Chapter 2
Coupled Climate and Earth System Models

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Glossary

Climate model	A numerical model consisting of four components: atmosphere, ocean, land, and sea ice.
Earth system model	A climate model with additional components, which must include a carbon cycle in the land, atmosphere, and ocean components.
Troposphere	The lower part of the atmosphere where most of the weather occurs.
Stratosphere	The region of the atmosphere above the troposphere, and is the location of the ozone layer.
Carbon cycle	The processes by which carbon in all its forms interacts and moves around in the land, atmosphere, and ocean components of the climate system.
Positive feedback	A set of processes whereby a small perturbation in the climate system amplifies and increases in size.
Negative feedback	A set of processes whereby a small perturbation in the climate system decays and reduces in size.
Control simulation	A run of a climate model or earth system model where the forcing is kept constant in time.
Ensemble simulations	A set of runs which have the identical forcing, but start from slightly different initial conditions.

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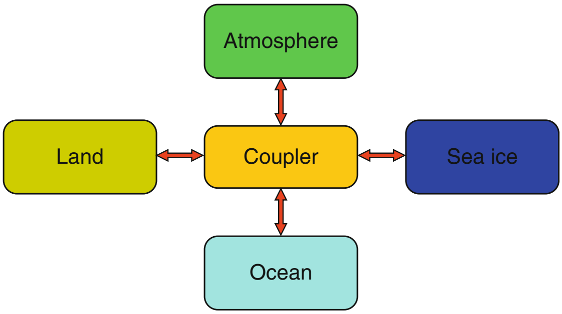
Chaotic system	A system of equations with the property that two runs starting from slightly different initial conditions diverge from each other, often quite quickly.
Climate projection	A simulation of the climate system into the future with prescribed forcing, where the model has not been initialized to the observed climate.
Climate forecast	A simulation of the climate system into the future with prescribed forcing, where the model has been initialized to the observed climate.
Equilibrium climate sensitivity	The increase in the globally averaged surface temperature in a model when the atmosphere concentration of carbon dioxide is doubled.
Atmosphere Model Intercomparison Project	A standard simulation of the atmosphere component of a climate or earth system model, which allows different models to be compared to each other.
El Nino-Southern Oscillation	The largest interannual signal in the climate system, which occurs primarily in the tropical region of the Pacific Ocean.
Thermohaline circulation	The overturning circulation in the global oceans where water sinks at very high latitudes, spreads very slowly horizontally to all the ocean basins, and then slowly returns toward the surface.
Conveyor belt	Another popular name for the thermohaline circulation.
Deep water formation	The process by which very dense water near the surface sinks to near the ocean bottom at high latitudes, which forms the sinking part of the thermohaline circulation.

Definition of the Subject

We are all familiar with weather forecasts that predict the local weather for the next few days. These are made using a high-resolution numerical model of the atmosphere, and sometimes extend out as far as 10 days. Most meteorological centers also produce seasonal outlooks, which give probabilities of the average temperature and precipitation being above, near, or below normal. These outlooks do not forecast the weather for a particular day, but give predictions of the seasonal averages. Seasonal outlooks are also made with an atmosphere model, but use climatological observed values for the evolving state of the surface ocean, land, and sea ice conditions. However, if forecasts are to be made more than a season ahead, then using just an atmosphere model is not sufficient, and the evolution of the ocean, land, and sea ice states must also be made using numerical models for these

Fig. 2.1 Configuration of a climate model



components of the climate system. The reason is that the surface ocean, land, and sea ice states interact strongly with the atmosphere and influence its future evolution because they change on a much slower timescale than the atmosphere.

A climate model is used to understand how the climate system works, and how the various components interact with each other. It is used to simulate the present day climate, the recent past climate, and the climates of different paleoclimatic epochs. It can also be used to simulate the future statistical state of the atmosphere a decade or a century into the future, but does not predict the local weather on particular days. The atmosphere resolution of a climate model is much reduced compared to that used in a weather forecast, so that climate information is given on regional to global scales, and not on local scales. The climate state a long time ahead depends on the future levels of quantities that force the climate system, such as the concentrations of carbon dioxide and other greenhouse gases, several different atmospheric aerosols, and the levels of solar and volcanic activity. Therefore, these climate projections depend on many future choices to be made by mankind, which will determine the concentrations of greenhouse gases and aerosols over the next century. Each climate projection needs a scenario for the future concentrations of greenhouse gases and aerosols before it can be carried out.

Thus, a physical climate model consists of four components; atmosphere, ocean, land, and sea ice. These components are used to calculate the future state of the component given an initial state and the various quantities that force the component. These four basic components have to interact with each other, so that most climate models have a fifth component, often called the coupler, see Fig. 2.1, which has two main functions. The first function is to start, oversee the time evolution, and finish each model simulation. The second is to receive all the information from each component that is required by the other components and to send back to each component all the information that it requires to continue its simulation forward in time. For example, the ocean component needs the atmosphere-ocean wind stress that drives the ocean currents, the net heat flux and net fresh water flux (precipitation plus river runoff and sea ice melt minus evaporation) going from the atmosphere, ice, and land into the ocean. These are most often calculated in the coupler, and depend on the atmosphere surface wind, temperature, and humidity, etc., and the ocean sea surface temperature and currents, which are fields that are sent to the coupler.

There is another reason why the set up using a coupler shown in Fig. 2.1 is extremely useful. Only a relatively small fraction of climate model runs are in fully coupled mode, and there is a large number of different ways to run the model components. In runs described in more detail later, one or more of the components is replaced by its data equivalent, which provides the observed data required by the coupler to force the active components. For example, in an Atmosphere Model Intercomparison Project (AMIP) run, the numerical ocean and sea ice components are turned off and replaced by simple data components that provide observed time series of surface ocean and sea ice temperatures to the coupler. The coupler framework shown in Fig. 2.1 then ensures that the fluxes exchanged between various components are always calculated consistently, whether using observations or predicted model fields.

There is no universally accepted definition of an Earth System Model (ESM), but it must have more components than the four in a climate model. The usual additional components are a model for the distribution of carbon on the land surface, and an ocean ecosystem component, which are required if the ESM is to simulate the earth's carbon cycle. However, an ESM will often have additional components as well. The commonest of these is an atmospheric chemistry component, but some ESMs have an atmosphere component that simulates the upper levels of the atmosphere, including the stratosphere, not just the troposphere, which is the lowest layer of the atmosphere where most of the weather takes place. Finally, several ESMs will soon include a component that simulates the Greenland and Antarctic ice sheets, in order to estimate the future rate of ice loss that will raise the level of the earth's oceans.

Introduction

Numerical model simulation of the atmosphere has a long history that goes back over 60 years. The first integrations were done on the ENIAC machine at the Advanced Study Institute in Princeton by 1950 [1]. It took another 10 years for this to develop into weather forecasts that used models that had vertical structure and could be initialized using atmospheric observations. The first numerical ocean models were developed in the mid 1960s by Kirk Bryan at the Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton [2], which used simplified sector geometry for the ocean basins. The first coupled atmosphere/ocean model was developed at GFDL when the global atmosphere model of Syukuro Manabe was coupled to Bryan's ocean model, and the results were published in 1969 [3]. However, the first real coupled climate model that had realistic geometry for the ocean basins and very elementary components for the land and sea ice was developed over the first half of the 1970s. The first results were published in two landmark papers by Manabe, Bryan, and coworkers in 1975 [4, 5]. The horizontal grid-spacing of this model was $5° \times 5°$, and there were nine vertical levels in the atmosphere component, and five levels in the ocean component. Even this coarse resolution was sufficient that the climate model ran slowly on GFDL's supercomputer of the early 1970s. Other meteorological and weather centers in several countries followed the GFDL lead and produced similar climate models of their own over the 1980s. As supercomputers became faster and larger, so the four components became more sophisticated, and the resolution of climate models improved.

However, there was a serious problem with all climate models when trying to obtain a control run for the present day climate. All the components would be initialized using the best set of observations available. It is most important to initialize the ocean component because it has by far the largest heat capacity, and its evolution is governed by much longer time scales than the other components. The problem was that, as the control run continued in time, the ocean and sea ice solutions would drift away from the realistic initial conditions. The drift was fast enough that rather quickly the model climate became significantly different than that of the present day earth.

The cause of this problem was diagnosed as follows. When the atmosphere and ocean components were run in standalone mode with the other component replaced by a data component that provides observations, the fluxes of heat and fresh water at the air–sea interface can be calculated. These fluxes from the atmosphere and ocean were very different, so that they were incompatible when coupled together. The problem was overcome by a very unphysical fix called flux correction [6]. The diagnosed heat and fresh water fluxes from atmosphere and ocean stand alone runs were differenced, and this difference was added to the fluxes exchanged between the atmosphere and ocean every time step of the coupled run. This enabled a climate model to maintain a non-drifting solution in a present day control run. However, it disguised the fact that the climate model components needed further development work to improve the simulations and make their fluxes of heat and fresh water across the air–sea interface compatible with each other. Use of flux corrections in climate models remained the standard method of running until the late 1990s.

The first model that could maintain the present day climate in a control run without the use of flux corrections was the first version of the Community Climate System Model (CCSM) developed at the National Center for Atmospheric Research (NCAR). A 300 year present day control simulation that showed virtually zero drift was run during the second half of 1996 and documented in 1998 [7]. The reason for this success was further refinement of the atmosphere, and especially the ocean [8] components, so that the surface heat and fresh water fluxes produced by the two components were compatible. Quite quickly, the climate centers in Australia and the UK implemented two of the new ocean parameterization improvements from the CCSM and were also able to run their models without flux corrections [9, 10]. Now, a large majority of climate models run without flux corrections, although some of the coarser resolution models still use this technique. Coarse horizontal resolution now means a grid-spacing of about $3° \times 3°$, whereas many climate models currently use about $1^\circ \times 1^\circ$ grid-spacing, or slightly higher, for their standard runs.

The number of climate models maintained around the world has steadily increased over the last decade, so that results from 18 different models were submitted to the 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), which was published in February 2007. This 4th Assessment Report [11] was the joint recipient of the 2007 Nobel Peace Prize.

Earth System Models

All ESMs contain components that enable the carbon cycle in the land, ocean, and atmosphere to be predicted, rather than being passive in simulations of the earth's climate, for the following reason. Only about half the carbon dioxide (CO_2) emitted into the atmosphere over the past 150 years has stayed in the atmosphere; the other half has been taken up by the land and oceans in about equal measure. Climate models need past and future concentrations of CO_2 and other greenhouse gases in order to simulate the past and future climates. For future climate projections, it is currently assumed that the land and oceans sinks will continue to be as effective as in the past in taking up CO_2, so that future atmosphere concentrations will be based on about half of the future emissions staying in the atmosphere. However, there are real concerns that in the future, the ocean especially will not be able to take up the same fraction of CO_2 emissions because it is becoming warmer and more saturated with CO_2 [12]. Whether the land will continue to take up the same fraction of CO_2 is also not obvious and strongly depends on future land use practices. Over the last 30 years, deforestation of tropical forests has rapidly increased, which results in less CO_2 taken up by the land and more emitted into the atmosphere if the wood is burnt. This is now the cause of a substantial fraction of the recent increase in atmospheric CO_2 concentration. In contrast, there has been reforestation at some locations in the northern hemisphere mid-latitudes, such as the eastern part of the USA. Rather than assuming how much of the emitted CO_2 stays in the atmosphere, this fraction is predicted by an ESM with a carbon cycle. Thus, if the model predicts that the ocean will take up less CO_2 in the future, then a larger fraction will stay in the atmosphere to act as a greenhouse gas. This is a positive feedback in the climate system that is in ESMs, but not in climate models. Interactive carbon cycles have been put into a number of climate models around the world, and there has been an intercomparison project that compares their results [13]. The strength of the positive feedback from the carbon cycle is quite different in these various models, so the strength of this positive feedback is presently quite uncertain and needs to be constrained better.

There is some evidence that the stratospheric circulation can affect phenomena such as the Arctic and Antarctic Oscillations [14, 15] and will be important in how quickly the observed "ozone hole" in the southern hemisphere stratosphere will recover over the first half of the twenty-first century. If these processes are to be included in an ESM, then the atmosphere component needs to include all of the stratosphere, which is located above the troposphere. The region usually modeled by the atmosphere component of a climate model is the troposphere and just the lower part of the stratosphere. How important these processes are to the future trajectory of climate change has not been fully evaluated at present. In addition, an atmospheric chemistry component may be important to model the future levels of atmospheric aerosols. These are important in reflecting incoming solar radiation and in the formation of clouds, which are extremely important in the radiation budget of the atmosphere. A chemistry component is also needed if an ESM is to evaluate future levels of natural and man-made pollution in the very large cities of the future.

Another component of the earth system that has recently taken on more importance is the role of the Greenland and Antarctic ice sheets. There is growing evidence that the Greenland ice sheet has lost mass more quickly in the first decade of the twenty-first century than previously [16, 17], and there are changes in how quickly it is moving [18]. There are also observations of accelerations in Antarctic glaciers, especially after small ice shelves have collapsed [19, 20]. This has two important effects. The first is that the fresh water input to the ocean from these ice sheets increases the mean sea level [21], although it is important to note that this increase is not uniform over the ocean. The second is that fresh water input from the Greenland ice sheet can possibly cause a future weakening of the so-called thermohaline circulation in the North Atlantic Ocean [22, 23]. This circulation carries a lot of heat northward and certainly affects the climate of Western Europe, and is discussed in more detail in the next section. These possible future effects are not included in climate models at present. A new ice sheet component to evaluate these future climate change possibilities will be a vital component of ESMs over the next few years.

Climate Model Simulations

One or Two Active Components

As a climate model is being built and assembled, the first type of simulation that is performed and analyzed is runs using either one or two of the components in active mode, with the other components being replaced by simple data components that provide observed time series of the required fields. The best known of this type of run is when the atmosphere and land components are active, and the ocean and sea ice are replaced by observations of sea and sea ice surface temperature. When the observations are over the period 1960–2005, this is called an AMIP run, which is named after the Atmosphere Model Intercomparison Project, which first formalized this type of run. Results from AMIP runs made with the atmosphere and land components of many different climate models have been compared in this type of intercomparison for 20 years or more [24]. These comparisons have given, and continue to give, insight into the validity of the parameterizations used to simulate the many important processes in the atmosphere component of different climate models.

Scientists developing the land component of a climate model use these AMIP runs to validate their component. However, in order to isolate parameterizations in the land component, they frequently make simulations with just the land component active. In this type of run, the land is forced by a time series of observations from 1960 to 2005 of all the surface atmosphere variables that are required to force the land component.

This same time series of surface atmosphere variables, but over the oceans, is very frequently used to force the ocean component of climate models run in standalone mode. This type of run is done to validate the ocean component because the ocean observations available for comparison are mainly from the period 1960–2005. One of the difficulties in setting up this type of run is how to force the ocean under sea ice. The interaction between the ocean and sea ice is very important, especially when ice is being formed. Sea ice is formed with a salinity of about 5 parts per 1000 from sea water with a salinity of about 35 parts per 1000. Therefore, this process rejects brine into the surface water, and at cold temperatures, the ocean salinity is more important than temperature in determining its density. Thus, sea ice formation produces very dense surface water, and when this is denser than the water below, the water column overturns down to a depth of 2 km or more, resulting in what is called "deep water formation." This only occurs in winter in a very few locations in the world oceans. Off Antarctica, it occurs in the Weddell and Ross Seas, producing Antarctic Bottom Water, which is the densest water mass in the oceans. It also occurs in the North Atlantic Ocean in the Greenland–Iceland–Norwegian Seas north of Iceland and in the Labrador Sea between Canada and western Greenland. This forms North Atlantic Deep Water, which flows south at 2–3 km depth, and is the return flow of the North Atlantic thermohaline circulation. This overturning circulation is often called the "Conveyor Belt," following Broecker [25], and a schematic is shown in Fig. 2.2. The deep water formation regions in the North Atlantic and off Antarctica are the sinking branches of the Conveyor Belt. The dense water near the bottom of the ocean very slowly makes its way into the Indian and Pacific Oceans, and then slowly rises toward the surface in all the oceans. It has been estimated from ocean observations and models that deep water formed near Antarctica, which then goes into the Pacific Ocean, will take between 800 and 1,000 years before it returns to the ocean surface. It is also interesting to note that deep water formation does not occur in the North Pacific Ocean. The main reason is that the salinity there is much less than in the North Atlantic, and the surface water is never dense enough to overturn.

In order to overcome the difficulty of how to force the ocean under ice, the ocean and sea ice components are sometimes run together in active mode, forced by the time series of atmospheric surface observations. Often the scientists developing the sea ice component wish to isolate that component, and make stand alone sea ice runs forced by atmospheric observations, and allowing the sea ice to interact with a much simpler ocean component called a slab ocean. A slab ocean component only models the upper mixed layer near the ocean surface. This is needed because there are no observations of the surface ocean under ice, so that a slab ocean component is used

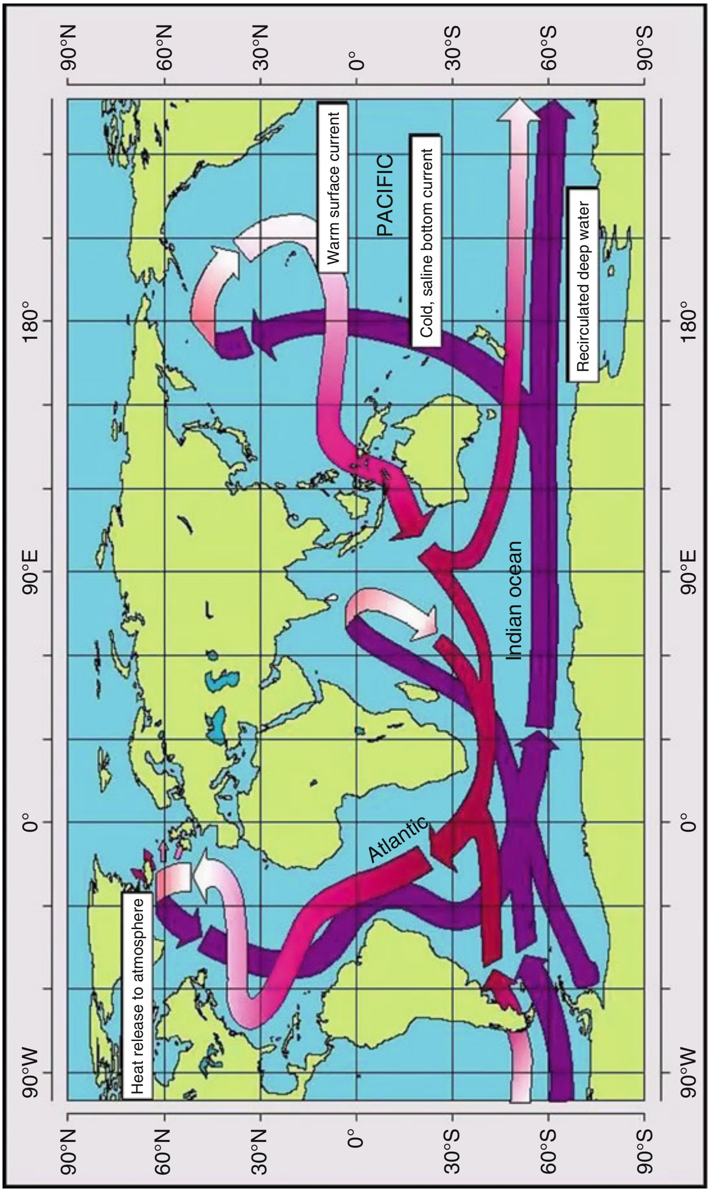


Fig. 2.2 Schematic of the thermohaline circulation, or the "Conveyor Belt," after Broecker [25]

which exchanges heat and salt with the sea ice above. As stated earlier, given this very large variety of ways required to run the climate model components, it becomes obvious why the setup using a coupler shown in Fig. 2.1 is extremely useful.

Fully Coupled Simulations

The first fully coupled simulation performed with a new version of a climate model is a present day control run. The model is given the year 2000 values of CO_2 and other greenhouse gases, the observed levels of natural and man-made aerosols, and the level of solar radiation. As discussed in the Introduction, the first requirement of the model is that the drift in this control run is small, so that the model does not drift very far from the present day initial conditions. Once that is established by a run of at least 100 years, then the simulation is continued for a longer period, sometimes for as long as 1,000 years, and carefully examined for its variability. There is variability on all time scales, such as the diurnal cycle, seasonal variability, the annual cycle, interannual variability, for example, the El Nino-Southern Oscillation (ENSO), and decadal variability. There is also plenty of data for comparison, see the next section. However, this control run assumes that the climate forcings are fixed, and the earth's present day climate is in a statistical equilibrium, which means that the climate is not in a truly steady equilibrium state, but has variability on all time scales around a steady state climate. This is clearly not the case in 2000, as the levels of CO_2 and other greenhouse gases have been increasing substantially over the twentieth century.

The last time the earth's climate was essentially in a statistically steady state was before mankind had started making large changes to the planet. This date can be argued over because man's changes to how land was used and trees felled changed the earth's climate somewhat. However, the date is usually taken to be before the atmospheric CO_2 level had increased significantly over the level at the Industrial Revolution. In simulations to be submitted to the 5th IPCC Assessment Report, this date has been chosen to be 1850. Therefore, most climate models will run another control for 1850 conditions, forced by the CO_2, aerosol, and solar values of that year. A very desirable outcome of this control run is that the simulated climate system does not lose or gain heat and fresh water over the duration of the control run. In practice, it is extremely difficult to balance these budgets precisely to zero, especially for heat, and all climate models lose or gain some heat from the ocean during any control run. However, in modern climate models this drift is very small, and is not a substantial problem. The real problem is that we do not have observations of the climate system in 1850 to compare with the model results. For example, we do not know the extent or thickness of Arctic and Antarctic sea ice in 1850.

The real purpose of an 1850 control run is to provide initial conditions for runs that simulate the period from 1850 to 2005, which are often called twentieth century runs. Time series over this period of four quantities are needed to force this type of run. They are the atmospheric concentrations of CO_2 and other greenhouse gases, the levels of natural and man-made aerosols, the level of solar output, and the level of aerosols in the atmosphere from volcanic eruptions. The last quantity is determined from the observed levels of aerosols from recent eruptions, such as El Chichon in 1982 and Pinatubo in 1991, and then scaled by the size of significant eruptions earlier in the 1850–2005 period. Very often an ensemble of these twentieth century simulations is run, where the initial conditions are taken from different times in the 1850 control run. If a climate model is to be useful, then its twentieth century runs must reproduce well many of the observed changes in the earth's climate over the last 150 years. Most of the comparisons with observations will use the last 50 years of these runs, which is when virtually all of the observations were made.

Note that for ESMs, which have an active carbon cycle, the twentieth century runs will be forced by CO_2 emissions, rather than atmospheric concentrations. A severe test for twentieth century ESM simulations will be to reproduce the time history of atmospheric CO_2 concentration over the time period 1850–2005. The reason is that to accomplish this, the ocean and land components of the ESM will have to take up the correct fraction of CO_2 emitted into the atmosphere. This nicely illustrates the fact that as a climate model or ESM becomes more complicated with more components, then it is required to perform at a higher level. The reason is that very important quantities, such as the atmospheric CO_2 concentration, are now being predicted by the model, instead of being prescribed from observations.

The ensemble of twentieth century runs will then be continued to make projections of future climate changes over the rest of the twenty-first century. In order to make a future climate projection, time series of two quantities are required: the atmospheric CO_2 concentrations (for climate models) or emissions (for ESMs) and other greenhouse gases, and the levels of natural and man-made aerosols. In these projections, the solar output is kept constant at its 2005 level, and only a background level of volcanic aerosols is used to account for future small volcanic eruptions. In all climate models, the magnitude of future climate change depends crucially on the concentrations of CO_2 and other greenhouse gases in the future, and to a smaller extent on the future levels of man-made aerosols, which are expected to keep reducing, as they have done over the last 30 years. For the 4th IPCC Assessment Report, three scenarios for the future concentrations of CO_2 were used, which all had CO_2 levels strongly increasing until 2100. For the 5th Assessment Report, scenarios will be used where the CO_2 concentrations increase at a much slower rate during the second half of the twenty-first century because it has been assumed that emissions will be much reduced over that period.

The second crucial factor that determines the magnitude of a model's future climate change over the twenty-first century is its climate sensitivity. Equilibrium climate sensitivity (ECS) is defined as the increase in the globally averaged surface temperature that results from a doubling of CO_2 in the atmosphere component when it is coupled to a slab ocean model. This setup of a climate model only takes about 30 years to come into equilibrium, whereas the full depth ocean component takes about 3,000 years. However, it has recently been shown [26] that the ECS using a full depth ocean is not very different than that obtained using a slab ocean model. Transient climate sensitivity (TCS) is defined as the increase in globally averaged surface temperature that occurs when CO_2 has doubled after 70 years of a transient simulation where CO_2 concentration increases at the rate of 1% per year. In general, a model with a small (large) ECS will also have a small (large) TCS, but the relationship is not one-to-one because models differ in the rate of heat uptake into the ocean and the timescales of other feedbacks. It is interesting to note that the ECS of every climate model ever developed has been positive, which is a very strong indication that the equilibrium climate is warmer when there is an increased concentration of atmospheric CO_2. Almost all models used in the IPCC 4th Assessment Report have an ECS in the range of 2°C–4.5°C. Despite dramatic improvements in climate models over the last 20 years, this range of ECS is the same as in the IPCC 1st Assessment Report [27]. It can be viewed as a disappointment that the range of ECS in climate models has not been reduced over this time period, but it reflects the fact that climate models still have to parameterize several important processes that affect climate sensitivity, the most important of which is clouds. The earth's climate sensitivity has also been estimated using observations [28], but this estimate has also not reduced the possible spread in its value. This brings up the subject of how climate models are validated.

Model Validation

The atmosphere component is the easiest to validate because there is a whole host of observations to compare its results against. These include observations taken by instruments, including satellites, and the so-called atmospheric reanalyses, which use a numerical model to assimilate many different observations to provide a time history of the state of the global atmosphere. These observations and reanalyses are compared with the results from AMIP simulations, which are described in the previous section. AMIP runs use a time history of observed sea surface temperature (SST), which is a relatively accurately observed quantity, especially since the start of the satellite era. There are a large number of variables that can be compared, which include temperature, winds, pressure, cloud amount, precipitation, shortwave solar radiation, and long-wave radiation emitted by the earth. These quantities can also be compared on many timescales from diurnal, seasonal, annual to interannual variability. In general, most of these comparisons are quite good, with cloud amount and precipitation being two of the more difficult variables for the atmosphere component to simulate well. As an example, Fig. 2.3a shows the mean annual cycle of precipitation from an AMIP simulation using the CCSM4 atmosphere component compared to long-term observations made at the Southern Great Plains site in Oklahoma. The difference between the model and observations is plotted in Fig. 2.3b, and shows that the model has too little precipitation during the fall and winter, but has too much precipitation in the late summer. Overall, the

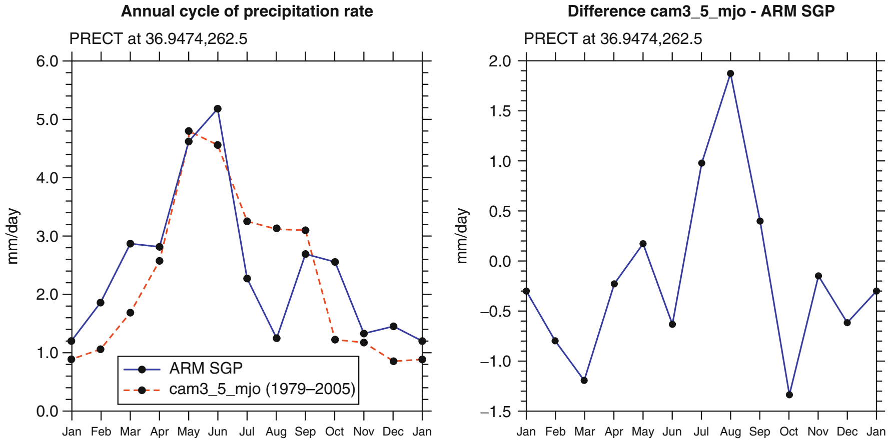


Fig. 2.3 Mean annual cycle of precipitation from an AMIP run of the CCSM4 atmosphere component and observations in the Southern Great Plains of the USA

comparison is reasonable because the annual mean values from the model and observations are quite close. Literally hundreds of such comparisons can be made, but what is a lot more difficult is how to synthesize and interpret the comparison results in order to produce better parameterizations for the clouds and precipitation in the atmosphere component.

It is a different story for the ocean component because there are far fewer observations to compare to ocean alone simulations. There is a compendium of temperature and salinity observations at prescribed depths [29] that can be used to compare to average conditions in the late twentieth century. In the best observed oceans, these observations can be split into the four seasons, so that the annual cycle in the upper ocean can be verified. It should be pointed out that satellites can only measure surface ocean quantities, so that their observations do not give information about the ocean vertical structure, unlike the atmosphere. However, there are direct observations in a few regions of the ocean, such as the upper, tropical Pacific Ocean, which can be used to make comparisons. Figure 2.4 shows the zonal current along the equator in the upper 400 m of the Pacific Ocean from an ocean alone simulation of the CCSM4 and observations [30]. It shows that the component does quite a good job in reproducing the westward surface current, and the very strong eastward equatorial undercurrent, which is one of the fastest ocean currents with a maximum speed of about 100 cm/s. The model simulation depends on the atmosphere winds used to force it, as well as some of the model parameterizations, and it is frequently difficult to decide whether a poor comparison with observations is the result of poor forcing fields or a problem with the model parameterizations.

The situation is worse for sea ice because there are even fewer observations. Sea ice extent and concentration were not well known until they began to be observed from satellites in 1979. Sea ice thickness is still not well observed, although the general spatial patterns are known from accumulating point measurements over the

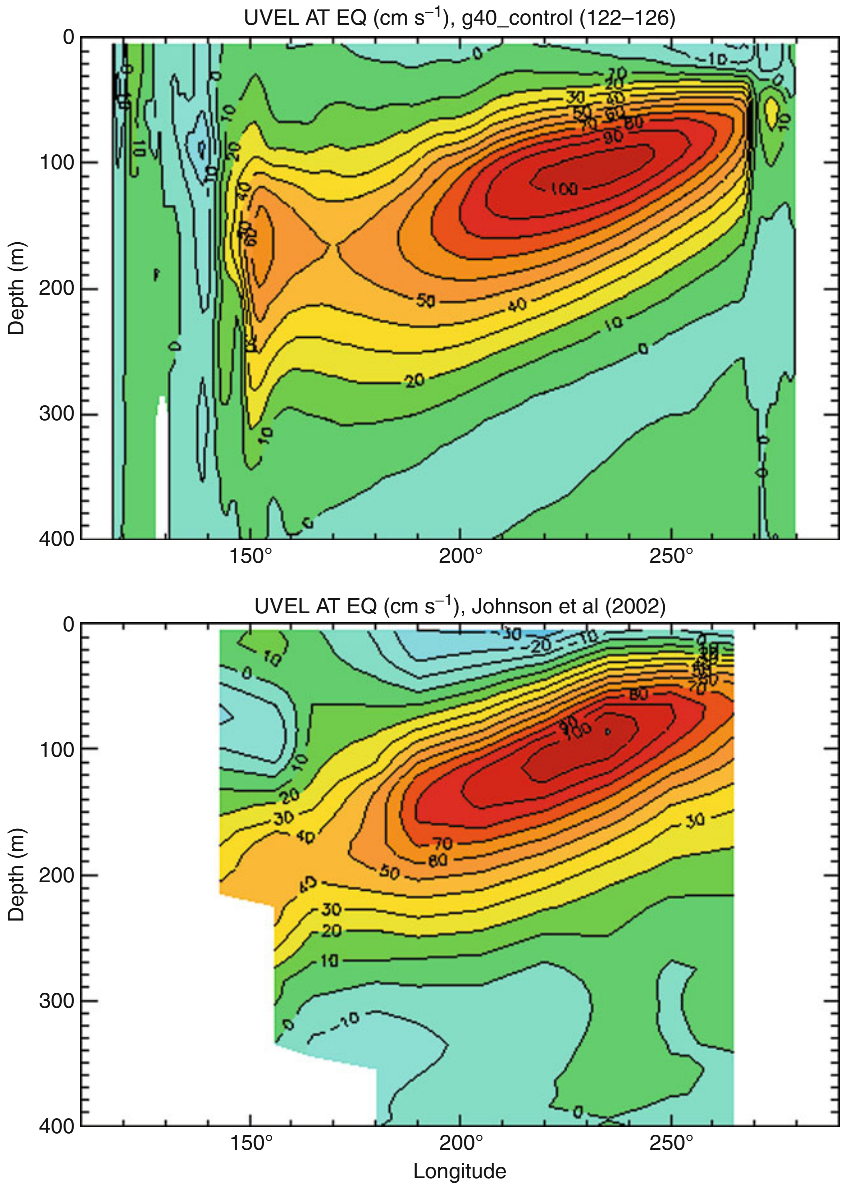


Fig. 2.4 Comparison of zonal velocity along the equator in the upper Pacific Ocean between the ocean component of the CCSM4 and the observations in [30]

years. However, there are many processes that affect sea ice, such as ridging, the formation of polynas, and melt ponds, and how snow aging affects the albedo that have to be parameterized, although there are few observations of them. There are also not too many measurements to compare with the variables in the land component, although more than for sea ice. The measurements of quantities such as soil temperature and moisture, albedo, and the leaf area amount have to be taken in areas with natural vegetation, as well as in man-made areas such as croplands. Again, there has been a large increase in observations over the past 20 years or so during the satellite era, and from land based observations at several specific sites.

As mentioned in the previous section, there are difficulties comparing both present day and 1850 control simulations with observations because the present climate is not in equilibrium, and there are not many observations from 1850. The only quantity from that time that can be estimated directly from observations is the globally averaged surface temperature. Also, the global SST pattern from 1850 to the present has been estimated in the HadISST dataset [31] by determining the principle variation patterns from the period when SST has been well measured and using these patterns to produce global data in the early part of the period when there were only a few measurements. However, the best simulations to compare with observations are the ensemble of twentieth century runs from 1850 to 2005.

There are a very large number of variables that can be compared to observations from the second half of the twentieth century, but some of the most important are large-scale patterns of interannual variability, such as ENSO and the North Atlantic Oscillation [32]. ENSO is the largest interannual signal in the earth's climate and much about it has been learned from observations over the last 25 years. The variable that is most often used to characterize ENSO is called the nino3 SST, which is the SST averaged over the area 90°W–150°W, 5°S–5°N in the central Pacific Ocean. Figure 2.5 shows the nino3 monthly SST anomalies, and a wavelet analysis, which is a method to plot the time variation of the amplitude of the anomalies as a function of the frequency content. The three smaller boxes show the power spectrum (variance against period in years), the autocorrelation against lag time in months, and the annual cycle of the variance amplitude.

Figure 2.5 shows that the amplitude of nino3 SST anomalies in the CCSM4 is a little smaller than in the HadISST observations, especially the warm events which have a maximum amplitude of just over 3°C in the data, but are only 2.5°C in the model. This means that the wavelet and power spectrum are also a little weak in the CCSM4. However, the amplitude of nino3 SST anomalies from earlier periods of the twentieth century run is larger than the HadISST data, which shows there is strong decadal variability in the CCSM4 ENSO amplitude. The CCSM4 power spectrum peaks at a period of 3–4 years compared to 4–5 years in the data, the autocorrelation compares quite well, and the annual cycle of variance is quite good with a minimum in May compared to April in the HadISST data. This good comparison is independent of the period of the run examined and is a very important improvement over all the previous versions of the CCSM, which had ENSO spectra that had a dominant peak at 2 years. This improvement was due to two changes made to the convection parameterization scheme in the atmosphere component [33]. The CCSM was one of many climate models that had a poor ENSO simulation for a long time [34], which was not a good situation given that ENSO is the largest interannual signal in the earth's climate.

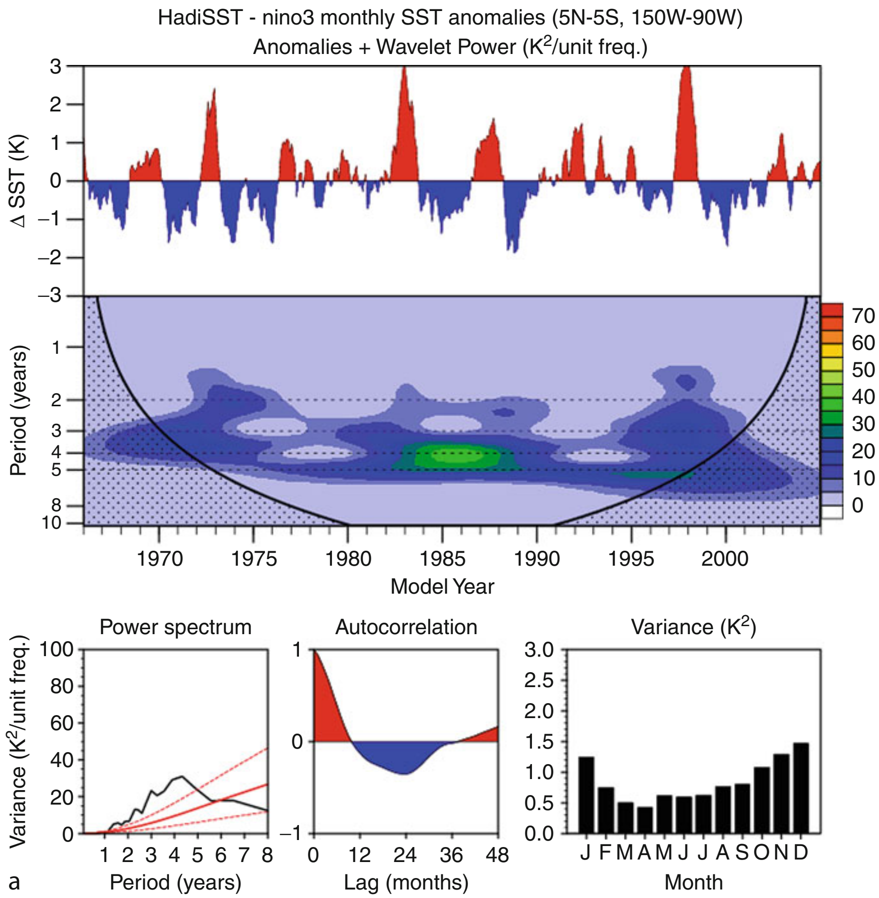


Fig. 2.5 Nino3 monthly SST anomalies between 1966 and 2005, wavelet power, power spectrum, autocorrelation, and variance from (**a**) HadISST observations, and (**b**) a twentieth century simulation using the CCSM4

Probably the only well-measured variable that can be compared to the model over the whole period of a twentieth century run is the globally averaged surface temperature. Figure 2.6 shows this comparison over 1890–2000 between the HadISST data and an ensemble of twentieth century runs using the CCSM version 3. The red line is the mean value from the ensemble, and the shading indicates the standard deviation across the eight member ensemble. This comparison is not perfect, but the data is not too often outside the shading. The model was then integrated forward to make an ensemble of projections for the twenty-first century [35] that were submitted to the IPCC 4th Assessment Report.

Another quantity that has been given a lot more attention in recent years is the sea ice extent in the Arctic Ocean. In order to give realistic projections of the future state of Arctic sea ice, a climate model must simulate it well at the end of the

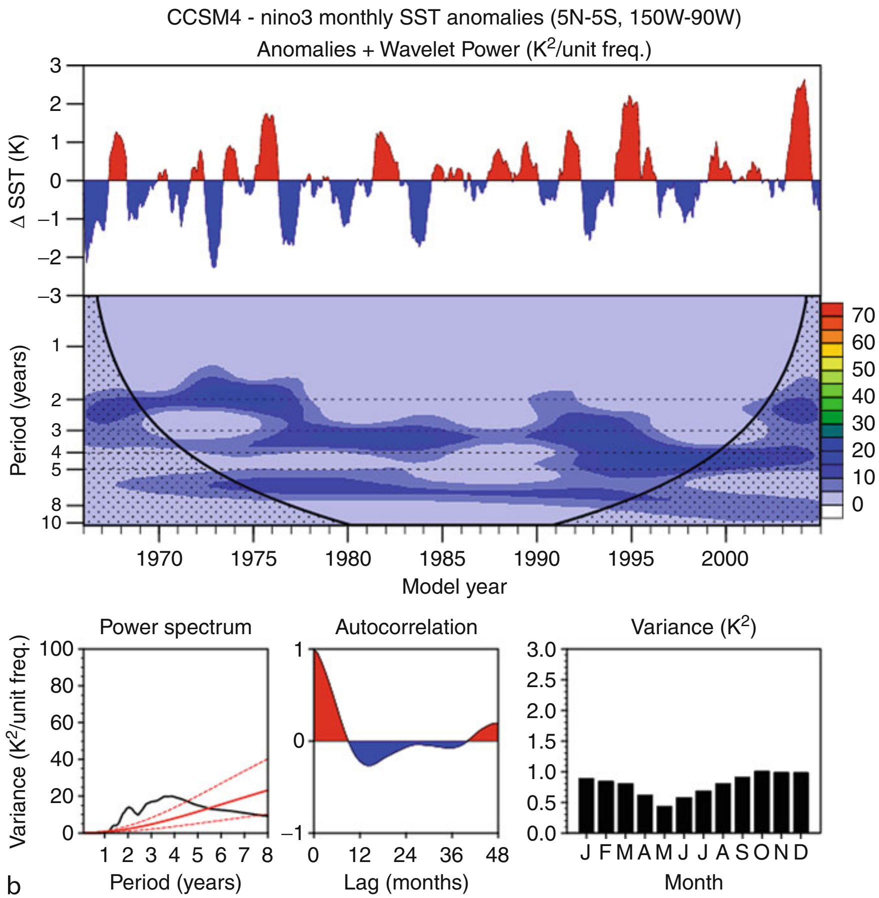


Fig. 2.5 (continued)

twentieth century. Arctic sea ice has a minimum extent in September, and this has been well measured by satellite since 1979. Figure 2.7 shows the observed September Arctic sea ice extent from observations and the latest two versions of the CCSM. For the CCSM3, the twentieth century run forced by observed concentrations of CO_2 ends in 2000, and the model then used a scenario for the future levels of CO_2. The projected decline in the CCSM3 ice extent between 2000 and 2009 is not quite as large as has been observed. However, the actual rise in CO_2 concentration in the earth's atmosphere in the decade since 2000 has been somewhat larger than in the forcing scenario used in the CCSM3 projection shown in Fig. 2.7. It is important to remember that results from future projections strongly depend on the forcing scenario used. This same projection suggests that the Arctic Ocean will become virtually ice free in September by 2040 [36], but again the actual year when this might occur will depend on the concentrations of CO_2 and

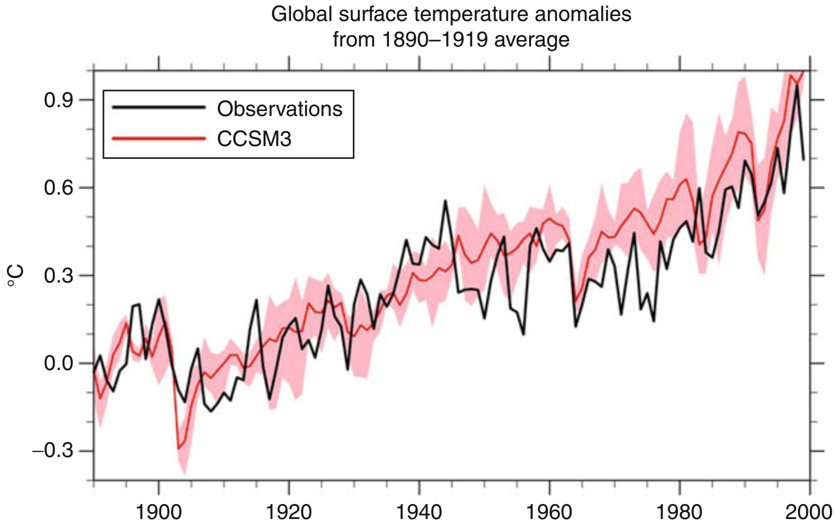


Fig. 2.6 Globally averaged surface temperature anomalies from HadISST data plotted against the results of an ensemble of twentieth century runs using the CCSM3

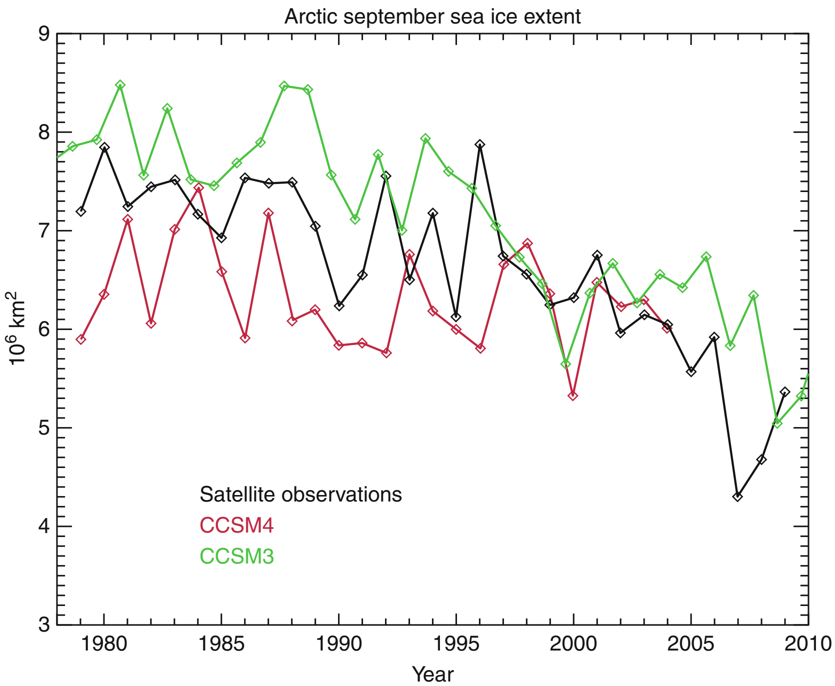


Fig. 2.7 Arctic September sea ice extent from observations, CCSM3, and CCSM4

other greenhouse gases over the next 30 years. The result from the CCSM4 shown in Fig. 2.7 is just from a twentieth century run, which goes to the beginning of 2005. Again the comparison is good, and the CCSM4 will be used to make future projections for the IPCC 5th Assessment Report.

Other comparisons to validate the ability of a climate model to simulate the historical evolution of the earth's climate can be made, but the observations are probably not as accurate as for surface temperature and sea ice extent. Two examples are ocean heat content and the distribution of chlorofluorocarbon-11 (CFC-11) in the ocean. The time history of CFC-11 concentration in the atmosphere is well known, so this can be used as an input to the ocean component during a twentieth century simulation. Observations of both ocean heat content and CFC-11 are sparse in both time and space, but estimates of their changes can be made and compared to model results [37]. This comparison helps to determine whether the ocean component is taking up quantities at the correct rate. It is very important in an ESM that the ocean takes up the correct fraction of the CO_2 that is emitted into the atmosphere. It is more difficult to make comparisons of changes in the land component because the largest changes in land use over the twentieth century are man-made and not changes in the natural vegetation. Changes in how land has been, and might be, used are often imposed in the land component during twentieth and twenty-first century simulations, which allows an assessment of how these changes have affected the past climate and might affect future climate changes [38]. On the global scale, these changes are much smaller than changes due to increases in CO_2 and other greenhouse gases, but they can be important in affecting the climate locally.

Climate Forecasts

First, the difference between a forecast and a projection needs to be explained. When a weather forecast is made, there are two separate factors that determine the quality of the forecast. The first is the quality of the atmosphere model used; all models are not perfect, but some are better than others. However, just as important is the quality of the analysis of the current state of the atmosphere that is used as the initial condition for the forecast. Even if the model were perfect, if the initial condition is slightly incorrect, then the model forecast and the real evolution of the atmosphere will diverge. The reason is that both the real atmosphere and the forecast model are examples of a chaotic system. What defines a chaotic system of equations is that, if they are integrated forward from two very slightly different initial conditions, then the two future solutions will diverge from each other, often quite quickly. Chaos theory was founded by a famous meteorologist, Edward Lorenz, who published a classic paper in 1963 [39]. He made drastic approximations to the equations that represent the atmosphere to produce a set of three, quite simple ordinary differential equations. When he integrated them forward in time from two slightly different initial states, the solutions diverged, which is the characteristic of what came to be called a chaotic system. In practice, it is very difficult to separate these two sources of error in a weather forecast because the model is also used to create the initial conditions on the model grid using all the latest meteorological observations from around the world. In order to reduce the likelihood of a bad weather forecast, an ensemble of forecasts is made using a set of slightly different initial conditions. If all the ensemble forecasts predict that something will occur, then it is forecast with a high probability; whereas if the ensemble forecasts differ markedly, then it is forecast with a low probability.

Virtually all long climate model simulations of the future done so far are projections, not forecasts. The reason is that most twenty-first century runs are just a continuation of a twentieth century run of the model, and no attempt is made to initialize the climate model to the observed climate in 2005, or whatever year the twenty-first century run starts. All results submitted to the IPCC 4th Assessment Report were from future climate projections. If something, such as a large ENSO event or a sudden reduction in the September extent of Arctic sea ice for example, occurs in 2015 in a projection, then this is not a forecast that it will actually happen in 2015, but a strong indication that this type of event might very well occur in the years around 2015. The case of ENSO events is interesting and instructive because ENSO forecasts up to a year in advance are now regularly made by a number of centers around the world using climate models [40].

For a weather forecast using an atmosphere model, it is important to start with the correct initial state of the atmosphere. However, for a seasonal or ENSO forecast, a full climate model must be used because the land, ocean, and sea ice evolve on these time scales. For these forecasts, therefore, initial conditions for the climate model are needed, and the most important component to initialize correctly is the ocean because it has the slowest time scales and by far the largest heat capacity. For an ENSO forecast, what is needed is the correct thermal state of the upper 300–400 m of the tropical Pacific Ocean between about 15° north and south. ENSO forecasts could not become a reality until there was an observing system in the tropical Pacific to continuously measure and report upper ocean temperatures [41]. An analysis is performed on these observations to produce a temperature field on the model grid, and this is used as the ocean component initial condition. As the forward integration starts, the tropical atmospheric circulation comes into balance with the sea surface temperature field in about a week, which is why it is not necessary to initialize the atmosphere component. As always, an ensemble of ENSO forecasts is made by slightly changing the initial conditions used in the ocean component. For an ENSO forecast, it is important to initialize correctly the upper tropical Pacific Ocean, but for a climate forecast over a decade, there are many more aspects of the climate model that need to be initialized correctly: the ocean deeper than the upper 400 m, especially in the North Atlantic Ocean where the thermohaline circulation occurs, the sea ice distribution in both the Arctic and Antarctic, and some aspects of the land component, such as where the soil moisture content is above or below normal. We do not know precisely all the quantities that need to be initialized correctly, but we are absolutely certain that there are not adequate observations of all these quantities.

Forecasts of climate changes over the next decade on a regional basis are what would be most helpful in planning for the future. A few preliminary decadal forecasts have been made by centers in the UK and Germany [42, 43], and many centers will submit a suite of decadal forecasts to the IPCC 5th Assessment Report. However, the science of decadal climate forecasts is in its infancy [44], and there is a very large amount of research to be done before they will become reliable. Decadal forecasts are now where weather forecasts were 50 years ago, but they have another disadvantage. Weather forecasts are made and verified every day, so that there is a very large number of realizations that can be used to make improvements. By their very nature, decadal forecasts are only verified after 10 years, so that the number of opportunities to compare model predictions to observations is reduced enormously. However, the outlook for decadal forecasts has improved over the last few years. First, there is now an ocean observing system called ARGO floats (named after the mythical Greek ship used by Jason and the Argonauts to seek the Golden Fleece), that since about 2003 has been giving nearly global coverage of temperature and salinity down to a depth of 2 km, which has improved enormously our ability to correctly initialize the ocean component [45]. However, no decadal forecast initialized using ARGO data, which can start at the beginning of 2005 at the earliest, has yet had enough time to be verified. There are also satellite observations of Arctic and Antarctic sea ice extent and the soil moisture content over the continents, which could potentially be used in the initialization. Second, as the computing capacity continues to increase, then the resolution of climate models used for predictions will continue to improve, which will enable decadal forecasts to be more accurate on the regional scales that are required for future planning.

Future Directions

The computational power available to climate modelers will continue to increase in the future, so how should it be used? Should it be used to increase the resolution of present day climate models or used to increase the range of components in ESMs? This is an extremely difficult question to answer definitively. Increased resolution will undoubtedly improve some aspects of climate model simulations, but omitting an additional component may well leave out feedbacks that are potentially important. The answer will almost certainly be to push forward in both directions because scientists with different interests will lead the work in the two different directions. Another possibility is to increase the ensemble size used in future projections and predictions, which will give more reliability to simulated changes in extreme events [46], for example, which is a very important factor in planning for the future.

As mentioned above, clouds have to be parameterized in the atmosphere, and the way this is done can change the ECS of a climate model. Clouds also have to be parameterized in weather forecast models, but are often done so in a different way because the weather forecast model is run at a much higher resolution than the climate model. Over the last few years, there has been the suggestion, called Seamless Prediction, that the same atmosphere component should be used in both weather and climate prediction. In this situation, the cloud parameterization used would have to work well across all the scales involved in both weather and climate predictions. This is not as easy as it sounds because both groups have developed their own parameterizations over past years, which make rather different assumptions. There have even been suggestions that both models should use extremely fine resolution on the order of 1 km, so that clouds can be resolved rather than parameterized, but running climate models at this resolution is still many years away. Seamless Prediction is a long-term goal, but it will probably not be realized over the next few years.

Another example of a phenomenon that is not resolved in present day climate models is mesoscale eddies in the ocean. These are the equivalent of atmospheric highs and lows, but occur at a range of scales from 200 to 300 km near the equator to 20–30 km in the very high latitude oceans. Only the equatorial eddies are partially resolved if the ocean component has a grid-spacing of about 1°. So, the effect of these energetic eddies on the large-scale mean flow has to be parameterized in present day climate models. However, it has been shown that a majority of these eddies can be resolved when using a grid-spacing of $1/10^\circ$ in the ocean component [47, 48]. Diagnosis of these simulations has shown that the eddy parameterization used in the 1° simulations works quite well, but still the question remains: will future climate change projections in models that resolve the mesoscale eddies give very similar answers to future projections where they are parameterized? The answer to this important question should be found in the next few years because some climate change runs with resolved eddies are now possible with the available computer time.

Examples of new components that are currently being incorporated into ESMs have been discussed earlier, and include chemistry-air quality, hydrological, dynamic vegetation, and crop model components. The new component to simulate the Greenland and Antarctic ice caps is a very nice example of an important new component. However, there is a long list of possible feedbacks that have not been included in any ESM so far. Good examples are the increased release of methane, which is a very potent greenhouse gas, from Arctic tundra as the Arctic region warms [49], the possible release of methane from ocean clathrates [50, 51], and the possible fast breakup of the West Antarctic Ice Sheet [52]. All these are examples of possible abrupt climate changes that could result in large future changes that would have very far reaching consequences. However, all are very difficult to simulate accurately in an ESM and to assess quantitatively the possibilities that they will occur.

The science of decadal forecasts will also be advanced in the near future, both by new ideas and experience in how they should be initialized, and by increasing the resolution of the components used that will give more regional information. As explained in the previous section, there is a lot to learn and much experience needs to be gained before decadal forecasts become reliable. However, they will produce the most useful kind of information that is required by people planning for the future.

Finally, what motivates the scientists working to develop climate models and ESMs? First, it is a very stimulating intellectual challenge to understand what controls the earth's past, present and future climates, and to build an ESM that gives a faithful representation of this. This requires the expertise of many scientists across a large and diverse set of sciences ranging from several earth sciences to computer science. It is a real challenge to make these models run correctly and efficiently on several of today's massively parallel supercomputers. I also know from experience, that managing an ESM project is very challenging because it is such a diverse scientific enterprise. A second motivating factor is also very important to many scientists working on ESMs. It is that they believe these models are the best means we have available to anticipate possible future changes to the earth's climate, and that their results should be made freely and widely available to anyone who wants to see them.

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