Chapter 23
Introduction to Climate Change and Climate Models

Mrinmoy Majumder

Abstract Climate change is defined as the change in the weather pattern of a region. The models which are employed to predict climate change of the future are collectively called as climate models. The present note describes the formation, structures, and working principles of global as well as regional climate models. The note also describes the climate change scenarios that are presently created.

Keywords Climate • climate models • global warming • IPCC

23.1 Climate Change and Climate Models

Global warming is defined as a natural- or human-induced increase in the average global temperature of the atmosphere near the earth's surface. The earth as a planet is a complex combination of many elements which constitute the solid earth, atmosphere, biosphere, cryo-sphere, and the hydrosphere. These components interact with each other in a non-linear manner involving the feedbacks of energy, mass, and momentum. The energy is derived from the sun in the form of shortwave solar radiation which penetrates the earth's surface with little loss of energy in transit. In the process, the heated earth emits thermal or long wave radiation outward which mostly gets absorbed by the atmospheric constituent. Water vapor and several other gases including carbon dioxide, methane, and CFCs warm the earth's atmosphere because they absorb and remit radiations. They trap some of the heat energy radiations from the earth's atmospheric system. The trapping or warming is somewhat analogous to a greenhouse, which also traps heat; thus the process has

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M. Majumder (✉)
Senior Research Fellow, School of Water Resources Engineering, Jadavpur University, Kolkata-700032, West Bengal, India
and
Geo-information Scientist, Regional Center, National Afforestation and Eco-development Board, Jadavpur University, Kolkata-700032, West Bengal, India
e-mail: mrinmoy@majumder.info

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been called the greenhouse effect. The excessive increase in the concentration of green house gases makes the atmosphere warmer which in turn induces the climate to change.

23.2 Impact of Global Warming

The effect of global warming is now predominant in many parts of the world. Twelve warmest years have occurred in 1900s among which ten have occurred between 1987 and 1998. The energy availability which was increased due to increase in temperature had created a ripple effect throughout the Earth system with local, regional, and global positive feedbacks feeding on each other to amplify and accelerate warming (Stewart and Vemuri 2006). Abnormality in climatic pattern, induced by the accelerated warming, had started to effect catchment specific hydrologic cycles. In the last 10 years, floods have caused more damage than in the previous 30 years. Higher temperatures lead to a high rate of evaporation and very dry conditions in some areas of the world. Severe weather events are now more common. The number and strength of hurricanes, tornadoes, and other events had increased over the last 15–20 years. As per IPCC (2007), global climate change is expected to affect the performance of water resource systems according to current indicators and findings.

23.3 Special Report on Emissions Scenarios

The Special Report on Emissions Scenarios (SRES) was a report prepared by the Intergovernmental Panel on Climate Change (IPCC) for the Third Assessment Report (TAR) in 2001, on future emission scenarios to be used for driving global circulation models to develop climate change scenarios. It was used to replace the IS92 scenarios used for the IPCC Second Assessment Report of 1995. The SRES Scenarios were also used for the Fourth Assessment Report (AR4) in 2007.

23.3.1 Purpose

Because projections of climate change depend heavily upon future human activity, climate models are run against scenarios. There are 40 different scenarios, each making different assumptions for future greenhouse gas pollution, land-use, and other driving forces. Assumptions about future technological development as well as the future economic development are thus made for each scenario. Most include an increase in the consumption of fossil fuels; some versions of B1 have lower levels of consumption by 2100 than in 1990. Overall, the world GDP will increase with a factor between 5 and 25 in the emission scenario. It is questionable whether this form of assumptions will hold as several limits to growth appears to be upon the world. Peak Oil is for instance not discussed in the emission scenarios.

These emission scenarios are organized into families, which contain scenarios that are similar to each other in some respects. IPCC assessment report projections for the future are often made in the context of a specific scenario family.

23.3.2 Scenario Families

Scenario families contain individual scenarios with common themes. The six families of scenarios discussed in the IPCC's Third Assessment Report (TAR) and Fourth Assessment Report (AR4) are A1FI, A1B, A1T, A2, B1, and B2.

Scenario descriptions are based on those in AR4, which are identical to those in TAR.

23.3.2.1 A1 Scenario

The A1 scenarios are of a more integrated world. The A1 family of scenarios is characterized by

- Rapid economic growth
- A global population that reaches 9 billion in 2050 and then gradually declines
- The quick spread of new and efficient technologies
- A convergent world-income and way of life converge between regions
- Extensive social and cultural interactions worldwide

There are subsets to the A1 family based on their technological emphasis:
A1FI – an emphasis on fossil fuels
A1B – a balanced emphasis on all energy sources
A1T – emphasis on non-fossil energy sources

23.3.2.2 A2 Scenario

The A2 scenarios are of a more divided world. The A2 family of scenarios is characterized by

- A world of independently operating, self-reliant nations
- Continuously increasing population
- Regionally oriented economic development
- Slower and more fragmented technological changes and improvements to per capita income

23.3.2.3 B1 Scenario

The B1 scenarios are of a world more integrated, and more ecologically friendly. The B1 scenarios are characterized by

- Rapid economic growth as in A1, but with rapid changes towards a service and information economy

- Population rising to 9 billion in 2050 and then declining as in A1
- Reductions in material intensity and the introduction of clean and resource efficient technologies
- An emphasis on global solutions to economic, social, and environmental stability

21.3.2.4 B2 Scenario

The B2 scenarios are of a world more divided, but more ecological friendly. The B2 scenarios are characterized by

- Continuously increasing population, but at a slower rate than in A2
- Emphasis on local rather than global solutions to economic, social and environmental stability
- Intermediate levels of economic development
- Less rapid and more fragmented technological change than in A1 and B1

23.3.3 SRES Scenarios and Climate Change Initiatives

While some scenarios assume a more environment friendly world than others, none include any climate-specific initiatives, such as the Kyoto Protocol.

Total cumulative SRES carbon emissions from all sources through 2100 range from approximately 770 GtC to 2,540 GtC. According to the IPCC Second Assessment Report (SAR), "any eventual stabilized concentration is governed more by the accumulated anthropogenic CO_2 emissions from now until the time of stabilization than by the way emissions change over the period."

Total anthropogenic methane (CH_4) and nitrous oxide (N_2O) emissions span a wide range by the end of the twenty-first century. Emissions of these gases in a number of scenarios begin to decline by 2050. The range of emissions is wider than in the IS92 scenarios due to the multimodel approach, which leads to a better treatment of uncertainties and to a wide range of driving forces. These totals include emissions from land use, energy systems, industry, and waste management.

Methane and nitrous oxide emissions from land use are limited in A1 and B1 families by slower population growth followed by a decline, and increased agricultural productivity. After the initial increases, emissions related to land use peak and decline. In the B2 family, emissions continue to grow, albeit very slowly. In the A2 family, both high population growth and less rapid increases in agricultural productivity result in a continuous rapid growth in those emissions related to land use.

The range of emissions of Hydro Fluro Carbons (HFC) in the SRES scenario is generally lower than in earlier IPCC scenarios. Because of new insights about the availability of alternatives to HFCs as replacements for substances controlled by the Montreal Protocol, initially HFC emissions are generally lower than in previous IPCC scenarios. In the A2 and B2 scenario families HFC emissions increase rapidly in the second half of the this century, while in the A2 and B2 scenario families the growth of emissions is significantly slowed down or reversed in that period.

Sulfur emissions in the SRES scenarios are generally below the IS92 range, because of structural changes in the energy system as well as concerns about local and regional air pollution. These reflect sulfur control legislation in Europe, North America, Japan, and (more recently) other parts of Asia and other developing regions. The timing and impact of these changes and controls vary across scenarios and regions.

23.4 Climate Models

Climate models use quantitative methods to simulate the interactions of the atmosphere, oceans, land surface, and ice. They are used for a variety of purposes from study of the dynamics of the climate system to projections of future climate.

All climate models take account of incoming energy as short wave electromagnetic radiation (which in this context means visible and ultraviolet, not to be confused with shortwave) to the earth as well as outgoing energy as long wave (infrared) electromagnetic radiation from the earth. Any imbalance results in a change in the average temperature of the earth.

The most talked-about models of recent years have been those relating temperature to emissions of carbon dioxide. These models project an upward trend in the surface temperature record, as well as a more rapid increase in temperature at higher altitudes.

Models can range from relatively simple to quite complex.

A simple radiant heat transfer model that treats the earth as a single point and averages outgoing energy this can be expanded vertically (radiative-convective models), or horizontally.

Finally, (coupled) atmosphere–ocean–sea ice global climate models discretize and solve the full equations for mass and energy transfer and radiant exchange.

This is not a full list; for example “box models” can be written to treat flows across and within ocean basins. Furthermore, other types of modeling can be interlinked, such as land use, allowing researchers to predict the interaction between climate and ecosystems.

Climatic models are broadly divided into Global Climate Models and Regional Climate Models. The uncertainty in the climatic pattern had made the estimation of future climate more complex.

23.4.1 Global Climate Models

The Global Climate Models (GCM) were widely used to estimate future climatic parameters but the complexity of the present climatic pattern had forced many modifications.

HadCM2 AOGCM model was developed by Met Office Hadley in 1994 and its successor, HadCM3 AOGCM (Atmosphere-Ocean General Circulation Models), was published in 1998. AOGCM coupled with an atmospheric chemistry model which can predict the changes in concentration of other atmospheric constituents in response to climate change and to the changing emissions of various gases was later

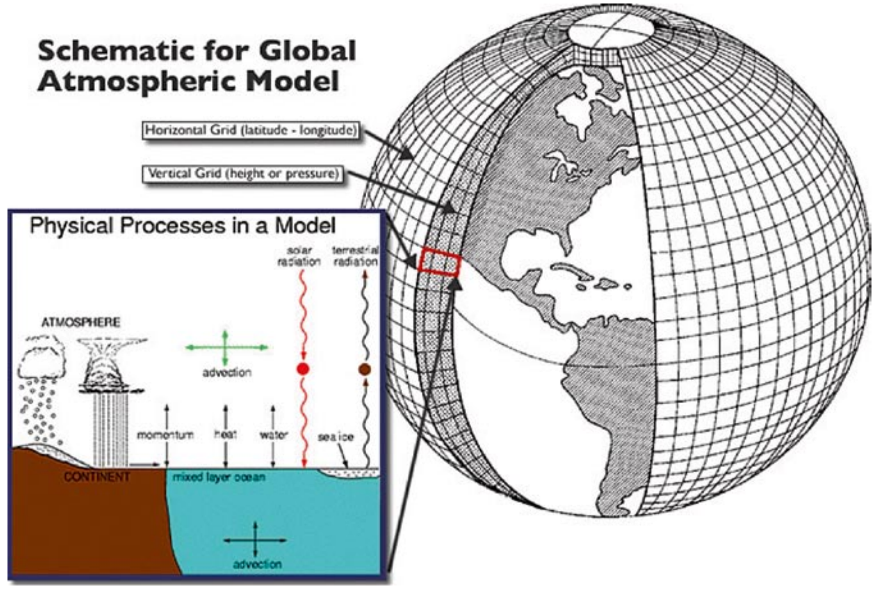

Fig. 23.1 Figure showing a schematic diagram of global atmospheric model

built on 1999. In HadCM3, thermohaline circulation, ventilation, vertical mixing of chemical constituents along with decadal variability in the ocean was included.

Local climate change is influenced greatly by local features such as mountains, which are not well represented in global models (GCMs) because of their coarse resolution, and models of higher resolution could not practically be used for global simulation for long periods of time due to spatial variance of the considered parameters. These problems were tried to be mitigated with the help of regional climate models (RCM). The RCM had higher resolution (typically 50 km), were constructed for limited areas and allowed to run for shorter periods (20 years or so). The Met Office Hadley Centre had run RCMs for three regions, Europe, the Indian subcontinent and southern Africa and had developed an RCM to run on PCs for any region as part of a regional climate modeling system called PRECIS (Fig. 23.1).

23.4.1.1 Structure of Global Climatic Models

Three-dimensional (more properly four-dimensional) GCMs discretize the equations for fluid motion and integrate these forward in time. They also contain parametrizations for processes – such as convection – that occur on scales too small to be resolved directly. More sophisticated models may include representations of the carbon and other cycles.

A simple general circulation model (SGCM), a minimal GCM, consists of a dynamical core that relates material properties such as temperature to dynamical properties such as pressure and velocity. Examples are codes that solve the primitive equations, given energy input into the model, and energy dissipation in the form of scale-dependent friction, so that atmospheric waves with the highest wavenumbers are the ones most strongly attenuated. Such models may be used to study atmospheric processes within a simplified framework but are not suitable for future climate projections.

Atmospheric GCMs (AGCMs) model the atmosphere (and typically contain a land-surface model as well) and impose sea surface temperatures (SSTs). A large amount of information including model documentation is available from AMIP (Atmospheric Model Intercomparison Project 2009) they may include atmospheric chemistry.

A GCM contains a number of prognostic equations that are stepped forward in time (typically winds, temperature, moisture, and surface pressure) together with a number of diagnostic equations that are evaluated from the simultaneous values of the variables. As an example, pressure at any height can be diagnosed by applying the hydrostatic equation to the predicted surface pressure and the predicted values of temperature between the surface and the height of interest. The pressure diagnosed in this way then is used to compute the pressure gradient force in the time-dependent equation for the winds.

Oceanic GCMs (OGCMs) model the ocean (with fluxes from the atmosphere imposed) and may or may not contain a sea ice model. For example, the standard resolution of HadOM3 is 1.25° in latitude and longitude, with 20 vertical levels, leading to approximately 1,500,000 variables.

Coupled atmosphere-ocean GCMs (AOGCMs) (e.g., HadCM3, GFDL CM2.X) combine the two models. They thus have the advantage of removing the need to specify fluxes across the interface of the ocean surface. These models are the basis for sophisticated model predictions of future climate, such as are discussed by the IPCC.

AOGCMs represent the pinnacle of complexity in climate models and internalize as many processes as possible. They are the only tools that could provide detailed regional predictions of future climate change. However, they are still under development. The simpler models are generally susceptible to simple analysis and their results are generally easy to understand. AOGCMs, by contrast, are often nearly as hard to analyze as the real climate system.

23.4.1.2 Model Grids

The fluid equations for AGCMs are discretized using either the finite difference method or the spectral method. For finite differences, a regular grid (i.e., with constant grid spacing) in latitude and longitude is most common. However, variable resolution grids can be used. The “LMDz” model can be arranged to give high resolution over any given section of the planet. HadGEM1 (and other ocean models) use an ocean grid with higher resolution in the tropics to help resolve processes believed to be important for ENSO. Spectral models generally use a Gaussian grid, because of the mathematics of transformation between spectral and grid-point space. Typical AGCM resolutions are between 1° and 5° in latitude or longitude: the Hadley Centre model HadAM3, for example, uses 2.5° in latitude and 3.75° in longitude, giving a grid of 73 by 96 points; and has 19 levels in the vertical. This results in approximately 500,000 "basic" variables, since each grid point has four variables (u, v, T, Q), though a full count would give more (clouds; soil levels). HadGEM1 uses a grid of 1.25° in latitude and 1.875° in longitude.

For a standard finite difference model, the gridlines converge towards the poles. This would lead to computational instabilities (see CFL condition) and so the model variables must be filtered along lines of latitude close to the poles. Ocean models suffer from this problem too, unless a rotated grid is used in which the North Pole is shifted onto a nearby landmass. Spectral models do not suffer from this problem. There are experiments using geodesic grids (UniSci 2001) and icosahedral grids, which (being more uniform) do not have pole-problems.

23.4.1.3 Different Types of GCMs Based on Model Structure

One-Dimensional Models

One-Dimensional Radiative-Convective Atmospheric Models

These models are globally averaged horizontally but contain many layers within the atmosphere. They treat processes related to the transfer of solar and infrared radiation within the atmosphere in considerable detail, and are particularly useful for computing the changes in net radiation – one of the possible drivers of climatic change – associated with changes in the composition of the atmosphere (e.g., Lal and Ramanathan 1984; Ko et al. 1993). The change in atmosphere water vapor amount as climate changes must be prescribed (based on observations), but the impact on radiation associated with a given change in water vapor can be accurately computed. The increase in water vapor in the atmosphere is thought to be the single most important feedback that amplifies an initial radiative perturbation, and radiative-convective models provide one means for assessing this feedback through a combination of observations and well-established physical processes.

One-Dimensional Upwelling-Diffusion Ocean Models

In this type of model, which was first applied to questions of climatic change by Hoffert and Hseih (1980), the atmosphere is treated as a single well-mixed box that exchanges heat with the underlying ocean and land surface. The absorption of solar radiation by the atmosphere and surface depends on the specified surface reflectivity and the atmosphere transmissivity and reflectivity. The emission of infrared radiation to space is a linearly increasing function of atmospheric temperature in this model; this increase serves to "dampen" temperature changes and thus limits the final temperature response for a given radiative perturbation through an appropriate choice of the constant of proportionality in the parameterization of infrared radiation to space. The model can be forced to have any desired climate responsiveness to a given radiative perturbation. This process is in turn useful if one is trying to replicate the behavior of more complex models in a computationally efficient way for the purpose of scenario analysis and testing the interactions between different model components. The ocean is treated as a one-dimensional column that represents a horizontal average over the real ocean, excluding the limited regions where deep water forms and sinks to the ocean bottom, which are treated separately.

One-Dimensional Energy Balance Models

In these models, the only dimension that is represented is the variation with latitude: the atmosphere is averaged vertically and in the east west direction, and often combined with the surface to form a single layer. The multiple processes of meridional (north-south) heat transport by the atmosphere and oceans are usually represented as diffusion, while infrared emission to space is represented in the same way as in the upwelling diffusion model. These models have provided a number of useful insights concerning the interaction of horizontal heat transport feedbacks and high-latitude feedbacks involving ice and snow (e.g., Held and Suarez 1974).

Two-Dimensional Atmosphere and Ocean Models

Several different two-dimensional (latitude-height or latitude-depth) models of the atmosphere and oceans have been development (e.g., Peng et al. 1982, for the atmosphere: Wright and Stocker 1991, for the ocean). The two-dimensional models permit a more physically based computation of horizontal heat transport than in one-dimensional energy balance models.

Three-Dimensional Atmosphere and Ocean General Circulation Models

The most complex atmosphere and ocean models are the three-dimensional atmosphere general circulation models (AGCMs) and ocean general circulation models (OGCMs), both of which are extensively reviewed in Gates et al. (1996) and in various chapters of Trenberth (1992). These models divide the atmosphere or ocean into a horizontal grid with a typical resolution of 2–40 longitude in the latest models and typically 10–20 years in the vertical. They directly simulate winds, ocean currents, and many other features and processes of the atmosphere and oceans. Figure 23.1 provides a schematic illustration of the major processes that occur within a single horizontal grid cell of an AGCM. Both AGCMs and OGCMs have been used extensively in a stand-along mode, with prescribed ocean-surface temperature in the case of AGCMs and with prescribed surface temperatures and salinities, or the corresponding heat and freshwater fluxes, in the case of OGCMs. Only when the two models are coupled together do we have what can be considered to be a climate model, in which all the temperatures are freely determined. Coupled AOGCMs automatically compute the feedback processes associated with water vapor, clouds, seasonal snow and ice, as well as the uptake of heat by the oceans when driven by a prescribed, anthropogenic increase of atmospheric CO_2. The uptake to heat by the oceans delays and distorts the surface temperature response but contributes to sea-level through expansion of ocean water as it warms. AOGCMs compute radiative transfer through the atmosphere (explicitly modeling clouds, water vapor, and other atmosphere components), snow and sea-ice, surface fluxes, transport of heat and water by the atmosphere and ocean, and storage of heat in the ocean. Because of computational constraints, the majority of these processes are parameterized to some extent (see Dickinson et al. 1996, concerning processes in atmosphere and oceanic GCMs). More detailed representations are not practical, or have not been developed, for use in a global model. Some parameterizations inevitably include constants which have been tuned to observations of the current climate (1991), the intensity of the thermohaline overturning is determined by the model itself, while in others (e.g., de wolde et al. 1995), it is prescribed, as in the one-dimensional upwelling-diffusion model. The one-dimensional energy balance atmosphere–surface climate model has also been coupled to a two-dimensional ocean model (Harvey 1992; Bintanja 1995; de wolde et al. 1995.

23.4.1.4 Different Types of GCMs Based on Model Parameters

Models of Carbon Parameter

The upwelling-diffusion model that was described above can be used as the oceanic part of the carbon cycle, as in the work of Hoffert et al. (1981). The global mean atmosphere–ocean exchange of CO_2, the vertical mixing of total dissolved carbon by themohaline overturning and diffusion, and the sinking of particulate material produced by biological activity can all be represented in this model. A two-dimensional ocean model has been used as the oceanic component of the global carbon cycle (Stocker et al. 1994). Finally, OGCMs can be used as the oceanic component of the global carbon cycle, in which the model-computed ocean currents and other mixing processes, are used, in combination with simple representations of biological processes and air–sea exchange (e.g., Bacastow and Maier-Reimer 1990; Najjar et al. 1992). CO_2 uptake calculations using 3-D models have so far been published only for stand-alone OGCMs, in which the circulation filed and surface temperature have been fixed. In a coupled simulation, changes in both of these variables in response to increasing greenhouse gas concentrations would alter the subsequent uptake of CO_2 to some extent.

The terrestrial biosphere can be represented by a series of interconnected boxes, where the boxes represent components such as leafy material, woody material, roots, detritus, and one or more pools of soil carbon. Each box can be globally aggregated such that, for example, the detrital box represents all the surface detritus in the world. The commonly used, globally aggregated box models are quantitatively compared globally aggregated terrestrial biosphere model, where numbers inside boxes represent the steady state amounts of carbon (Gt) prior to human disturbances, and the numbers between boxes represent the annual rates of carbon transfer (Gt a-1). In globally aggregated box models, it is not possible to separate responses in different latitude zones (e.g., net release of carbon through temperature effects at high latitudes, net uptake of carbon in the tropics due to CO_2 fertilization). Since regional responses vary nonlinearly with temperature and atmospheric CO_2 concentration, extrapolation into the future using globally aggregated models undoubtedly introduces errors. An alternative is to separate box models for major regions, as in van Minnen et al. (1996), rather than lumping everything together.

The role of the terrestrial biosphere in global climatic change has also been simulated using relatively simple models of vegetation on a global grid with resolution as fine as 0.50 latitude × 0.50 longitude. These models have been used to evaluate the impact on net ecosystem productivity of higher atmospheric CO_2 (which tends to stimulate photosynthesis and improve the efficiency of water use by plants) and higher temperatures (which can increase or decrease photosynthesis and increase decay processes). These models distinguish, as a minimum, standing biomass from soil organic matter. The more sophisticated varieties track the flows of both carbon and nitrogen (taken to be the limiting nutrient), and include feedbacks between nitrogen and the rates of both photosynthesis and decay of soil carbon (e.g., Rastetter et al. 1992; Melillo et al. 1993).

Grid-point models of the terrestrial biosphere have been used to assess the effect on the net biosphere–atmosphere CO_2 flux of hypothetical (or GCM-generated) changes in temperature and/or atmospheric CO_2 concentration, but generally without allowing for shifts in the ecosystem type at a given grid point as climate changes. More advanced ecosystem models are being developed and tested that link biome models (which predict changing ecosystem types) and ecophysiological models (which predict carbon fluxes) (e.g., Plochl and Cramer, 1995). Different biomes vary in the proportion of "plant functional types," examples of which are tropical evergreen forest, cool-temperate evergreen trees, and cool grasses. An alternative to simulating the location of specific ecosystems is to predict the proportions of different plant functional types at each grid cell based on the carbon balance for each functional type, as determined from an ecophysiological model (Foley et al. 1996). This effectively allows for the simulation of both rapid biophysical processes and the long-term adjustment of ecosystems to changing climate and atmospheric CO_2 concentration. Simulations with these and earlier models demonstrate the potential importance of feedbacks involving the nutrient cycle and indicate the potential magnitude of climate-induced terrestrial biosphere–atmosphere CO_2 fluxes. However, individual models still differ considerably in their responses (VEMAP Members 1995). As with models of the oceanic part of the carbon cycle, such simulations have yet to be carried out interactively with coupled AOGCMs. These models also have not yet been combined with ocean carbon uptake OGCMs.

Rather detailed models of the marine biosphere, involving a number of species and interactions, have also been developed and applied to specific sites or regions (e.g., Gregg and Walsh 1992; Sarmiento et al. 1993; Antoine and Morel 1995; Oschlies and Garcon 1999; Oschlies et al. 2000).

Models of Atmospheric Chemistry and Aerosols

Atmospheric chemistry is central to the distribution and amount of ozone in the atmosphere. The dominant chemical reactions and sensitivities are significantly different for the stratosphere and troposphere. These processes can be adequately modeled only with three-dimensional atmospheric models (in the case of the troposphere) or with two-dimensional (latitude-height) models (in the case of the stratosphere). Atmospheric chemistry is also critical to the removal of CH_4 from the atmosphere and, to a lesser extent, all other greenhouse gases except H_2O and CO_2 in the case of CH_4, a change in its concentration affects its own removal rate and, hence, subsequent concentration changes. An accurate simulation of changes in the removal rate of CH_4 requires specification of the concurrent concentrations of other reactive species, in particular NO_x (nitrogen oxides), CO *carbon monoxide), and the VOCs (volatile organic compounds); and use of a model with latitudinal and vertical resolution. However, simple globally averaged models of chemistry–climate interactions have been developed. These models treat the global CH_4-CO-OH cycle in a manner which takes into account the effects of the heterogeneity of the chemical and transport processes, and provide estimates of future global or hemispheric mean changes in the chemistry of the earth's atmosphere. Some of the models also simulate halocarbon concentrations and the resulting atmospheric chorine concentration as well as radiative effects due to halocarbons (Prather et al. 1992). An even simpler approach, adopted by Osborn and Wigley (1994), is to treat the atmosphere as a single well-mixed box but to account for the effects of atmospheric chemistry by making the CH_4 lifetime depend on CH_4 concentration in a way that roughly mimics the behavior of the above-mentioned globally averaged models or of models with explicit spatial reevaluation. Atmospheric O_3 and CH_4 chemistry has not yet been incorporated in AGCMs used for climate simulation purposes, although two-dimensional interactive chemistry–climate models have been built (Wang et al. 1998).

Atmospheric chemistry is also central to the distribution and radiative properties of small suspended particles in the atmosphere referred to as aerosols, although chemistry is only part of what is required in order to simulate the effects of aerosols on climate. The primary aerosols that are affected by atmospheric chemistry are sulfate aerosols (produced from the emission of SO_2 and other S-containing gases), nitrate aerosols (produces from emission of nitrogen oxides), and organic carbon aerosols (produces from the emission of a variety of organic compounds from plants and gasoline). The key processes that need to be represented are the source emissions of aerosols or aerosol precursors; atmospheric transport, mixing, and chemical and physical transformation; and removal processes (primarily deposition in rainwater and direct dry deposition onto the earth's surface). Since part of the effect of aerosols on climate arises because they serve as cloud condensation nuclei, it is also important to be able to represent the relationship between changes in the aerosol mass input to the atmosphere and, ultimately, the radiative properties of clouds. Establishing the link between aerosol emissions and could properties, however, involves several poorly understood steps and is highly uncertain.

Geographically distributed sulfur–aerosol emissions have been used as the input to AGCMs and, in combination with representations of aerosol chemical and physical processes, have been used to compute the geographical distributions of sulfur–aerosol mass using only natural emission sources and using natural + anthropic emission sources (e.g., Langner and Rodhe 1991; Chin et al. 1996; Pham et al., 1996). Given the differences in the GCM-simulated aerosol distributions assumptions concerning the aerosol optical properties, other studies have estimated the possible range of direct (cloud-free) effects on radiative forcing (e.g., Haywood et al. 1997). With yet further assumptions concerning how clouds respond to sulfur aerosols, a range of indirect (cloud-induced) effects can also be computed (e.g., Boucher and Lohmann 1995; Jones and Slingo 1996; Kogan et al. 1996; Lohmann and Feichter 1997). The results of these and other calculations are extensively reviewed in Harvey (2000a: Chapter 7).

Models of Ice Sheets

High-resolution (20 × 20 km horizontal grid), two- and three-dimensional models of the polar ice sheets have been developed and used to assess the impact on global mean sea level of various idealized scenarios for temperature and precipitation changes over the ice sheets (e.g., Huybrechts and Oerlemans 1990; Huybrechts et al. 1991). AGCM output has also recently been used to drive a three-dimensional model of the East Antarctic ice sheet (Verbitsky and Saltzman 1995), but has not yet been used to assess the possible contribution of changes in mountain glaciers to future sea-level rise. Output from high-resolution ice-sheet models can be used to develop simple relationships in which the contribution of ice-sheet changes to future sea level is scaled with changes in global mean temperature.

23.4.2 Regional Climate Models

A key limitation of GCMs is the fairly coarse horizontal resolution. The climate *prediction*.net atmospheric resolution is 3.75° × 2.5°. For the practical planning of water resources, flood defences, etc., countries require information on a much more local scale than GCMs are able to provide. There are three possible solutions to this problem:

- Run the full GCM at a finer resolution. As the model would then take much longer to complete a simulation, either a very powerful computer (such as the Earth Simulator in Japan) or a much shorter simulation period (e.g., 5 years) is required.

- Use statistical techniques to "downscale" the coarse, GCM results to local. These techniques assume that the relationship between large-scale climate variables (e.g., grid box rainfall and pressure) and the actual rainfall measured at one particular rain gauge will always be the same. So, if that relationship is known for current climate, the GCM projections of future climate can be used to predict how the rainfall measured at that rain gauge will change in the future.
- Embed a Regional Climate Model (RCM) in the GCM. RCMs are a more dynamically consistent way than statistical downscaling to produce a regional forecast.

RCMs work by increasing the resolution of the GCM in a small, limited area of interest. An RCM might cover an area the size of western Europe, or southern Africa – typically 5,000 × 5,000 km. The full GCM determines the very large-scale effects of changing greenhouse gas concentrations, volcanic eruptions, etc. on global climate. The climate (temperature, wind, etc.) calculated by the GCM is used as input at the edges of the RCM. The models are typically coupled together (information is only passed from the GCM to the RCM) once every 24 modeled hours. RCMs can resolve the local impacts given small-scale information about orography (land height), land use, etc., giving weather and climate information at resolutions as fine as 50 or 25 km (Fig. 23.2) Climate Prediction (2009).

In regions where the land surface is flat for thousands of kilometers, and there is no ocean anywhere near, the coarse resolution of a GCM may be enough to accurately simulate weather changes. However, most land areas have mountains, coastlines, changing vegetation characteristics, etc. on much smaller scales, and RCMs can represent the effects of these on the weather much better than GCMs (Figs. 23.3–23.5).

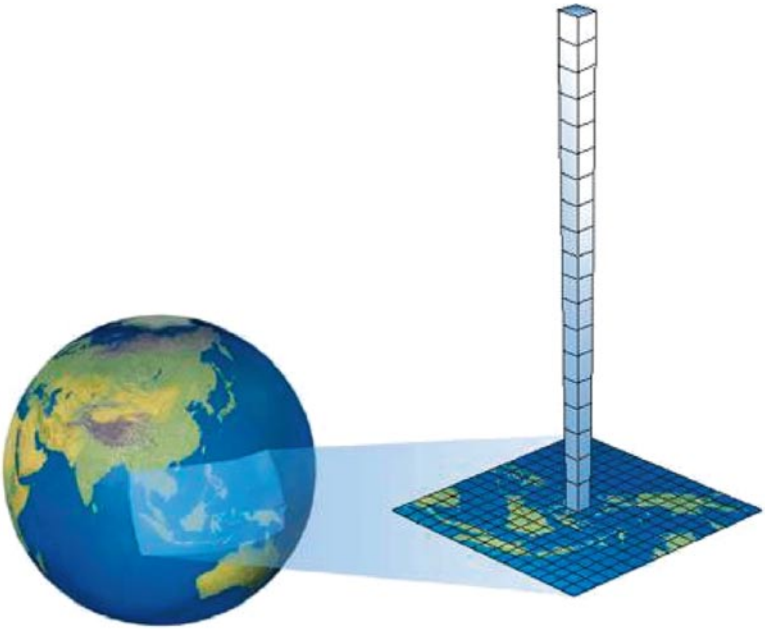

Fig. 23.2 Figure showing model domain of GCMs and RCMs

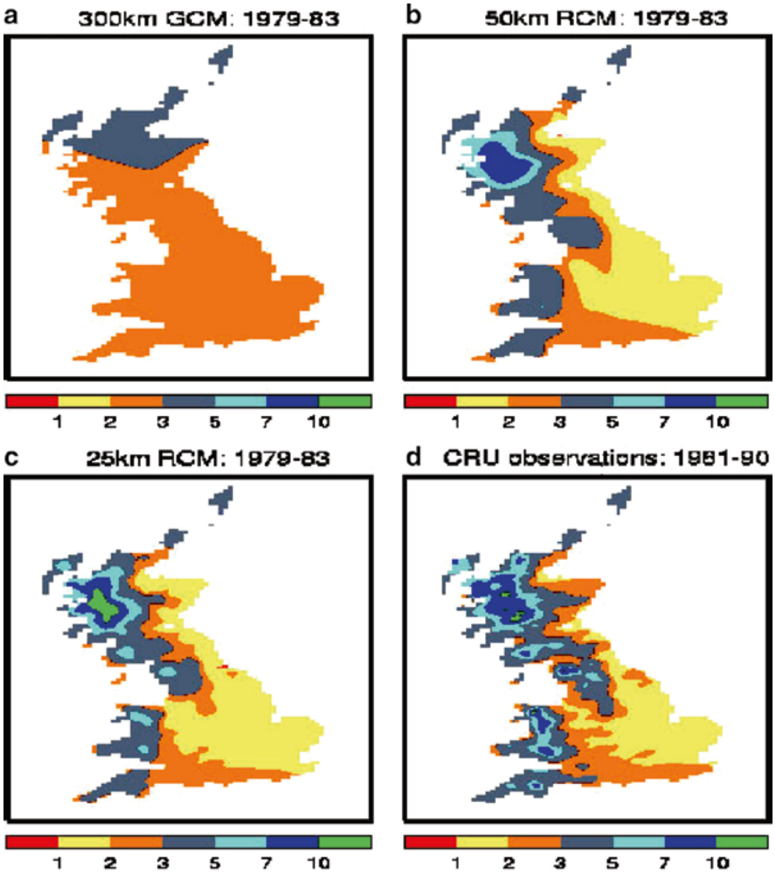

Fig. 23.3 Winter precipitation over Britain as predicted by (**a**) a GCM with resolution 300 km, (**b**) a regional model with 50 km resolution and (**c**) a regional model with 25 km resolution compared to (**d**) actual observations

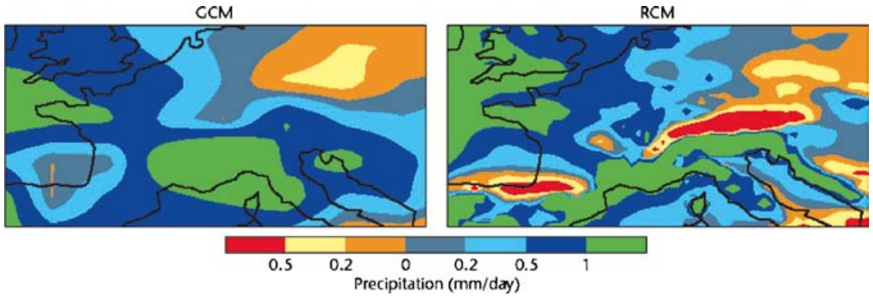

Fig. 23.4 Predicted changes in winter precipitation over central/southern Europe between the present day and 2080. The areas of red, where precipitation has fallen by more than 0.5 mm/day, indicate large reductions over the Alps and Pyrenees predicted by the RCM (*right*), but not the large scale GCM (*left*)

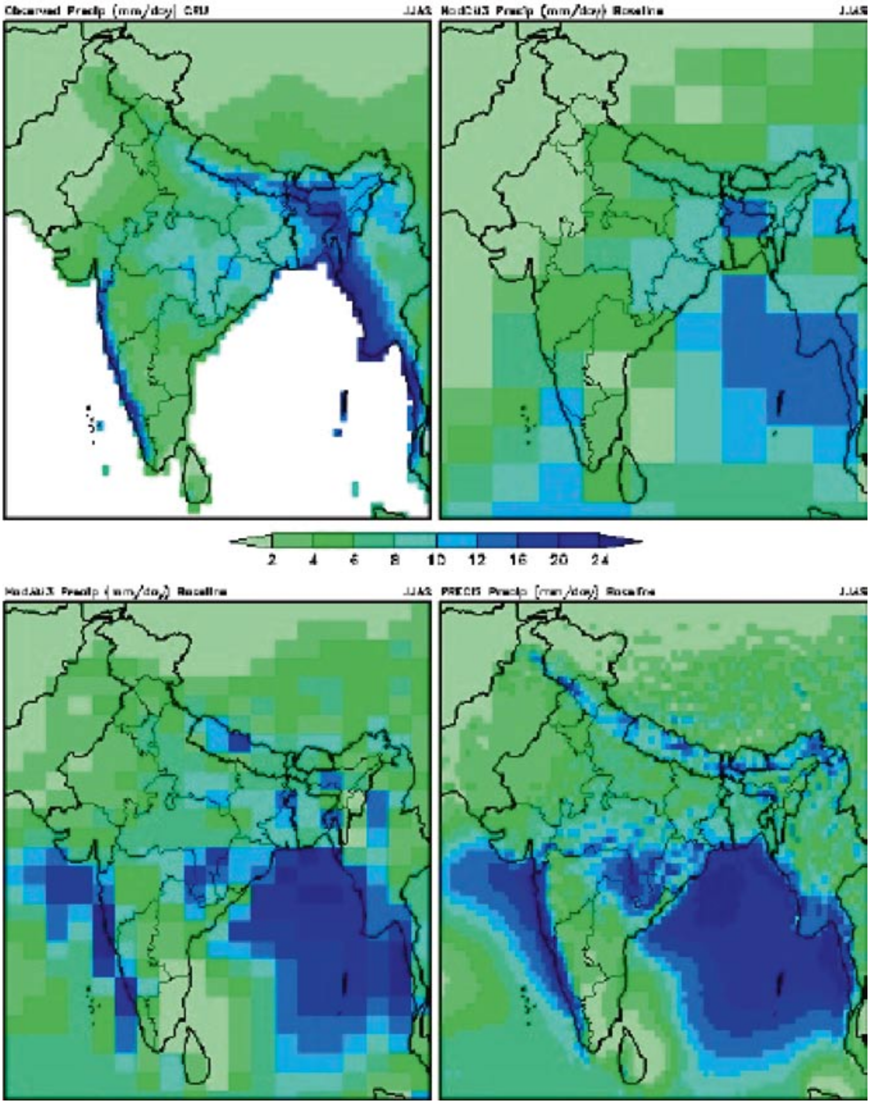

Fig. 23.5 Prediction of seasonal precipitation over India as predicted by PRECIS model with 50 km resolution (Krishnakumar 2009)

The weather in one part of the world is not independent of the weather elsewhere in the world. For example, the El Nino Southern Oscillation, focused in the South Pacific, has effects which can be detected over most of the planet.

23.4.3 Examples of Climate Models

23.4.3.1 Reading Intermediate General Circulation Model (IGCM)

The Reading Intermediate General Circulation Model (IGCM), is a simplified or "intermediate" Global climate model, which is developed by members of the Department of Meteorology at the University of Reading, and by members of the Stratospheric Dynamics and Chemistry Group of the Department of Atmospheric and Oceanic Sciences at McGill University

The IGCM is a fast GCM based on the primitive-equations baroclinic model of Hoskins and Simmons, which has been converted to run on workstations. Several versions have been developed with representations of the physics.

- IGCM1: Portable version of the original spectral dry baroclinic model formulated in sigma-levels, with an option for Newtonian relaxation and Rayleigh friction, no surface.
- IGCM2: Includes simplified moist parameterizations, a cheap "radiation scheme" (i.e., constant tropospheric cooling), a bulk formulation scheme for the boundary layer, fixed surface temperatures and humidity, a uniform vertical diffusion, and can advect tracers.
- IGCM3x: Intermediate climate model which includes more sophisticated moist/clouds parameterizations, a radiation scheme with various gas absorbers, and a more realistic surface with an orography and land, sea surface schemes.

The adiabatic version, IGCM1, is freely available. Access to IGCM2 and IGCM3 is restricted to members of the Department of Meteorology at the University of Reading and collaborating researchers.

23.4.3.2 Hadley Centre Coupled Model, Version 3 (HadCM3)

HadCM3 (abbreviation for Hadley Centre Coupled Model, version 3) is a coupled atmosphere–ocean general circulation model (AOGCM) developed at the Hadley Centre in the United Kingdom (Gordon et al. 2000, Pope et al. 2000, and Collins et al. 2001). It was one of the major models used in the IPCC Third Assessment Report in 2001.

Unlike earlier AOGCMs at the Hadley Centre and elsewhere (including its predecessor HadCM2), HadCM3 does not need flux adjustment (additional "artificial" heat and freshwater fluxes at the ocean surface) to produce a good simulation. The higher ocean resolution of HadCM3 is a major factor in this; other factors include a good match between the atmospheric and oceanic components; and an improved ocean mixing scheme (Gent and McWilliams). HadCM3 has been run for over 1,000 years, showing little drift in its surface climate.

HadCM3 is composed of two components: the atmospheric model HadAM3 and the ocean model (which includes a sea ice model). Simulations often use a 360-day calendar, where each month is 30 days.

23.4.3.3 Hadley Centre Atmospheric Model, Version 3 (HadAM3)

HadAM3 is a grid point model and has a horizontal resolution of 2.5° × 3.75° in latitude × longitude. This gives 96 × 73 grid points on the scalar (pressure, temperature, and moisture) grid; the vector (wind velocity) grid is offset by 1/2 a grid box (this gives a resolution of approximately 300 km, roughly equal to T42 in a spectral model. There are 19 levels in the vertical).

The timestep is 30 min (with three sub-timesteps per timestep in the dynamics). Near the poles, fields are Fourier-filtered to prevent instabilities due to the CFL criterion.

This is the model behind PRECIS (Providing Regional Climates for Impacts Studies)

23.4.3.4 Hadley Centre Global Environmental Model, Version 1 (HadGEM1)

HadGEM1 is a coupled climate model developed at the Met Office's Hadley Centre. It represents a significant advance on its predecessor, HadCM3, in terms of its science and provides an enhanced capability for carrying out new climate experiments. HadGEM1 also provides a foundation for further modeling advances across a range of applications, particularly involving enhanced resolution and full Earth System modeling.

Evaluation of the atmospheric performance of HadGAM/GEM1,

23.4.3.5 Geophysical Fluid Dynamics Laboratory Coupled Model, Version 2.X (GFDL CM2.X)

GFDL CM2.X is a coupled atmosphere–ocean general circulation model (AOGCM) developed at the NOAA Geophysical Fluid Dynamics Laboratory in the United States. It is one of the leading climate models used in the Fourth Assessment Report of the IPCC, along with models developed at the Max Planck Institute for Climate Research, the Hadley Centre and the National Center for Atmospheric Research. The solutions of these GFDL CM2 models are described in a series of papers published in the Journal of Climate in 2006.

23.4.3.6 EdGCM

EdGCM is a global climate model (GCM) that has been ported for use on desktop computers and integrated with a relational database, a graphical user interface, and scientific visualization utilities, all of which are aimed at helping improve the quality of teaching and learning of climatology. EdGCM is developed at Columbia University by scientists and programmers in the Center for Climate Systems Research. The Global Climate Model at the core of EdGCM was developed at NASA's Goddard Institute for Space Studies and is referred to in climate modeling literature as the GISS Model II. It is currently in use by researchers to study climates of the past, present, and future. EdGCM permits teachers and students to conduct in-depth investigations of current climate science topics, in near real-time, just as they are being studied by climate scientists.

23.4.3.7 Providing REgional Climates for Impacts Studies (PRECIS)

PRECIS (pronounced as in the French précis – "PRAY-sea") is based on the Hadley Centre's regional climate modeling system. It has been ported to run on a PC (under Linux) with a simple user interface, so that experiments can easily be set up over any region.

PRECIS was developed in order to help generate high-resolution climate change information for as many regions of the world as possible. The intention is to make PRECIS freely available to groups of developing countries in order that they may develop climate change scenarios at national centers of excellence, simultaneously building capacity, and drawing on local climatological expertise. These scenarios can be used in impact, vulnerability and adaptation studies, and to aid in the preparation of National Communications, as required under Articles 4.1 and 4.8 of the United Nations Framework Convention on Climate Change (UNFCCC).

23.4.3.8 Fifth-Generation NCAR/Penn State Mesoscale Model (MM5)

The MM5 is a regional mesoscale model used for creating weather forecasts and climate projections. It is maintained by Penn State University and the National Center for Atmospheric Research.

Mesoscale meteorology is the study of weather systems smaller than synoptic scale systems but larger than microscale and storm-scale cumulus systems. Horizontal dimensions generally range from around 5 km to several hundred kilometers. Examples of mesoscale weather systems are sea breezes, squall lines, and mesoscale convective complexes.

Vertical velocity often equals or exceeds horizontal velocities in mesoscale meteorological systems due to nonhydrostatic processes such as buoyant acceleration of a rising thermal or acceleration through a narrow mountain pass.

As in synoptic frontal analysis, literature about mesoscale analysis uses cold, warm, and occluded fronts on the mesoscale to help describe phenomena. On weather maps mesoscale fronts are depicted as smaller and with twice as many bumps or spikes as the synoptic variety. In the United States, opposition to the use of the mesoscale versions of fronts on weather analyses, has led to the use of an overarching symbol (a trough symbol) with a label of outflow boundary as the frontal notation (Roth 2006).

23.5 Use of Connected Climatic and Hydrologic Models

A dynamic downscaling method, referred as pseudo-warming, was used by Fujihara et al. (2008), to connect the output of raw general circulation models (GCMs) into river basin hydrologic models which was applied to explore the potential impact of climate change on hydrology and water resources of the Seyhan River Basin in Turkey. The results showed that the decreased precipitation as formulated by the climate model would result in a considerably decreased inflow and time of peak. Hotchkiss et al. (2000) predicted the changes in global river flow under the IPCC SRES A1B and A2 scenarios found from HadGEM1-TRIP model and concludes that there will be significant change in the seasonality of river flow, such as earlier peaks in spring runoff, large increases in monthly maximum flow, and decreases in monthly minimum flow. Cliimatologic databases (SICLIM and CLICOM) built by the Servicio Meteorológico Nacional (SMN) of Mexico (Mendoza et al. 2008) was fed to a hydrologic model to predict the annual volume of superficial available water. A climate variability indicator (the El Niño-Southern Oscillation, ENSO) was applied by Muluye and Coulibaly (2007) to predict seasonal reservoir inflows. Global climate models (GCM), CGCM2, CSIROMk2, and HadCM3 was applied by Merritt et al. (2006) to estimate future water availability of Okanagan Basin in England. Each of the research work advocates decrease in quantity of water as the common effect of climate change.

Acknowledgement The authors would like to state that the above article is only for education purpose. The concepts are well discussed in different literatures. The reason for addition was merely to educate readers about development of climate models.

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