections in recent decades. One possibility is that there is missing physics involved —related, for example, to the mechanics of ice fracturing and deformation, that is causing the models to underpredict the fragility of sea ice and the possible feedbacks involved.

Following the dramatic decline of summer 2007 (the minimum value in the red curve below), there was even fear that we had crossed a previously unknown *tipping point* from which Arctic sea ice would not be able to recover (we will have far more to say about possible climate *tipping points* [5]later in this lesson). If so, that would have dire implications for, e.g., animal species such as the polar bear, which require sea ice environment for their existence. Recent scientific work suggests that there is no such tipping point, however, and that the environment of the polar bear can be preserved given ongoing efforts aimed at mitigating future climate change (see this news account [6] from the Churchill "Plight of The Polar Bear" video [7] introduced in our first lesson—you may recognize the lead scientist on the study, Steven Amstrup,). Those efforts would not be easy, however; the study finds that future warming would have to be kept below 1.25°C, which corresponds to roughly 2°C warming relative to pre-industrial time. As we have seen before, such a target would likely require stabilizing CO_2 concentrations at 450 ppm or lower.

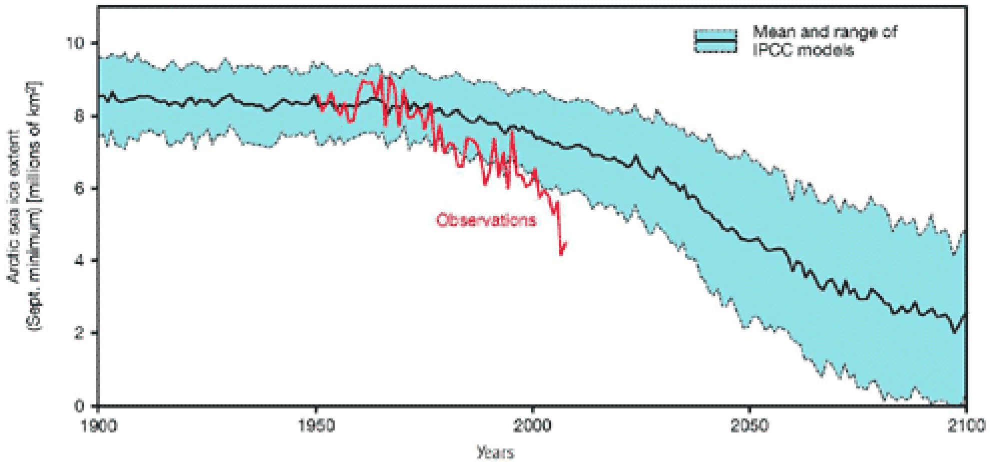


Figure 8.1: Observed Trend in Summer Minimum Arctic Sea Ice Extent Compared Against IPCC Model Historical Simulations and Projections.
Credit: The Copenhagen Diagnosis [8]

One problem that declining sea ice does not contribute to (at least, not to any practical extent) is the problem of global sea level rise. The melting of land ice, nonetheless, will contribute to sea level rise. As we saw in a previous lesson, mountain glaciers and ice caps around the word have undergone substantial retreat [9] over the past century. They are projected to contribute a fraction of a meter of sea level rise over the next century (for example, see this news article about a study recently published in the journal *Nature Geoscience* [10]).

The melting of the major continental ice sheets will also contribute to future sea level rise. This is part of the reason that so much attention is paid to the stability of the two major ice sheets: the Antarctic and Greenland ice sheets. In a previous lesson, we already saw that the two ice sheets appear to have entered into a regime of negative mass balance, i.e., they are now losing ice [9]. Let us take a look at the best available projections for what is likely to happen to these ice sheets under a global warming scenario.

Shown below is a simulation of the process of Antarctic sea ice retreat in response to global warming. The simulation was done by one of the leading ice sheet modelers, Penn State's own David Pollard [11]. As we see here, it is primarily the low elevation West Antarctic half of the Ice Sheet that is prone to melting, and the process of collapse, at least in this simulation, is potentially quite slow, occurring on the millennial timescale.

Simulation of collapse of West Antarctic ice sheet in global warming scenario.
Credit: Penn State Earth System Science Center [12]

A similar finding is obtained for the Greenland ice sheet. Shown below is a simulation using NCAR climate model coupled to a dynamical model of the Greenland ice sheet. This particular simulation suggests that it might take a millennium or longer for substantial loss of Greenland ice due to projected global warming.

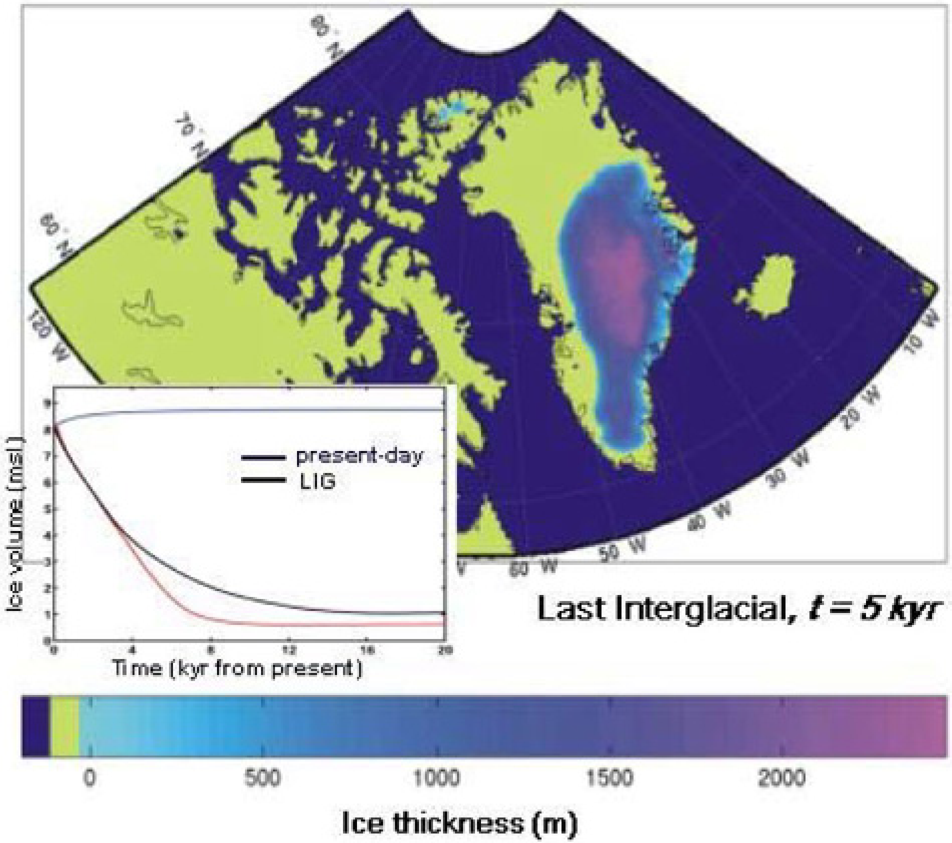
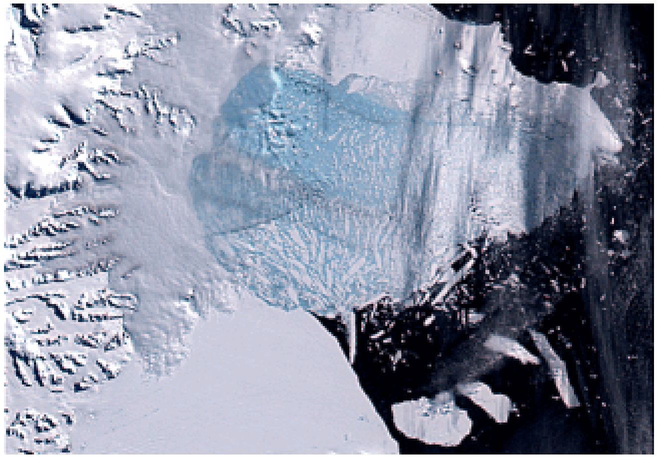


Figure 8.2: Simulation of Climate Change Influence on Greenland Ice Sheet Based on NCAR Climate Model (the red curve Indicates the response to an anthropogenic quadrupling of CO2 concentrations relative to pre-industrial levels).
Credit: National Center for Atmospheric Research [13]

Yet, processes discussed on the Sea Ice page of Lesson 3 [9] could lead to ice sheet collapse on timescales much faster than suggested by these model simulations. The formation of fissures known as *moulins* allow meltwater to penetrate to the bottom of the ice sheet, where it lubricates the base of the ice sheet, allowing ice to be more easily exported through ice streams out into the ocean. The physics responsible for this phenomenon are not well represented in current ice sheet models.

Figure 8.3: A moulin that formed in the Greenland ice sheet.
Credit: Roger Braithwaite, UNEP

Another effect that is not well represented by the models is the *buttressing* effect provided by ice shelves. Ice shelves provide support to the interior ice sheet through an effect not unlike that of the flying buttress [14] employed so widely in medieval architecture. As the ice shelves themselves disintegrate, there is the potential for destabilization of the inland ice, which is then free to break up and calve into the ocean. This effect was well documented during the disintegration of the Larsen B ice shelf of the Antarctic Peninsula in January-March (austral summer) 2002. The ice shelf, roughly the size of the state of the Rhode Island, disintegrated in little over a month. In the months following the breakup of the ice shelf, an acceleration in the streaming of inland ice to the ocean was observed, suggesting the possibility that such dynamical processes could accelerate the collapse of the West Antarctic ice sheet—the part of the Antarctic Ice Sheet most susceptible to break-up as a rule of anthropogenic warming. An even more recent, though less dramatic, example is discussed here. [15] Once again, the observation of such processes in nature, and the fact that the ice sheets already appear to be losing ice mass [9], suggests that the breakup of continental ice shelves could proceed considerably faster than is suggested by current generation ice sheet models.



Collapse of Larsen ice shelf B during Jan-Mar 2002.
Credit: National Snow and Ice Data Center [16]

Regardless of the precise timescale of decay of the continental ice sheets, it is quite possible, as discussed in the "Greenland ice sheet faces 'tipping point in 10 years' " [17] article by Richard Alley [18]—another of the world's leading ice sheet experts also here at Penn State—that we might commit to the melting of the Greenland ice sheet much sooner than the models project—in as soon as a decade—by reaching a critical level of greenhouse gases in the atmosphere whereby we commit to the initial warming necessary to set in motion the sequence of positive feedbacks leading to the ultimate destruction of the ice sheet. Once again, we encounter the notion of a *tipping point*—a notion to be explored later in this lesson.

Sea Level Change

There are several components involved in projecting future sea level. One—the thermal expansion of the oceans, is fairly straightforward, and the only real uncertainty involved with that component is the warming itself, and the rate at which it is mixed down beneath the ocean surface. This contribution is projected to be modest, amounting to only a fraction of a meter over the next century. The 2nd component is the contribution from melting mountain glaciers and ice caps. This contribution, too, is likely to be modest, only a small fraction of a meter within the next century. The 3rd contribution—that from the melting of the two major ice sheets—is both the largest and the most uncertain.

As alluded to earlier, even modest additional warming could set in motion the collapse of all or most of the Greenland Ice Sheet (which would add 5-7 meters of sea level rise) and the west Antarctic Ice Sheet (which would add roughly another 5 meters). In our discussion of the projected changes in the Greenland and Antarctic Ice Sheet in the previous section, we saw that there are significant uncertainties regarding the timescale of this disintegration, however. Current ice sheet models suggest that the collapse of the ice sheets may take many centuries. Yet we know there are reasons to be skeptical about current ice sheet models. They are missing some physics that appears to be important in the real world—i.e., the physics responsible for the formation of moulins, and the possible lost of buttressing support by decaying ice shelves—that could allow for much faster disintegration. Indeed, the very same ice sheet models that predict a slow, multi-century breakup of the ice sheets did not predict that ice sheet loss would be observed for many decades, and yet, as we have seen that this loss already appears to be underway [9].

The uncertainties in projecting the ice sheet melt obviously complicate projections of future sea level rise, since this is potentially the largest contributor to global sea level rise. In the IPCC AR4 report from 2007, the IPCC simply neglected this contribution because they considered it too uncertain to estimate. This means that that their formal projections were almost certainly an absolute lowest estimate. (However, the IPCC AR5 report does include an estimate of the ice sheet contribution, leading to an increased sea level change projection of about 0.60 m by 2100 under SRES A1B.) Is it possible to provide a more realistic estimate? German climate scientist Stefan Rahmstorf [19] and collaborators have used an alternative, so-called semi-empirical approach to projecting future sea level rise. This approach uses the historical relationship between past changes in sea level rise and global mean temperature to construct a statistical model, and, in principle, incorporates the contribution from melting ice sheets, though obviously with some amount of uncertainty. The semi-empirical projections suggest the possibility of more than a meter (roughly 3 feet) of sea level rise by 2100, and more than 3 meters (roughly 9 feet) of sea level rise by 2200. We will look at the likely impacts of such amounts of sea level rise when we focus on climate change impacts later on in the course.

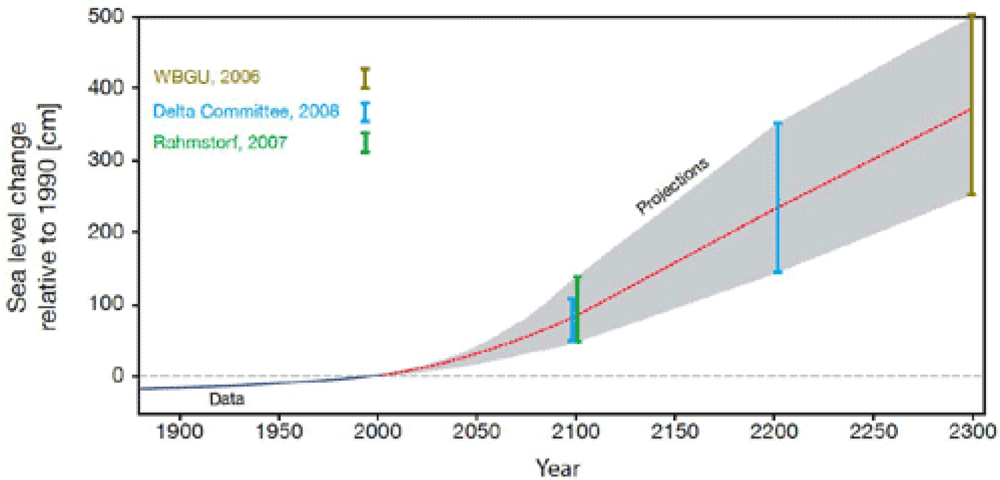


Figure 8.4: Projections of future global sea level rise ranging over the various IPCC scenarios, based on semi-empirical projections. Credit: The Copenhagen Diagnosis [8]

This example also provides a nice introduction to the concept of semi-empirical models. We will examine a similar semi-empirical modeling approach in our discussion of projected changes in Atlantic tropical cyclone activity in the next section.

Tropical Cyclones / Hurricanes

Like global sea level rise, climate change impacts on tropical cyclone activity could have profound societal and environmental implications. And, as with global sea level rise, impacts of tropical cyclone activity represent a substantial challenge scientifically, as there are many uncertainties that are involved. Tropical cyclones occur at spatial scales that are not well resolved by current generation climate models. Various approaches have been used to try to get around this problem, and you can find a discussion by your course author of the relative merits of these different approaches on the RealClimate website [20].

One approach has been to take a finer-scale atmospheric model that is capable of producing tropical cyclone or at least tropical cyclone-like disturbances, and nest it within a larger-scale climate model. The large-scale boundary conditions from the climate model simulation are then used to drive the storm-resolving model. However, the storm-resolving models used do not generally resolve the critical inner core region of the tropical cyclone, and the cyclones produced are not especially realistic. The models, for these reasons, cannot reproduce major hurricanes (category 4 or 5), and, for this reason, one might call into question their ability to capture changes in hurricane behavior associated with climate change.

An alternative approach used by hurricane scientist Kerry Emanuel [21] of MIT employs embedded modeling. Small-scale disturbances, similar to those that generate real-world tropical cyclones, are randomly distributed in a climate model in a way that mimics the distribution of real world disturbances. Some of these disturbances will find themselves in a favorable environment, others will not—that is determined by the large-scale climate as represented by the climate model. A finely resolved dynamical model, that does indeed resolve the key inner core structure of a tropical storm, is embedded within the climate model and is used to track each such disturbance and model any potential development and intensification. Using this approach, Emanuel is able to closely match the observed tropical cyclone climatologies (i.e., the numbers and intensities of tropical cyclones) in the various basins of tropical cyclone activity. He is also able to reproduce the observed trend, including the increase in tropical cyclone numbers and intensities in the Atlantic in recent decades, when he uses the actual large-scale observations—in place of a climate model simulation—to drive his model of tropical cyclone genesis and intensification.

So, what results does this approach yield when driven with projections of future climate change? The results of the analysis are shown below. What we see, first of all, is that there is quite a bit of variability in the results you get, depending on (a) which particular climate model projection is used and (b) which particular tropical cyclone-producing basin you are looking at. Globally, the number of tropical cyclones may actually *decrease*, but the power dissipation and intensity are projected to *increase* globally. We are particularly interested in Atlantic tropical cyclones and hurricanes, since they pose the greatest threat as far as North American impacts are concerned.

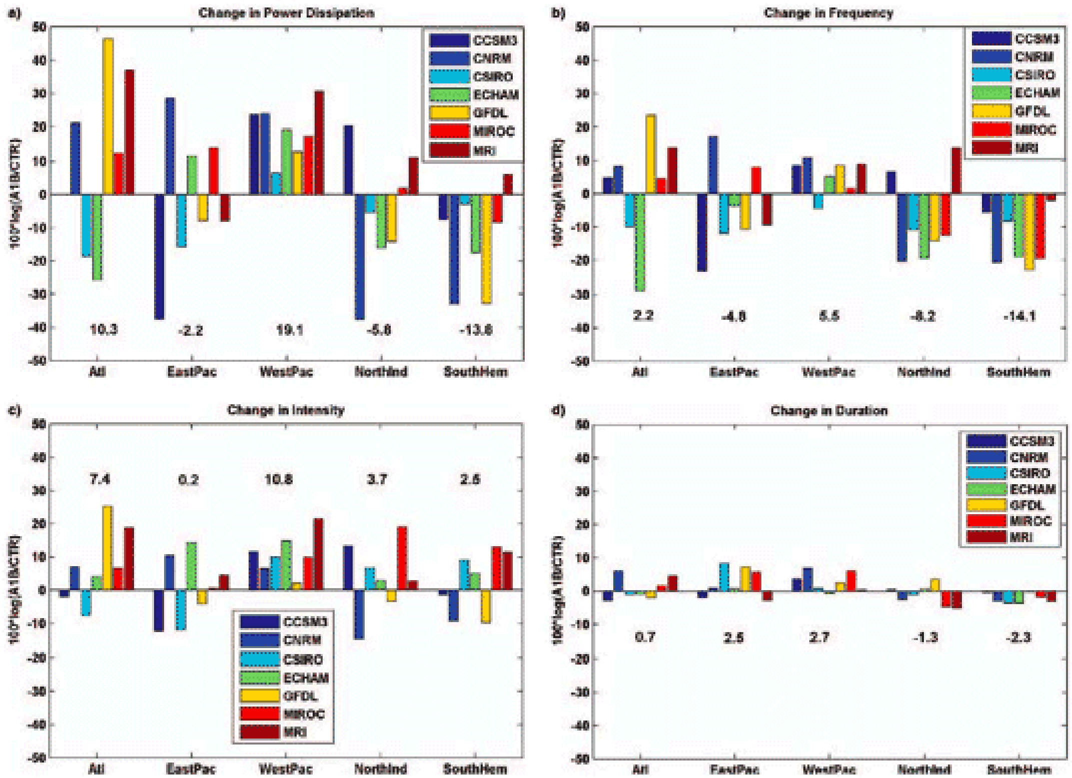


Figure 8.5: Projected changes in Tropical Cyclone Characteristics in various basins over the next two centuries based on the A1B projections based on an embedded modeling approach.
Credit: Emanuel et al, Hurricanes and Global Warming, Bulletin of the American Meteorological Society, 347-367, DOI:10.1175/BAMS-89-3-347, 2008.

We see that majority of the models yield a substantial increase in power/intensity of Atlantic tropical cyclones. A majority also indicate an increase in the number of Atlantic tropical cyclones, but this is highly variable, with at least one of the seven models examined indicating a substantial decrease. The divergence among the various projections of the different models reflects the competition between factors favoring increased power and activity—e.g., warmer oceans and greater energy for driving storms—and other factors, such as changes in atmospheric conditions influencing, e.g., vertical wind shear, that are tied to dynamical changes in the climate system. In particular, the uncertainty in projecting changes in ENSO dynamics (from Lesson 7) [22] comes into play here. El Niño events are associated with increased wind shear over key regions of the Caribbean and tropical Atlantic where tropical cyclone tend to form, so a more El Niño-like climate would tend to mitigate any increases in Atlantic tropical cyclone activity. By contrast, a more La Niña-like climate would mean an even more favorable atmospheric environment. So, the current uncertainty in projecting changes in ENSO and the Walker Circulation translate to uncertainties in projecting future changes in Atlantic tropical cyclone activity.

Yet, an entirely different approach to projecting changes in tropical cyclone activity involves the use of a *semi-empirical approach* similar in spirit to the semi-empirical modeling approach we encountered in our study of sea level rise projections in the previous section. The semi-empirical approach involves, once again, using a statistical model to relate the phenomenon of interest (tropical cyclone activity) to the climate factors we know appear to govern year-to-year changes in activity today (e.g., tropical Atlantic SSTs, El Niño, and the North Atlantic Oscillation). In fact, you may recall that this is the very same statistical model that you constructed yourself in problem set #2 [23] using these three factors as predictors of Atlantic annual tropical cyclone numbers in a multivariate regression. That approach has been validated, to some extent, by comparisons of predictions of pre-historical changes in Atlantic tropical cyclone activity with geological records of Atlantic tropical cyclone activity spanning the past millennium. You can hear about some work the course author has done in this area in this NSF video press conference [24].

We are now going to use the very same statistical model you developed in problem set #2 to project future changes in Atlantic tropical cyclone numbers. You can vary the predicted tropical Atlantic warming (over the rough range of IPCC projected changes in global mean temperature over the next century), and you can vary the scenario for how ENSO will change (anywhere from a substantial trend toward an El Niño-like state, i.e., positive Niño3 index values, to a substantial trend toward a La Niña-like state, i.e., negative Niño3 index values). For simplicity, we will assume that the NAO remains fixed at its modern day average (its role in the statistical model is pretty minute anyway). Applying the regression coefficients of the statistical model to these climate change projections then yields a semi-empirical projection of future annual Atlantic tropical cyclone numbers. The flash application is provided below—please play around with the two dropdown boxes in the lower part of the figure below and get a sense of how the range of uncertainty in the climate change projections translates to uncertainty in projected future tropical cyclone activity.

Be prepared to discuss your findings in this week's discussion forum.

Extreme Weather

We saw earlier in the course [25] that climate change already appears to have influenced the frequency and intensity of various types of extreme weather events. The observed warming so far amounts to less than a 1°C relative to pre-industrial time. Given projected warming of several more degrees C over the next century (depending on the precise emissions scenario), the future increases in extreme weather events can be expected to be far larger than what we have observed thus far.

A large increase in the incidence of extreme precipitation events is expected. As we know, warmer oceans evaporate water into the atmosphere at a faster rate, and a warmer atmosphere can hold more water vapor. These features imply a more vigorous hydrological cycle, and heavier individual events when conditions are conducive to precipitation. Basic atmospheric physics tells us that 1°C warming we have seen already implies roughly 2% higher concentration of water vapor in the atmosphere on average, and correspondingly, roughly 2% more precipitable water during any particular precipitation event. Depending on the particular emissions scenario, we can expect a several fold larger increase over the next century. Since flooding is associated with large accumulations of rainfall over short periods of time, this increase in precipitation intensity implies greater potential for flood conditions—ironically, even for regions that on average see greater drought, i.e., more dry days (something we alluded in our discussion of general precipitation trends [26] in the previous lesson).

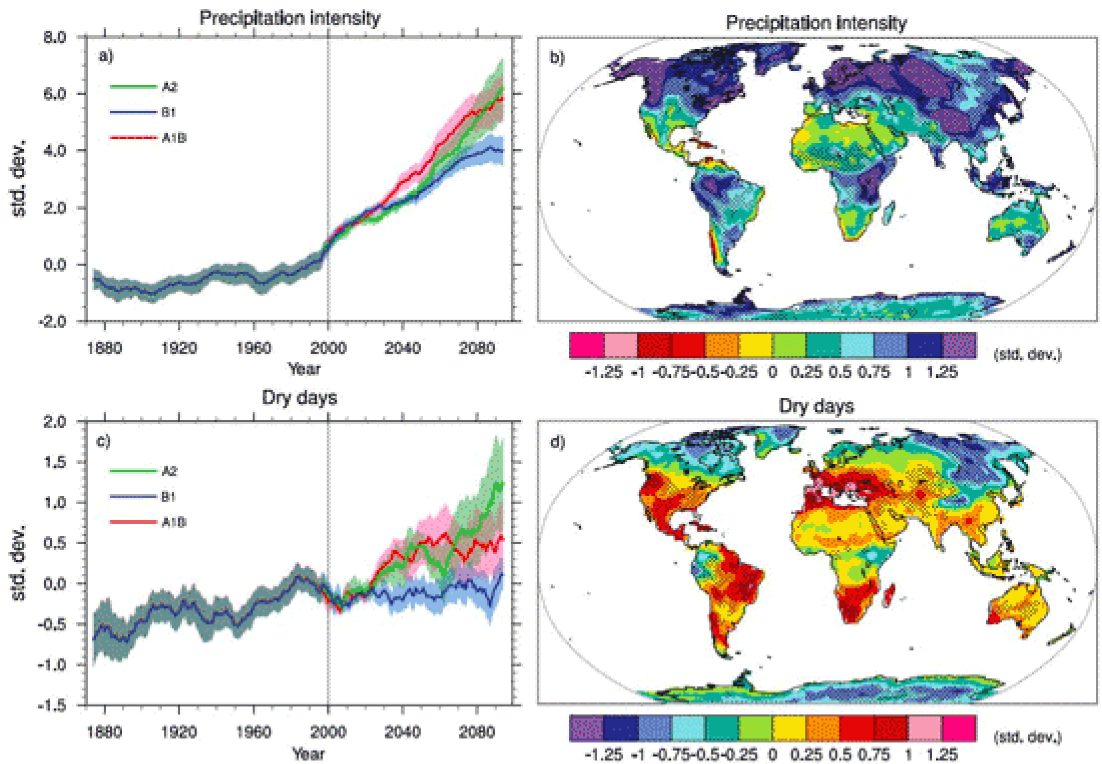


Figure 8.6: Model Projections of Changes in Precipitation Intensity (top) and Frequency of Dry Days (bottom) by end of 21st Century in Various Emissions Scenario (based on average over all IPCC models).
Credit: IPCC, 2007

Where atmospheric temperatures are above freezing, we expect precipitation to fall as rain, but where temperatures are below freezing, we expect it to fall as snow. Climate change deniers often claim [27] that heavy winter snowfalls argue against the reality of global warming. Nothing could be further from the truth, however. In any realistic scenario of the next century, we will still have winter. It will still be cold enough for snow over large parts of North America in winter, and as the atmosphere continues to warm and hold more water vapor, we expect those snowfalls to be heavier. In fact, there is a bit of a double whammy involved here: we also know that mid-latitude winter storms will likely become more intense—something we already see evidence of in meteorological observations [25]. These more intense storms will be associated with stronger frontal boundaries, further increasing the potential for large snowfalls (you can find your course author commenting on this issue [28] here).

Profound changes are, of course, also expected in temperature extremes. Heat waves, which, as we saw earlier in the course, have already increased [25] in duration and intensity owing to the warming of the past century, are projected to be subject to further increases over the next century, with the details depending, of course, on the emissions pathway. Not surprisingly, extreme cold days are projected to decrease in number.

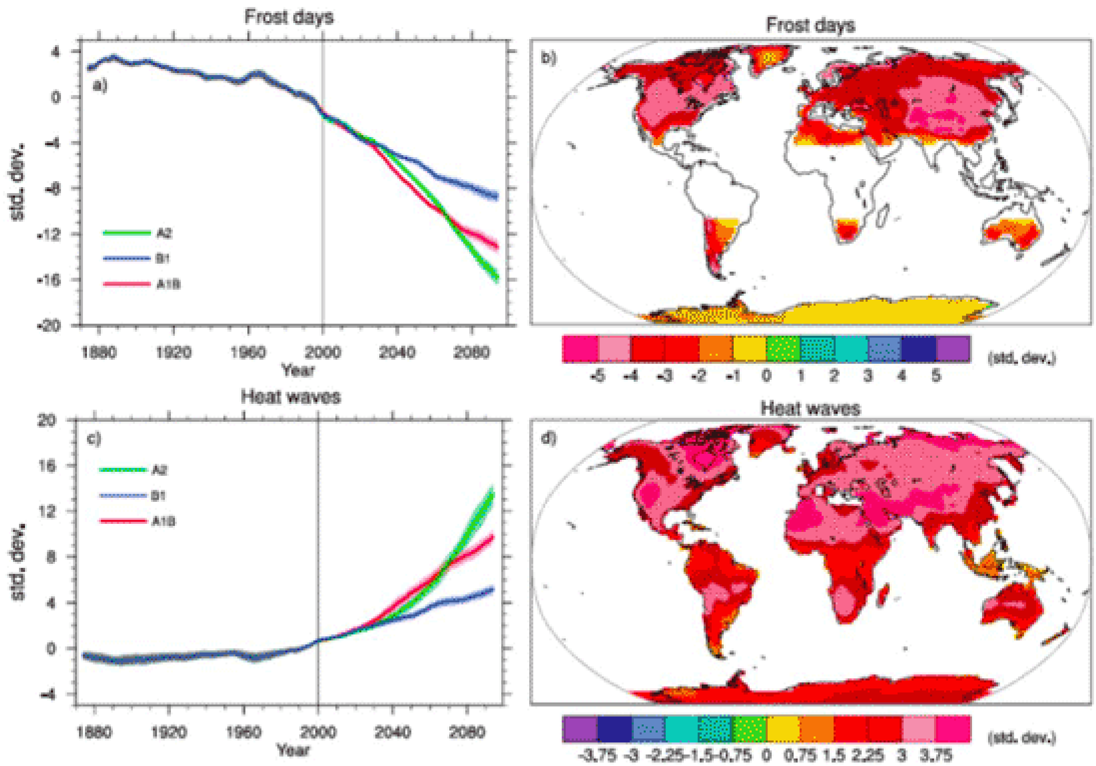


Figure 8.7: Model Projections of Changes in Frequency of Frost Days (top) and Heat Waves (bottom) by end of 21st Century in Various Emissions Scenario (based on average over all IPCC models).
Credit: IPCC, 2007

In our original discussion of extreme weather in Lesson 3 [25], we likened the incidence of extreme weather to the rolling of a die. Sixes come up relatively rarely in the roll of a *fair* die (1 in 6 rolls to be precise). Let us think of an unusually warm summer day (say, a 90F day in State College PA in July) as a rolling of a six. We have seen that the incidence of extreme warm days in the U.S. has roughly doubled since the mid 20th century. Think of that as a doubling of the probability of rolling a six. You got a sense for how apparent such a change in the odds might be in the day-to-day weather variations by playing a game where you compared a fair die and one that had been loaded to double the probability of sixes. It took a fair number of rolls in that case [25]—perhaps as many as 10 or so—to be pretty confident from the pattern of rolls as to which one was the loaded die. Now, we will *double* the probability once more—so there is now a *four-fold increase* in the likelihood of rolling a six in the loaded die relative to a fair die. Using the updated version of the dice rolling application below, see how many rolls of the die it takes you *now* to figure out which one is loaded and which one is fair. What does this tell you about the degree to which the "loading of the die" will become more apparent in observations of extreme weather as time goes on?

Be prepared to discuss your observations in this week's discussion.

Carbon Cycle Feedbacks

As we saw earlier in the course, the airborne fraction of CO_2 in the atmosphere has increased by only half as much as it should have given the emissions we have added through fossil fuel burning and deforestation. We know that CO_2 must be going somewhere.

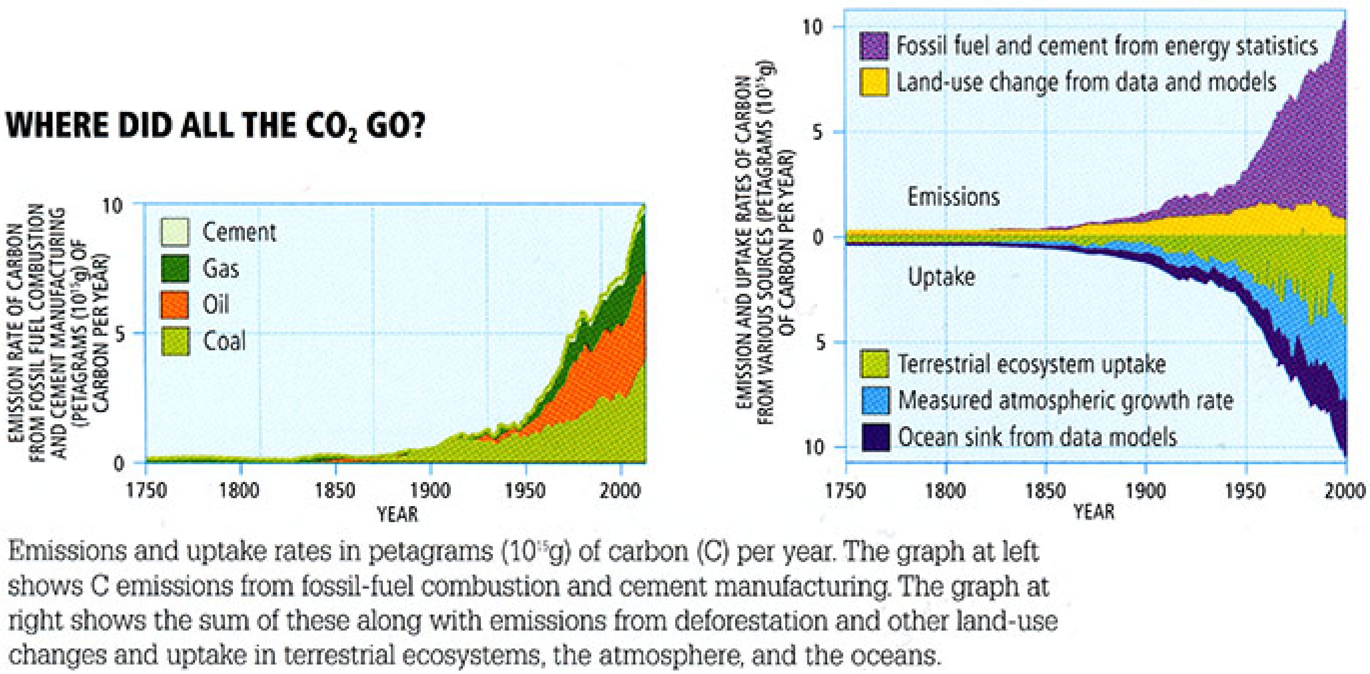


Figure 8.8: Annual change in atmospheric CO_2 concentrations.
Credit: Mann & Kump, *Dire Predictions: Understanding Climate Change, 2nd Edition*

Indeed, it is being absorbed by various reservoirs that exist within the global carbon cycle. As we saw earlier, in Lesson 1 [29], only 55% of the emitted carbon has shown up in the atmosphere, while roughly 30-35% appears to be going into the oceans, and 15-20% into the terrestrial biosphere.

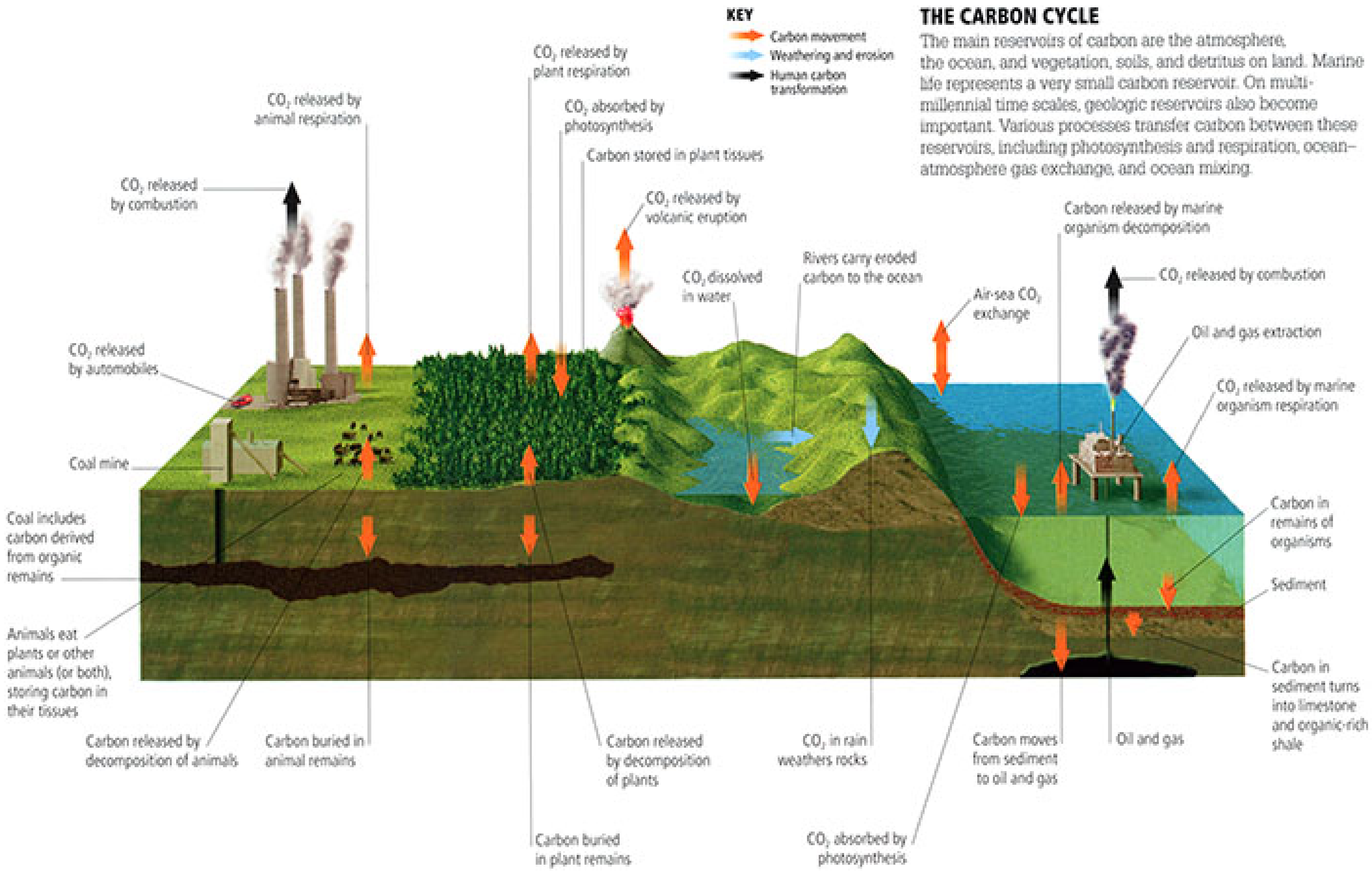


Figure 8.9: Global carbon cycle.[Enlarge [30]]
Credit: Mann & Kump, *Dire Predictions: Understanding Climate Change, 2nd Edition*
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The problem is that this pattern of behavior may not continue. There is no guarantee that the ocean and terrestrial biosphere will continue to be able to absorb this same fraction of carbon emissions as time goes on, and that leads us into a discussion of so-called *carbon cycle feedbacks*.

If we consider the oceans, for example, there are a number of factors that could lead to decreased uptake of carbon as time goes on. Like a warm can of Coke, which loses its carbonation when you warm it up and remove the top, the ocean's CO_2 solubility decreases as the ocean warms. When we look at the pattern of carbon uptake in the upper ocean, we see that one of the primary regions of uptake is the North Atlantic. This is, in part, due to the formation of carbon-burying deep water in the region. In a scenario we have explored in Lesson 7 [31], the North Atlantic overturning circulation could weaken in the future (though as we have seen, there is quite a bit of uncertainty regarding the magnitude and time frame of this weakening). If that were to happen, it would eliminate one of the ocean's key carbon-burying mechanisms, and allow CO_2 to accumulate faster in the atmosphere. On the other hand, the biological productivity of the upwelling zone of the cold tongue region of the eastern and central equatorial Pacific is a *net source* of carbon to the atmosphere, *from* the ocean. More El Niño-like conditions in the future could suppress this source of carbon, but more La Niña-like conditions could increase this source, further accelerating the buildup of CO_2 in the atmosphere. So uncertainties in the future course of oceanic uptake abound, but, on balance, it is likely that this uptake will decrease over time, yielding a *positive carbon cycle feedback*.

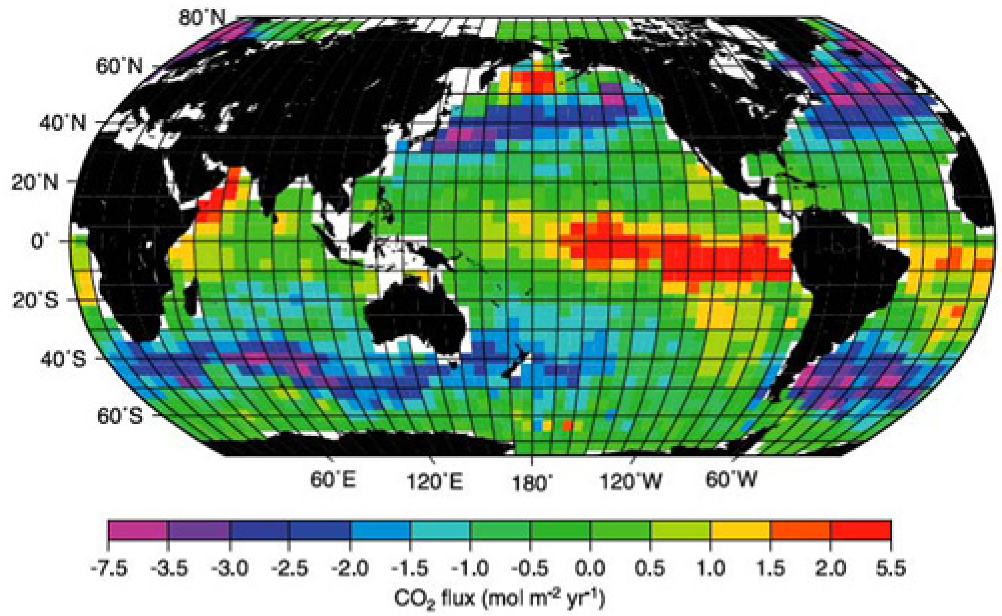

Figure 8.10: Ocean CO_2 fluxes: positive numbers indicate flux out of the ocean.
Credit: IPCC, 2007

Other ocean carbon cycle feedbacks relate to the phenomenon of *ocean acidification*, which results from the fact that increasing atmospheric CO_2 leads to increased dissolved bicarbonate ion in the ocean (a phenomenon will discuss further in our next lesson on climate change impacts). On the one hand, this process interferes with the productivity of calcite-skeleton forming ocean organisms, such as zooplankton, which bury their calcium carbonate skeletons on the sea floor when they die. This so-called *oceanic carbon pump*, is a key mechanism by which the ocean buries carbon absorbed from the atmosphere on long timescales. So any decrease in the effectiveness of the ocean's carbon pump would represent a positive carbon cycle feedback. On the other hand, since calcifying organisms release CO_2 into the water as they build their carbonate skeletons, a decrease in calcite production by these organisms will reduce CO_2, amounting to a negative carbon cycle feedback.

There are a number of other carbon cycle feedbacks that apply to the *terrestrial biosphere*. They vary anywhere from a strong negative to a strong positive feedback. Among them are (a) warmer land increasing microbial activity in soils, which releases CO_2 (a small positive feedback), (b) increased plant productivity due to higher CO_2 levels (a strong negative feedback). Finally, there is the negative silicate rock weathering feedback which we know to be a very important regulator of atmospheric CO_2 levels on very long, geological timescales: a warmer climate, with its more vigorous hydrological cycle, leads to increased physical and chemical *weathering* (the process of taking CO_2 out of the atmosphere by reacting it with rocks), through the formation of carbonic acid, which dissolves silicate rocks, producing dissolved salts that run off through river systems, eventually reaching the oceans.

While each of these potential carbon cycle feedbacks are uncertain in magnitude—and even in sign in some cases (see the various coloured bars in the figure below), the net result of all of these feedbacks appears to be a *net positive carbon cycle feedback* (the black bar shown).

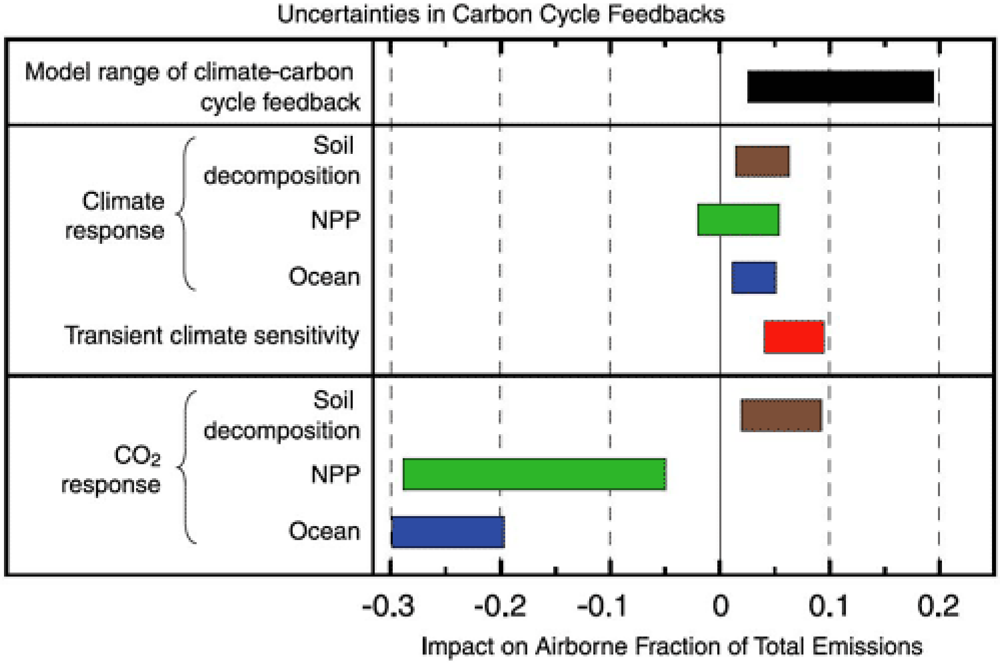

Figure 8.11: Estimated magnitudes (including uncertainty ranges) of various potential oceanic and terrestrial carbon cycle feedbacks, expressed in terms of positive or negative estimated change in the airborne fraction of $\mathrm{CO_2}$ (based on average net increase by 2100 among the various climate models).
Credit: IPCC, 2007

Other potential positive carbon cycle feedbacks that are even more uncertain, but could be quite sizeable in magnitude, are methane feedbacks, related to the possible release of frozen methane currently trapped in thawing Arctic permafrost, and so-called "clathrate"—a crystalline form of methane that is found in abundance along the continental shelves of the oceans, which could be destablized by modest ocean warming. Since methane is a very potent greenhouse gas, such releases of potentially large amounts of methane into the atmosphere could further amplify greenhouse warming and associated climate changes.

The key potential implication of a net positive carbon cycle feedback is that current projections of future warming such as those we have explored previously in Lesson 7 [32], may actually underestimate the degree of warming expected from a particular carbon emissions pathway. This is because the assumed relationship [33] between *carbon emissions and* $\mathrm{CO_2}$ *concentrations* would underestimate the actual resulting $\mathrm{CO_2}$ concentrations because they assume a fixed airborne fraction of emitted $\mathrm{CO_2}$, when, it fact, that fraction would instead be increasing over time. While the magnitude of this effect is uncertain, the best estimates suggest an additional 20-30 ppm of $\mathrm{CO_2}$ per degree C warming, leading to an additional warming of anywhere from 0.1°C to 1.5°C relative to the nominal temperature projections [32] shown in earlier lessons.

Earth System Sensitivity

As we saw in the previous section on carbon cycle feedbacks, there are some limitations in the traditional framework for assessing the climate response to anthropogenic forcing. In the case of carbon cycle feedbacks, the assumptions implicit in that framework regarding the relationship between carbon emissions and resulting CO_2 concentrations may underestimate the future increase in CO_2 levels, and the degree of climate change.

Another problem in the traditional framework is that the assessment of *climate sensitivity*—a topic we have looked at in depth in Lesson 5 of this course [34]—may be too limited. Implicit in the traditional definition of climate sensitivity is the so-called "Charney" notion of climate sensitivity—named after a famous climate scientist (Jule Charney [35]) and a late 1970s report of the National Academy of Sciences known as the "Charney Report" [36] which provided the first real estimate of the range of uncertainty in the equilibrium climate sensitivity. The concept of climate sensitivity described in this report, sometimes called the "Charney Sensitivity", envisions the equilibrium sensitivity of Earth's climate to CO_2 forcing as the equilibrium response of the climate system to a doubling of CO_2 concentrations including all *fast feedbacks*—that includes changes in water vapor, clouds, sea ice, and perhaps even small ice caps and glaciers.

The limitation implicit in this definition becomes apparent as soon as we start to think of the lasting, multi-century impacts of anthropogenic climate forcing. The fast feedbacks do not, for example, include the slow retreat of the continental ice sheets or the slow response of the Earth's surface properties and vegetation as, e.g., boreal forests slowly expand poleward. Accounting for these *slow feedbacks* leads to the possibility that the equilibrium long-term response to anthropogenic greenhouse gas emissions is larger than the IPCC projections we have focused on up until now. This more general notion of climate sensitivity is typically referred to as *Earth System senstivity*.

There is good evidence from long-term geological record of climate change that these slow feedbacks do indeed matter, and that the ultimate warming and associated changes in climate might be substantially larger than what is implied by the simple Charney definition of sensitivity implicit in the IPCC projections. For both the mid-Pliocene, roughly 2.8 MY ago, and the mid-Miocene, about 15 MY ago, global mean temperatures appear to have been warmer than would be expected from even the upper range of the estimated Charney sensitivity (4.5°C for CO_2 doubling). This suggests an earth system sensitivity that is substantially higher than the standard Charney estimate of climate sensitivity.

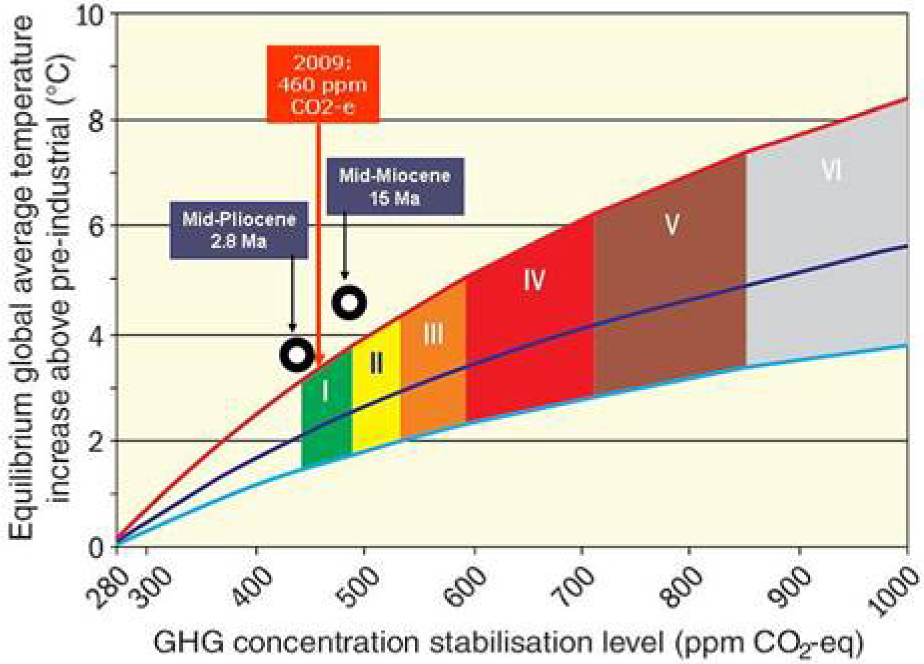

Figure 8.12: Equilibrium warming as a function of CO_2 concentration assuming a Charney sensitivity range of 3°C +/-1.5°C (lower curve=1.5°C, middle curve=3.0°C, upper curve=4.5°C), compared with actual estimates of CO_2 concentration and global mean temperature for past geological periods where CO_2 levels appear to have been higher than today (black circles).
Credit: Climate Himalaya Initiative [37]

Studies using climate models that incorporate these slow feedbacks find that the *Earth System sensitivity* is indeed substantially greater than the nominal Charney sensitivity, roughly 50% higher. Thus, a stabilization of CO_2 levels at twice pre-industrial levels over the next century might lead to a warming of 3°C over the next 1-2 centuries, but an eventual warming closer to 4.5°C once the land surface and vegetation has equilibrated to the new climate and the ice sheets have melted back to their new equilibrium configuration for the higher CO_2 concentration—a process that could take a thousand years, but perhaps substantially less.

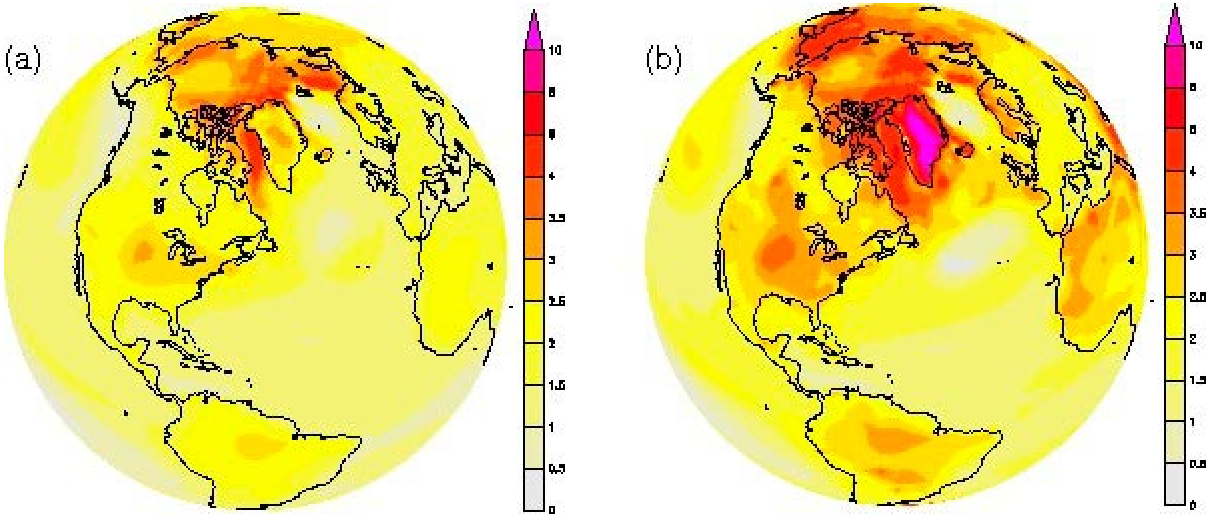

Figure 8.13: Temperature response of the Earth (in °C) to an increase in atmospheric carbon dioxide from a pre-industrial level of 280 ppm to 400 ppm. On left (a) is the projected temperature change based only on fast feedbacks, while the right (b) shows the eventual warming once slow feedbacks related to the land surface/vegetation changes fully kick in.
Credit: Institute of Physics [38]

Tipping Points

We will wrap up our discussion of climate change projections with a discussion of so-called *tipping points*. Tipping points are important because they represent possible threshold responses to forcing. While many of the climate change impacts we have looked at, like surface temperature increases, are projected to follow increasing atmospheric $\mathrm{CO_2}$ concentrations in a smooth manner, there are other responses that can be more abrupt—once a certain amount of warming takes place, some component of the climate system abruptly transitions to some other regime of behavior. We saw an example of this sort of behavior in our discussion in Lesson Five (see the series of jing videos at the bottom of this Lesson Five page [39]) of the role of ice-albedo feedback in the long-term evolution of the Earth's climate system. In that case, we saw that there is the potential for more than one equilibrium state of the Earth's climate under a given state of the solar constant. When that is the case, it is possible that one or more of the steady states is unstable. In that case, a small perturbation can cause the system to spontaneously transition from its current state to a very different, other equilibrium state.

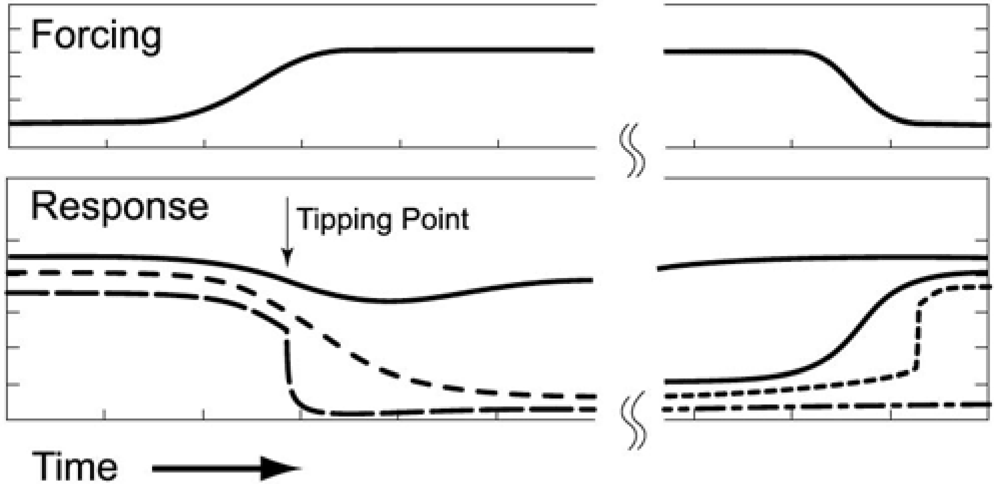

Figure 8.14: Schematic diagram of "tipping point" climate change behavior.
Credit: IPCC, 2007

We have already seen some examples of potential climate tipping points—e.g., in the potential response of the cryosphere [40] or patterns of ocean circulation [31] to ongoing warming. There are many other potential tipping points in the system, however. These include the possibility that the ENSO phenomenon might transition rather suddenly into a very different mode of behavior, or that the Indian monsoon system—whose role is so critical to fresh water availability in large parts of South Asia—might suddenly collapse. Other possibilities include one of the possible carbon cycle feedbacks alluded to previously in this lesson [41]; that a sudden release of previously frozen methane from thawing permafrost suddenly enters into the atmosphere. It is, of course, possible that other tipping points exist that we are not even aware of yet! *Can you think of any possibilities yourself?* If so—this would be another good topic to bring into this week's discussion.

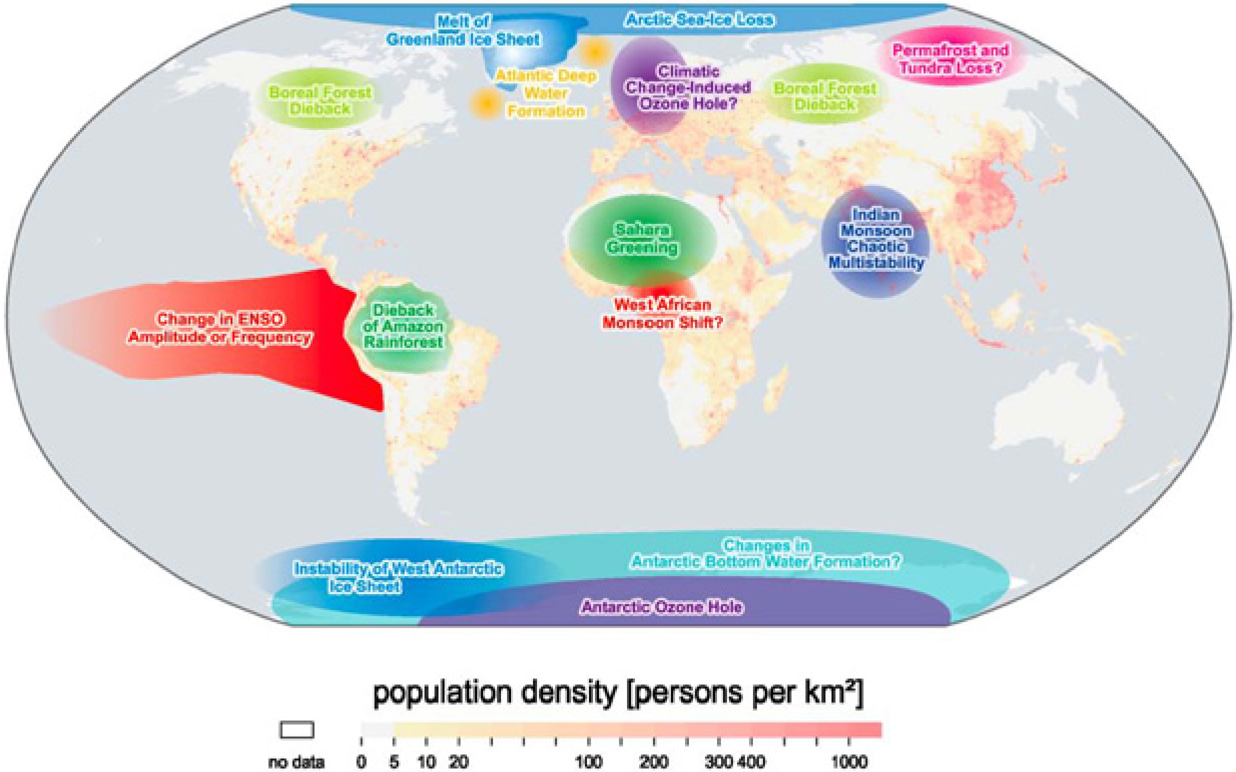

Figure 8.15: Possible Climate Change "Tipping Points".
Credit: The Copenhagen Diagnosis [8]

Lesson 8 Discussion

Activity

Please note that you will not receive a passing grade on this assignment if you wait until the last day of the discussion to make your first post.

Directions

Please participate in an online discussion of the material presented in Lessons 7 and 8: Projected Climate Change.

This discussion will take place in a threaded discussion forum in Canvas (see the Canvas Guides [42] for the specific information on how to use this tool) over approximately a week-long period of time. Since the class participants will be posting to the discussion forum at various points in time during the week, you will need to check the forum frequently in order to fully participate. You can also subscribe to the discussion and receive e-mail alerts each time there is a new post.

Please realize that a discussion is a group effort and make sure to participate early in order to give your classmates enough time to respond to your posts.

Post your comments addressing some aspect of the material that is of interest to you and respond to other postings by asking for clarification, asking a follow-up question, expanding on what has already been said, etc. For each new topic you are posting, please try to start a new discussion thread with a descriptive title, in order to make the conversation easier to follow.

Suggested topics

- What do the climate models project for the future surface temperatures? What are the two fundamental uncertainties associated with these projections? Is the warming projected to be uniform over the globe?
- What are the projected changes in precipitation and drought? What are the main causes for the large uncertainty in the precipitation projections?
- What are the projected changes in the large-scale atmospheric and ocean circulations?
- How well are the climate models able to project future changes in ENSO?
- How is the Earth's cryosphere projected to change?
- What are the projected changes of the sea level?
- What are the projected changes in tropical cyclones and extreme weather events?
- A very important point about all climate projections is that they are uncertain. One way we can attempt to assess how realistic the projections are is to compare the projections with the observations. We are in a position to do that because we have available climate projections that were done some time ago and now we have the observations that cover the projected period. Please share your thoughts on this comparison.
- What are the carbon cycle feedbacks? How many feedback mechanisms does the Earth's carbon cycle have?
- What is the difference between the Earth System Sensitivity and the Equilibrium Climate Sensitivity?
- In our current state of knowledge, what are the potential climate tipping points? Should we be concerned about these potential tipping points now or wait for a higher level of scientific certainty before we do anything?

Submitting your work

1. Go to Canvas.
2. Go to the *Home* tab.
3. Click on the *Lesson 8 discussion: Climate Change Projections.*
4. Post your comments and responses.

Grading criteria

You will be graded on the quality of your participation. See the online discussion grading rubric [43] for the specifics on how this assignment will be graded.

Lesson 8 Summary

In this lesson, we further examined potential anthropogenic climate change influences on a host of climate and meteorological phenomena. We found that:

- Arctic sea ice extent is projected to continue to decrease, and it is likely that summer sea ice will disappear if the globe warms up beyond 2°C. Observations suggest that the rate of decline is greater than what is projected by the models;
- mountain glaciers and small outlet glaciers around the world are projected to continue their decline under further warming, but there is greater uncertainty regarding the rate and magnitude of decline of the two major continental ice sheets—Greenland and Antarctic;
- while we may commit to enough warming to set in motion the ultimately disappearance of the Greenland and West Antarctic ice sheets within decades and given only modest additional warming, current generation ice sheet models suggest that the scenario could take many centuries or even millennia to play out, owing to the intrinsically slow nature of key governing processes;
- actual observations of ice mass suggest that both Greenland and West Antarctic ice sheets already have entered into a regime of negative mass balance, and it is quite possible that physical processes not well represented in current generation ice sheet models, such as ice shelf buttressing, could allow for a much faster retreat;
- there are several different components expected to contribute to global sea level rise, including the expansion of sea water with warming, the contribution of melting mountain glaciers, and ice loss from the major ice sheets; the latter component is both likely the largest and the most uncertain;
- semi-empirical models which attempt to account for all contributions to global sea level rise suggest the possibility of a meter of sea level rise or more by 2100, and perhaps as much as 5 meters by 2300;
- anthropogenic climate change is projected to lead to further increases in the incidence of specific types of extreme weather events. These include intense rainfall and snow events and flooding, and the incidence of high temperature extremes and heat waves. While the shifts in extreme weather thus far have been subtle, the projected increases are likely to be perceptible in the pattern of day-to-day-weather;
- climate change projections have traditionally neglected potentially important *carbon cycle feedbacks* which may serve to further accelerate anthropogenic climate change. For a given emissions pathway, CO_2 concentrations might increase more than indicated by the nominal CO_2 concentration scenarios because of feedbacks which tend to further increase levels of atmospheric CO_2. The impact is quite uncertain, but probably about 20-40 ppm additional CO_2 for each degree C of warming, which has non-trivial consequences for the magnitude of future warming;
- the traditional so-called "Charney" concept of equilibrium climate sensitivity may not be appropriate for assessing the full extent of anthropogenic climate change, because it neglects slow feedbacks like changes in vegetation and land surface properties, and the retreat of the continental ice sheets, which tend to further amplify the projected changes; the importance of these long-term feedbacks is suggested by the relationship between CO_2 levels and global warmth in the geological climate record. The so-called *Earth System Sensitivity*, which attempts to incorporate the amplifying effects of the slow-feedbacks, suggests a modestly (50%) greater amount of warming and associated climate change than the traditional notion of climate sensitivity;

- there are a number of phenomena, including the behavior of the cryosphere, the thermohaline circulation of the ocean, and certain carbon cycle feedbacks related to, e.g., currently frozen methane stores, which may behave in a threshold-like manner. Rather than exhibiting a steady trend in time, these phenomena may exhibit abrupt transitions in behavior in response to ongoing anthropogenic climate forcing. Other potential examples of systems that might exhibit tipping point behavior are ENSO and the Asian summer monsoon.

Reminder - Complete all of the lesson tasks!

You have finished Lesson 8. Double-check the list of requirements on the first page of this lesson [44] to make sure you have completed all of the activities listed there before beginning the next lesson.

Source URL: https://www.e-education.psu.edu/meteo469/node/155

Links
[1] https://www.ipcc.ch/report/ar5/wg1/
[2] https://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_SPM_FINAL.pdf
[3] http://news.google.com/news/search?pz=1&cf=all&ned=us&hl=en&q=warming+alarmist
[4] http://www.sciencemag.org/content/316/5825/709.abstract
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[6] http://www.msnbc.msn.com/id/40682752/ns/us_news-environment/
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[8] http://www.copenhagendiagnosis.com
[9] https://www.e-education.psu.edu/meteo469/node/130
[10] http://www.guardian.co.uk/environment/2011/jan/09/global-warming-glaciers-sea-levels
[11] http://www.eesi.psu.edu/people/pollard-dave.shtml
[12] http://www.essc.psu.edu/essc_web/research/movies/collapse_event.mov
[13] http://www.asr.ucar.edu/2004/CGD/ccr/GIS_LIG.jpg
[14] http://en.wikipedia.org/wiki/Flying_buttress
[15] http://www.msnbc.msn.com/id/41351840/ns/us_news-environment/
[16] http://nsidc.org/news/press/larsen_B/2002_animation.html
[17] https://www.theguardian.com/environment/2010/aug/10/greenland-ice-sheet-tipping-point
[18] http://www.geosc.psu.edu/academic-faculty/alley-richard
[19] http://www.pik-potsdam.de/%7Estefan/
[20] http://www.realclimate.org/index.php/archives/2008/05/climate-change-and-tropical-cyclones-yet-again/
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[29] https://www.e-education.psu.edu/meteo469/node/116
[30] https://www.e-education.psu.edu/meteo469/sites/www.e-education.psu.edu.meteo469/files/lesson08/CarbonCycleDP_2015.jpg
[31] https://www.e-education.psu.edu/meteo469/node/218
[32] https://www.e-education.psu.edu/meteo469/node/150

[33] https://www.e-education.psu.edu/meteo469/node/146
[34] https://www.e-education.psu.edu/meteo469/node/142
[35] http://en.wikipedia.org/wiki/Jule_Gregory_Charney
[36] http://www.ecd.bnl.gov/steve/charney_report1979.pdf
[37] http://chimalaya.org/2010/05/06/
[38] http://physicsworld.com/cws/article/news/41202
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