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Chapter 15C

Climate Change - An Introduction to Atmosphere-Ocean General Circulation Modeling

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Abstract: This chapter provides an introduction to the formulation of Atmosphere-Ocean General Circulation Models (AOGCMs), the state-of-the-art tool for attributing and projecting of earth-atmosphere climate change. The formulation topics summarized in this review include gridding, numerical solution and the parameterizations of physical processes used for both atmospheric and oceanic components. A sampling of the results from attribution and projection studies using AOGCMs, presented in the IPCC Fourth Assessment Report (AR4), are then shown. Sources for further reading are listed at the end of the review.

Key Words: Atmosphere-Ocean General Circulation Models, Coupled General Circulation Models, Climate Change, Numerical Modeling.

1 Introduction

Atmosphere-Ocean General Circulation Models (AOGCMs) are the current state-of-the art numerical tool for modeling the earth's climate system. They are most encompassing in representing the full suite of important processes affecting climate. By association, they are also the most computationally complex and expensive to run. It has been estimated that a full AOGCM would take between

25-30 person-years to code, and a multi-decadal simulation thousands of computer hours to run[1].

The main application of AOGCMs over recent years has been attribution and projection of climate change[2] due to the increased atmospheric concentrations of greenhouse gases (GHGs) that have built up over the last century and a half. This concentration increase is primarily made up of carbon dioxide (CO_2), which has built up in concentration primarily due to industrial emissions from fossil fuel combustion[3]. Attribution of climate change is addressed by running AOGCMs with and without anthropogenic radiative forcing[4], and comparing the simulated climates resulting from the model runs for each case to the observed climate of the last century. Projection is addressed by investigating the future climates simulated by AOGCMs when run with user-specified levels of future anthropogenic radiative forcing.

AOGCM attribution and projection studies of climate change are published abundantly in peer-reviewed scientific literature, and the body of this work has been summarized in periodic reports by the UNEP International Panel of Climate Change (IPCC) for the purpose of communicating the findings of climate change research to global policymakers. The most recent IPCC report, Assessment Report 4 (AR4), was published in 2007[5]. Among the major findings in AR4 is that climate change since the beginning of the industrial era *is* due to increased anthropogenic GHG emissions and that future climate change *will amplify* assuming that current trends in these emissions persist. Also, it is found that climate change will most likely occur, albeit to a lesser degree, even without any additional future GHG emissions. This has prompted increasingly intense action on the part of policy makers to develop policies to limit future global GHG emissions and/or mitigate the effects of future climate change.

Given this importance, development and application of AOGCMs will grow in the future as the need for updated and more detailed understanding of climate change continues. This chapter is therefore aimed at providing an introduction to AOGCMs. First, the formulation of AOGCMs is summarized. Their evaluation and key results from the climate change attribution and projection studies

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[1] See Chapter 1 of McGuffie and Henderson-Sellers, *A Climate Modelling Primer,* 3rd Edition, 2005; and Appendix L of Washington and Parkinson, *An Introduction to Three-Dimensional Climate Modeling*, 2nd Edition, 2005.

[2] The most studied aspect of climate change is the gradual warming of global temperatures over the last century and a half. The term "global warming" has therefore been used synonymously with climate change.

[3] CO_2 emissions from land-use change and biomass burning are approximately 10% of the contribution from fossil fuel combustion; see Figure 2.3 of the IPCC "Assessment Report 4" (AR4).

[4] The primary components of anthropogenic radiative forcing are those due to increased atmospheric GHG concentrations and increased levels of aerosols, also due to anthropogenic emissions. The concept of radiative forcing is discussed further in Section 3 of this review.

[5] See http://www.ipcc.ch/ for more details on the IPCC as well as links to AR4.

presented in AR4 are then briefly summarized. Areas where future development is needed as well as literature and weblinks for further reading are then listed.

2 AOGCM Formulation

Much of the material in this section is taken from Washington and Parkinson (2005), which we will hereafter refer to as WP05[6].

2.1 Basic Equations

AOGCMs are based on the fundamental conservation equations for atmospheric and oceanic motion, mass and heat, along with equations of state for air and water. These equations comprise a coupled set of non-linear partial differential equations requiring numerical solution. This involves discretization of the equations over finite spatial grid volumes and solution of the equations over finite time steps. Finite-difference numerical methods are generally used for the atmospheric component, although some models apply spectral methods horizontally in space. Atmospheric components currently have horizontal spatial grids of approximately 3° × 3°, and oceanic components usually less than 1° × 1°.

These grid sizes are too large to explicitly resolve all atmospheric and oceanic motions. The effects of these “sub-grid scale” motions must therefore be parameterized in AOGCMs to approximate the effects of these motions on the resolved scale fields. In the atmospheric component, parameterized motions include turbulent and organized buoyant convection. The need for parameterization also extends to processes not involved directly with sub-grid motions, for example radiative transfer and hydrometeor (rain, snow, cloud drops, etc.) formation. The manner of parameterizing these and other processes in AOGCMs is summarized below.

Most AOGCMs now also include representations for the change in mass and aerial coverage of sea ice, as well as a hydrology sub-model to represent the change in the global water balance resulting from changes in the mass of land ice and snow. These are important processes for representing the effects of average earth surface albedo on the climate system as well as for examining the effects of/on climate change on/by the hydrologic cycle.

The formulation and numerical solution procedure for the resolved-scale (also referred to as “core”) equations common to most AOGCMs are presented in detail in Chapters 3 and 4, respectively, of WP05. Summarizing, most AOGCMs are hydrostatic, incompressible and Boussinesq in both atmospheric and oceanic

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[6] Washington, W.M. and C.L. Parkinson, *An Introduction to Three Dimensional Climate Modeling*, 2nd Edition, University Science Books, 2005.

components. The equations are solved in the horizontal using spherical coordinates (special treatments are sometimes applied near the poles) and, in the atmospheric component, are solved in the vertical using various “sigma” type terrain-following coordinates. Ocean models employ various vertical coordinate systems, including depth, sigma and isopycnal. Numerical schemes are generally designed to globally conserve all or at least some of the following quantities: energy, mass, vorticity, heat, and moisture.

The atmosphere and ocean components are coupled through the vertical turbulent momentum, heat and moisture fluxes at the atmosphere-ocean interface. These comprise the lower boundary condition for ocean grid columns in the atmospheric component, as well as the upper boundary condition to the ocean component equations. These fluxes are computed by the turbulence parameterizations used in the atmosphere and ocean components.

For land grid columns, turbulent fluxes of momentum, heat and moisture at the land-air interface are computed through coupling the atmospheric turbulence parameterization within the lowest atmospheric grid layer to a land-surface parameterization scheme. The land-surface parameterization is based on the surface energy balance equation with coupling to parameterized equations to represent transfer of heat and moisture through the soil and vegetation canopy layer. Land-surface parameterizations are summarized in more depth below.

2.2 Parameterizations in the Atmospheric Component

2.2.1 Turbulence

Turbulent transport is a fundamental process in geophysical fluid flows. In the atmosphere, it is the primary process by which momentum, heat, moisture and other scalars are transported between the surface and atmosphere. Turbulence is a sub-grid scale motion, and therefore vertical turbulent fluxes must be parameterized. Most of the turbulence important for vertical transport is generated by wind shear and small scale thermal eddies in the lowest couple kilometers of the atmosphere, a layer called the “atmospheric boundary layer”. Turbulence schemes in atmospheric models are therefore also called “boundary-layer” schemes.

Vertical turbulent fluxes are parameterized in AOGCMs in a manner analogous to Fickian diffusion,

$$\text{Vertical turbulent flux of quantity “a”} = -K_a \partial A/\partial z \tag{1}$$

where z is used for the vertical coordinate and K_a is called the “eddy-diffusivity” for the arbitrary variable a. For momentum, the quantity is also called the “eddy-viscosity”. The rate of change of A due to turbulent transport is then the vertical flux-divergence of Equation 1.

Whereas molecular viscosity and diffusivities are essentially constant for typical atmospheric conditions, eddy-viscosity and diffusivities vary in time and space according to the local flow properties and density stratification of the background fluid. This leads to complex formulations for K_a, which, although having evolved over the years to a high degree of accuracy for common prototypical boundary-layer flow regimes, are still in an active state of research for more complex atmospheric situations. One important example is the strong interactions of flow and stratification with moisture and radiation fields involved in predicting stratocumulus cloud coverage over oceans. Marine stratocumulus prediction by AOGCMs is one of their biggest uncertainties[7,8].

2.2.2 Cumulus Convection

Whereas vertical turbulent fluxes in the atmosphere are due to relatively small or intermediate scale turbulent motions confined to the boundary layer, organized convective vertical motions due to strong buoyant instability can penetrate through the boundary layer and encompass the entire troposphere. Such motions are triggered by a combination of (a) surface forcing, for example surface heating or flow convergence near the surface, which initiates updrafts and (b) density instability, either absolute or conditional, which maintains vertical acceleration of updrafts once initiated. Such motions lead to cumulus cloud formation, and therefore organized convection is synonymously called “cumulus convection”. The main physical role of cumulus convection in the atmosphere is the vertical redistribution (“overturning”) of heat and moisture during times of density instability. The main mechanism for heat transfer is the latent heat release at higher levels in the troposphere by the cumulus cloud field. Important cumulus convection on the climatic scale occurs over the tropics due to trade-wind convergence. The persistent occurrence of this process over the tropics is one of the main drivers to the earth’s climate system.

Cumulus scale eddies are sub-grids in AOGCMs, and therefore the effects of cumulus convection on the resolved scale temperature and moisture fields must be parameterized. A variety of schemes exist, the basis of the main ones described in detail in Chapter 3 of WP05. The simplest scheme is the “convective adjustment” type, which simply resets the modeled vertical temperature and moisture profiles to theoretically or otherwise observationally constrained pre-set values during times when the resolved scale temperature profile is unstable. For temperature, for example, the pre-set value could be dry or moist adiabatic, or some other value determined from observations of cumulus cloud fields. More complex schemes are of the “mass flux” type, which attempt to parameterize cumulus convection according to the average vertical mass fluxes of individual updraft and downdraft

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[7] Zhu et al., 2005, “Intercomparison and Interpretation of Single-Column Model Simulations of a Nocturnal Stratocumulus-Topped Marine Boundary Layer”, *J. Atmos. Sci.*, **133**, 2741-2758.

[8] Randall et al., 2003, “Confronting Models with Data: The GEWEX Cloud Systems Study”, *Bull. Am. Meteorol. Soc.*, **84**, 455-469.

cumulus cloud ensembles. The heat and moisture transport linked to each ensemble presents the main closure problem, and requires empiricism. Mass flux schemes are generally preferred due to their better appeal on physical grounds, as well as by the tendency of convective adjustment schemes to predict too much condensation in the upper troposphere.

2.2.3 Resolved-Scale Clouds

AOGCM results are very sensitive to their parameterization of cloud coverage, particularly stratocumulus. Clouds affect climate primarily through their feedbacks on the radiation balance. Clouds block sunlight as well as absorb and reemit longwave radiation back to the surface. Since these feedbacks are large and in opposite direction, the magnitude and sign of the cloud feedback computed by AOGCMs is still a matter of great uncertainty, with the different results produced by AOGCMs most likely due to differences in the details in the models' parameterizations of the process. The parameterization of clouds involves predicting their aerial coverage, hydrometeor type, height and optical thickness. All of these factors strongly affect the radiation field.

In modeling, "resolved-scale" clouds occur when the resolved-scale temperature and water vapor values in an AOGCM grid box are such to lead to saturated conditions. In theory, saturation occurs at 100% relative humidity, yet models tend to use a lower threshold value (~ 90%) based on observations that complete cloud coverage occurs at slightly sub-saturated conditions. Partial cloud coverage is assumed to occur starting at even lower relative humidity (~ 60%). Equations for fractional aerial coverage of clouds within a grid box are formulated in such a way as to monotonically increase cloud coverage as relative humidity increases between these two threshold values. Once the cloud coverage at each level in a given vertical model column is obtained, the total aerial cloud coverage can in turn be obtained. The possibility of overlapping clouds at different grid layers is accounted for in this step.

Resolved scale clouds tend to form in locally stably-stratified conditions, and are therefore also called "stratiform clouds". Such clouds include tropospheric stratus and cirrus, as well as boundary-layer stratocumulus when mean conditions within the boundary layer are saturated at some vertical level within the boundary layer. "Resolved" stratocumulus is most common in primarily shear-driven marine boundary layer regimes.

More sophisticated schemes employ equations for aerial cloud coverage involving the grid-volume liquid water and ice content, rather than or in addition to relative humidity. Such schemes are used in conjunction with microphysical parameterizations, which are discussed below.

2.2.4 Sub-Grid Scale Clouds

Even though the resolved-scale moisture field may not be saturated, a portion of a model grid volume may still be cloudy due to sub-grid scale convection. This is the situation, for example, during unstable conditions when cumulus clouds form. Cumulus parameterizations, discussed above, must therefore output the amount of cloud coverage within and precipitation falling out of the vertical grid column due to cumulus processes. This is generally done through empirical equations relating cloud volume and precipitation to some property of cumulus convection involved in the closure. For example, for mass-flux schemes the cloud volume and precipitation could be related to the total upward mass-flux associated with the updraft, which, in turn, is parameterized empirically in this approach[9].

In addition to cumulus, boundary-layer stratocumulus clouds also have an unresolved component since some of the turbulent updrafts in a given vertical column could reach saturation within the boundary-layer. Such conditions are common in primarily buoyantly-driven marine boundary layer regimes. Parameterization of cloud processes in this case is done through inclusion of additional empirically based equations in the turbulence parameterization[10].

2.2.5 Radiation

The parameterization of radiation in AOGCMs is aimed at obtaining the total radiative flux (integrated over all wavelengths and incident directions) at each grid level in a vertical model column, including the surface. From this, the incident net radiative flux at the surface can be computed for use in the surface energy balance equation, employed in the land-surface parameterization, and to obtain the radiative heating rate at each vertical level of the atmosphere.

Schemes of various complexities have been developed to achieve this. In all schemes, solar (“shortwave”) and terrestrial (“longwave”) radiation are parameterized separately. This is because solar radiation is primarily in the ultraviolet and visible portions of the radiative spectrum and terrestrial radiation is primarily in the infrared part of the spectrum. Solar radiation is primarily affected by scattering of radiative energy by the surface, atmospheric gases and hydrometeors. Solar radiation is also affected by ozone absorption in the stratosphere and by water vapor absorption of near-infrared wavelengths within the troposphere. Terrestrial radiation is instead affected mainly by absorption by atmospheric gases and hydrometeors. Parameterizations of these scattering and absorption processes are the central part of radiation parameterizations. See

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[9] For further details, see Chapter 9 of Pielke, R. A., *Mesoscale Meteorological Modeling*, 2nd Edition, Academic Press, 2002.

[10] See references in footnotes 6 and 7. In addition, see Lock, A., and J. Mailhot, 2006, “Combining non-local scalings with a TKE closure for mixing in boundary-layer clouds”, *Bound.-Layer Meteorol.*, **121**, 313-338, and references therein.

Appendix J of WP05 and Pielke (2002, see footnote 9) for a review of some of these parameterizations.

Another important aspect of radiation schemes is that the radiative calculations are not done at each individual wavelength ("line-by-line"), since this would involve overly burdensome computational expense. Instead, radiation schemes define radiative properties (absorptivity, reflectivity, emissivity) across discrete wavelength "bands" over which the variation of properties is small enough to achieve robust averages across the bands. This can require many bands, given the strong line-by-line variation of properties over many parts of the radiative spectrum.

Major absorbing gases in the atmosphere accounted for in AOGCMs radiation parameterizations are water vapor (near-infrared and infrared), carbon dioxide (infrared), methane (infrared), ozone (ultraviolet and small part of infrared), nitrous oxide and CFCs. Account is also taken for scattering and absorption by hydrometeors (cloud drops, snow, rain, and ice) as well as by natural and anthropogenic aerosols, the latter discussed in more depth below. Obtaining sufficiently detailed knowledge of the radiative properties of clouds and aerosols for use in radiation parameterizations is one of the major areas of future development need in AOGCMs.

2.2.6 Cloud Microphysics and Precipitation Processes

Cloud microphysics encompasses the processes involved in the formulation of hydrometeors (e.g., cloud and rain drops, snow and hail). Given the increasingly realized importance of hydrometeor type on the radiation field, as well as the desire to include more direct coupling of climate to the hydrologic cycle, most AOGCMs include parameterizations to calculate the amount of water mass contained in various hydrometeor types.

Most microphysics schemes are "bulk" schemes, that is, they do not attempt to calculate the size distribution of a given hydrometeor, but only its total mass integrated over all sizes. They also categorize the water mass across a limited set of hydrometeor types. Common bulk parameterizations calculate the total mass of four hydrometeor types: cloud liquid water, cloud ice, rain and snow. Resolved scale fields for each of these are calculated through prognostic equations. Sub-grid values are calculated diagnostically within the cumulus parameterization and turbulence parameterization, as discussed above.

The mass of water within these hydrometeor classes at each model grid volume is then passed to the radiation parameterization.

2.2.7 Land-Surface Processes

Differential surface heating from equator to pole is the primary driver of climate. Surface heating results in a partitioning of input radiative energy absorbed at the surface into upward directed sensible heat and latent heat fluxes. The sensible and latent heat fluxes provide the heat to the atmosphere responsible for driving climatic wind circulations. Associated with the latent heat flux is water vapor flux, which is the driver of the global atmospheric water vapor, cloud and precipitation fields. Proper representation land surface processes is therefore of utmost importance for accurate climate prediction.

The primary role of the land surface parameterization is, given an incident amount of net radiative flux absorbed at the surface, to properly partition this flux into the correct amount of sensible and latent heat flux. To do this accurately, land surface models must represent a number of processes associated with the transport of heat and moisture transport through soil and vegetation. The scheme must also be coupled to the atmospheric turbulence parameterization to provide proper coupling to atmospheric wind, temperature and humidity near the surface.

Land surface schemes are all based on the surface energy budget equation,

$$0 = \mathrm{R_n} - \mathrm{H_s} - \mathrm{H_l} - \mathrm{G} \tag{2}$$

where R_n is net radiation, H_s is the sensible heat flux, H_l is the latent heat flux, and G is the ground heat flux. R_n is computed by the radiation parameterization. The remaining fluxes - H_s, H_l and G - necessitate representations for soil, vegetation heat and moisture transport. Such representations are strongly dependent on soil heat and moisture transfer coefficients. These, in turn, depend strongly on soil moisture content, which is generally a prognostic variable computed over a finite-differenced soil layer incorporated into the model. The linkage between the land surface and precipitation parameterization, which determines the climatic soil moisture fields, is therefore an important coupling in AOGCMs. Further details of the sensitivity of climate projections to the soil moisture field can be found in Chapter 8 of the IPCC AR4 report[11].

Other important roles of the land surface parameterization include the calculation of the amount and fractional aerial coverage of snow cover in each surface grid box, which is important in calculating surface albedo, as well as the calculation of land surface carbon dioxide uptake. The latter will be an issue of increasing importance in the future as more AOGCMs employ representations of the carbon cycle in their future climate projections.

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[11] http://ipcc-wg1.ucar.edu/wg1/wg1-report.html.

2.3 Ocean Component

2.3.1 Basic Formulation

The basic equations of the ocean component of an AOGCM are similar to the atmospheric component. The ocean model is formulated based on the standard conservation equations for momentum, heat and salinity, with the hydrostatic, incompressible and Boussinesq assumptions applied. An equation of state, analogous to the ideal gas law, is applied that relates density, pressure, temperature and salinity. The equations are solved numerically, usually using spherical coordinates in the horizontal, and height, sigma or isopycnal coordinates in the vertical. In some models, the computational pole is shifted to a location over land (usually in Northern Canada) to allow for better numerical treatment of the Arctic Ocean. Further discussion of these issues can be found in WP05.

2.3.2 Parameterizations

The number of parameterized processes involved in the ocean component is far less than in the atmospheric component, largely because radiation effects are much simpler and there is no need for cloud parameterization. The main parameterizations are turbulent transport and mesoscale motions. Turbulence parameterizations in the ocean component are generally first-order closures, similar to those discussed above in connection to the atmosphere component. Accuracy of the turbulence parameterization in ocean models has proved important, since one of its primary roles is to maintain proper vertical structure and depth of the ocean-mixed layer, which controls many important oceanic circulations.

Mesoscale circulations in the ocean are forced baroclinically (i.e., due to horizontal density gradients). The numerical grid in the ocean components of AOGCMs often does not resolve such circulations. A mesoscale contribution to the velocity components is therefore added to the resolved velocity to account for mesoscale transport. The mesoscale contribution is related to the resolved scale density gradients.

2.3.3 Linkage to Atmospheric Component

The ocean and atmospheric components are coupled through the vertical momentum, heat and water fluxes at the ocean-atmosphere interface. Ideally, the momentum and heat fluxes at the surface, produced as the lower boundary condition to the atmospheric model, would serve identically as the upper boundary conditions to the ocean model. Older versions of most AOGCMs (and current versions of some), however, have mitigated the effects of climate drift in their long-term climate simulations by applying artificial surface flux terms to the ocean model, a procedure called “flux-adjustment”. Certainly, this is not a desirable feature of these AOGCMs, and fortunately, most models have now improved their formulations and initialization schemes to the point where flux adjustment is no longer needed.

2.4 Sea-Ice Component

Most AOGCMs have algorithms to predict the aerial coverage and depth of sea ice. The amount of sea-ice affects many important feedbacks on the climate system, most importantly the ice-albedo feedback, whereby reduced ice coverage caused by induced warming would allow an increased amount of solar radiation to be absorbed by the earth’s surface, thereby leading to more warming.

The amount of sea ice within a given surface grid volume in the ocean is determined by parameterizing the energy balance across that volume, accounting for radiative inputs, turbulent heat transfer from the atmosphere to the surface, latent heating or cooling (due to evaporation, sublimation, freezing, melting, etc.), heat transfer across the lower and horizontally-adjacent ice-ocean interfaces, and heat transfer through the ice layer. These parameterizations account for cases where the ice is overlaid with snow.

Some models, furthermore, couple this thermodynamic treatment with a dynamic model in which the ice is allowed to move due to interactions with ocean currents as well as oceanic and atmospheric shear stresses. Some models furthermore incorporate parameterizations to allow for fractional aerial coverage of the ice over a grid surface (i.e., allowing for the existence of leads).

See Chapter 3.9 of WP05 for additional details on sea-ice modeling in AOGCMs.

2.5 River Hydrology Component

Some AOGCMs now include formulations to represent transport of fresh water into the oceans from continental river basins. This is important, for example, in determining ocean mixed layer salinity, which in turn impacts ocean circulations.

Continental regions are divided into distinct river basins. In each continental grid square, the inflow and outflow of river water as well as the amount of surface water runoff is computed. River inflow and outflow depend on the topography gradient across this and neighboring grid squares. Surface runoff is computed by coupling to the land surface parameterization as described above.

See Chapter 3.10 of WP05 for additional details on river hydrology modeling in AOGCMs.

2.6 Coupling to Carbon Cycle

To achieve more fundamentally based climate change projections, AOGCMs are beginning to implement models for land and ocean CO_2 exchange with the atmosphere. This allows for interactive coupling between climate change and the carbon cycle, since land and ocean carbon uptake is dependant on temperature as well as the amount of CO_2 accumulated in the land and oceans.

An example of a carbon cycle module is that of Doney et al. (2006)[12]. Here, CO_2 concentration is a prognostic variable, transportable within the atmosphere by mean advection and turbulence. The lower boundary conditions are the fluxes into and out of the land and oceans (four terms), which must be parameterized. The land fluxes involve uptake by plants (net primary productivity) and release to the atmosphere by respiration and decay. These fluxes are the total of individual components for various carbon pool sources, corresponding to, among other things, leaves, roots, wood as well as various classes of "dead" plant matter that release CO_2 over time. The coefficients and time scales used in the parameterization of each of these processes are empirically based. The land-surface model, discussed above, provides land surface characteristics (plant and soil types), as well as the atmospheric turbulent transfer coefficients needed for surface-to-atmosphere CO_2 fluxes.

Fluxes into and out of the ocean involve parameterizations of biogeochemical processes of ocean CO_2 uptake (solubility and uptake by ocean biota). This module is coupled with the ocean component for transport of CO_2 into the deeper ocean layers. As with the land fluxes, empiricism is employed to obtain various transfer coefficients and time scales associated with biogeochemical CO_2 uptake in the ocean.

2.7 Interactive Aerosols

Naturally occurring aerosols in the atmosphere include sea salt, sand and mineral dust. Anthropogenic aerosols include sulfate and black carbon. The current understanding is that the presence of anthropogenic aerosols provides an important negative radiative forcing on the earth's climate relative to pre-industrial conditions through the direct and indirect (through their role as cloud condensation nuclei) effects of these aerosols on back-scattering solar radiation. This negative forcing partially offsets the positive forcing associated with GHG concentration increases. Up until recently, AOGCMs incorporated the effects of anthropogenic aerosol scattering simply by increasing the surface albedo of each surface grid square by an amount consistent with observed estimates of vertically integrated sulfate aerosol optical depth. However, AOGCMs are beginning to implement algorithms to interactively predict atmospheric aerosol concentrations

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[12] Doney, S.C., K. Linsey, I. Fung and J. John, 2006: "Natural Variability in a Stable, 1000-year Global Coupled Climate-Carbon Cycle Simulation", *J. Climate.*, **19**, 3033-3054.

across a range of important species. These concentrations are then passed to the radiation parameterization.

Aerosol modules can be classified according to the manner in which they represent various properties and processes associated with aerosols. Bulk schemes only predict the mass of a given aerosol species, whereas "modal" or "bin" schemes represent the size distribution of these species through either predicting parameters associated with prescribed algebraic distribution equations ("modal") or by computing aerosol concentration in a finite number discrete size bins ("bin"). "External" schemes do not allow mixing of individual aerosol components, whereas "internal" schemes allow such mixing. Schemes also vary according to the degree and manner by which they represent removal processes (dry and wet deposition, sedimentation), interaction with the hydrometeor field (important in modeling the effects of aerosols on clouds), nucleation and coagulation. Advanced models also employ SO_2 rate equations to allow for a better fundamental treatment of sulfate formation.

Further details of several aerosol modules used in AOGCMs, along with an inter-comparison of several schemes, can be found in Textor et al. (2006)[13]. Also, the AERONET surface lidar observational network, which has been implemented at over 150 sites globally to monitor the concentration and optical properties of aerosols, is described in this paper and in Kinne et al. (2006)[14].

3 Applications of AOGCMs

The primary application of AOGCMs in recent years has been the attribution and projection of climate change resulting from the increased concentrations of greenhouse gases (GHG) in the atmosphere over the last century and a half. These applications have been summarized since 1988 in a series of UNEP-IPCC "Assessment Reports", the most current being Assessment Report 4 (AR4), which was published in 2007 (see footnote 5). Here, a small portion of the results of the AOGCM climate change attributions and projection studies of AR4 are presented. The complete presentation can be found in AR4[15].

Before proceeding, it is helpful to review a few concepts involved in climate change research:

- Climate Forcing – The change in net equilibrium radiative energy (expressed in watts per meter-squared) input to the earth-atmosphere system (EAS) caused by some prescribed change in a chosen radiative

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[13] Textor, C. et al., 2006, "Analysis and Quantification of the Diversities of Aerosol Life Cycles within AeroCon", *Atmos. Chem. Phys.,* **6**, 1777-1813.

[14] Kinne, S. et al., 2006, "An AeroCon Initial Assessment – Optical Properties in Aerosol Component Modules in Global Models", *Atmos. Chem. Phys.,* **6,** 1815-1834.

[15] http://ipcc-wg1.ucar.edu/wg1/wg1-report.html.

forcing agent (e.g., GHGs, aerosols, solar energy, among others). Positive forcing occurs when the change in net radiation is positive (increased energy to the EAS), and negative forcing occurs when the change in net radiation is negative (decreased energy to the EAS). Climate forcing is generally computed at the tropopause.

- Climate Feedbacks – Physical processes that occur in the EAS as a result of climate forcing that either enhance or suppress the change in globally-averaged temperature caused by the climate forcing. Positive feedbacks are those processes that enhance the temperature change induced by the forcing (i.e., enhanced warming as a result of positive climate forcing, enhanced cooling as a result of negative forcing), while negative feedbacks are those processes that suppress the temperature change induced by the forcing (offsetting cooling as a result of positive forcing and offsetting warming as a result of negative forcing).
- Climate Sensitivity – The change of some EAS property per unit climate forcing after the EAS re-achieves equilibrium subsequent to the prescription of some climate forcing. The new state of equilibrium in the EOS subsequent to forcing is a result of both the forcing itself, and the feedbacks caused by the forcing. Most commonly, the chosen quantities to define climate sensitivity are the equilibrium globally-averaged surface temperature change due to a doubling of atmospheric CO_2 concentration relative to pre-industrial times. Most AOGCMs have climate sensitivities in the range of about 2 to 4.5 °C for a doubling of CO_2, a range that has stayed very consistent over the years of climate model development. This range is generally consistent with observationally-based estimates[16].

The above definitions are conceptual. More formal definitions and other details related to climate forcing, feedbacks and sensitivity can be found in AR4 and references therein.

3.1 AOGCM Evaluation

AOGCM evaluation has traditionally focused on the ability of the models to simulate broad climate features, for example the latitudinal variation of surface temperature, pressure and precipitation patterns associated with the general circulation. AOGCMs are reasonably successful on this level. For example, the global distribution of the 1980-1999 average surface temperature as predicted by the contributing AOGCMs in AR4[17] is shown in Figure 1. Figure 1a shows color contours of the difference between the model-mean (i.e., the average of all models) predictions versus observations, while Figure 1b shows color contours of the root-mean square of the difference between each model prediction individually versus observations. It is seen that in most parts of the globe, errors are within a couple degrees Celsius. Greater errors are seen in areas of high

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[16] See Chapters 8.6 and 9.6.2 of AR4 for further discussion.

[17] There are 23 AOGCMs that contributed results to AR4, as listed in Table 8.1 of the report.

latitudes as well as on the eastern sides of the southern oceans, the latter probably due to problems in model representations of stratocumulus cloud. The fact that greater errors are exhibited in the root-mean square of the individual model error (Figure 1b) is an indication of a tendency that has been seen over the years in AOGCM analysis for the average of AOGCM predictions, as taken among models, to have better predictive skill than that of any individual model.

The successful prediction of the global surface temperature distribution is associated with successful prediction of zonally-averaged net (upward minus downward) shortwave and longwave radiation at the top of the atmosphere (Figure 8-4 in AR4), which have errors of 6% and 5% in multi-model mean, respectively. Correct zonal distribution of input radiation implies basically correct general circulation features, which largely control the zonally-averaged surface temperature distribution.

The global distribution of 1980-1999 average precipitation as predicted by the contributing AOGCMs in AR4 is shown in Figure 2. Figure 2a shows color contours of the observations, while Figure 2b shows color contours of the multi-model mean prediction. The broad expected features of the global precipitation pattern are reproduced by the models, with local maxima in the tropics and mid-latitudes, and local minima in the sub-tropics and poles. Again, this points to the model's ability to capture the overall general circulation. Deficiencies lie mostly in equatorial regions, where the models tend to underpredict precipitation, and in the southern-hemisphere oceans at mid-latitudes, where precipitation is overpredicted. The weaker skill in equatorial precipitation is probably related to problems in the ability of models to represent organized convective motions, which are parameterized in AOGCMs.

The model evaluation presented in AR4 goes much beyond evaluation of basic general circulation features. Additional focus is on inter-annual variability, frequency of El Nino events, spatial variability, the frequency of extreme weather events, the strength of semi-permanent regional scale climate features (e.g., the Indian Monsoon), among other aspects of the climate system. Less skill and greater differences from model to model are exhibited on this level, although there has been predictive improvement in several of these areas since TAR (Third Assessment Report, 2001). The observational database has a higher degree of uncertainty compared to that for basic general circulation features. Such a detailed evaluation is important because it more directly elucidates the skill of climate models to represent particular processes than would be the case if only broad features were focused on. This is particularly important in evaluating the skill of a model to represent important climate feedbacks, which are associated with individual processes. Also, the details of climate regarding temporal and regional variability are arguably more relevant for practical purposes, since people experience weather and climate at a local level.

3.2 AOGCM Attribution Studies

3.2.1 Climate Forcing

AOGCM attribution studies of climate change require specification of the temporally varying climate forcing for all important forcing agents since the beginning of the industrial era (circa 1750). The values of climate forcing for the main processes affecting global climate change are shown in Figure 3 for one of the AOGCMs used in the AR4, while Figure 4 shows a similar graph for the model used by Hansen et al. (2005)[18]. It is seen that the primary positive climate forcing is GHGs (labeled LLGHG in Figure 3), which results primarily from industrial emissions of CO_2. There is a high degree of confidence in the estimated GHG forcing values[19].

The primary negative forcing is tropospheric aerosols, which is divided into "direct" (Aerosol Direct and Reflective Tropospheric Aerosols on figures) and "indirect" (Cloud Albedo and Aerosol Indirect Effect on figures) contributions. It is seen that there appears to be large differences in the values assigned to aerosol forcing (particularly the direct contribution) between the two shown models. The level of uncertainty of aerosol forcing is high, which is especially problematic considering the sensitivity of model results to the value of this forcing. The findings of Knutti et al. (2002)[20], in fact, suggest that AOGCMs with a variety of different climate sensitivities can produce surface temperature trends consistent with observations as long as aerosol forcing is allowed to vary within its range of uncertainty. Clearly, this prompts the need to better understand aerosol forcing.

3.2.2 Results of Attribution Studies

Surface temperature predictions of AOGCM simulations incorporating anthropogenic and natural forcing versus those incorporating only natural forcing are shown in Figure 5. The temperature warming experienced over the 20th century is predicted accurately when applying both anthropogenic and natural forcing, whereas the warming is not reproduced when only natural forcing is included. This is the most direct manner by which AOGCMs positively attribute the warming of the 20th century to increased GHG emissions.

Such attribution has also been shown through "fingerprint" analyses (see AR4, Section 9.4.1.4). Here, it is shown that the results of runs employing only GHG forcing explain the most variation in the 20th surface temperature trend compared

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[18] Hansen et al., 2005, "Earth's Energy Imbalace: Confirmation and Implications", *Science*, **308**, 1431-1435.

[19] Figure 2-20 of AR4 shows the degree of scientific understanding assigned to various climate forcings.

[20] Knutti, R., T.F. Stocker, F. Joos, and G.-K. Plattner, 2002, "Constraints on radiative forcing and future climate change from observations and climate model ensembles", *Nature*, **416**, 719–723.

to runs employing only natural or other forcing agents individually. By applying forcing individually, the result is free of the spurious correlation to observations that can occur in runs employing all forcings together, which can be subject to error cancellation. The use of fingerprint analysis is therefore an important exercise given the large uncertainties in aerosol forcing.

The predicted versus observed surface temperature trends over the individual continents, as well as over land versus ocean, are shown in Figure 6. It is seen that anthropogenic forcing is necessary for AOGCMs to reproduce global warming.

Other investigated topics in the AR4 AOGCM attribution study are contained in Chapter 9 of AR4. These topics include analyses of extreme events, tropical storm activity, ocean heat content and precipitation trends.

3.3 AOGCM Projection Studies

AOGCM projection studies of future climate change are commonly designed by specifying a prescribed change in atmospheric GHG concentration and evaluating model results over approximately 100 years of future projected time. The AR4 multi-model mean surface temperature projections from this exercise are shown in Figure 7. Projections are made for four cases: a constant future GHG concentration at the current-day level, and cases of "low" (B1), "medium" (A1B) and "high" (A2) future GHG emission increases[21]. As shown, the AOGCMs project further warming in all cases, even for the case of constant GHG concentrations. In the cases with future specified emissions, the amount of warming is projected to be greater than that already experienced during the 20th century.

The zonal distribution of future projected warming and precipitation change are shown in Figure 8. Results are shown for the "commitment" run (constant GHG concentration at current-day level) and "high" emission case, A2. The changes plotted are for the 2080-2099 projected means relative to the 1980-1999 simulated mean and scaled according to the globally-averaged change for each case. Model projections show that the abundance of future warming will be in high-latitudes in the Northern hemisphere. Increased precipitation is projected at these latitudes alongside this warming. Warming is spread more uniformly at other latitudes. Increased precipitation over the tropics and decreased precipitation over the sub-tropical latitudes is projected.

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[21] The design of these runs corresponds to estimated emissions resulting from purely economic considerations in determining future emissions ("low", A2) to purely environmental considerations in determining emissions ("high", B1). Case A1B is intermediate between these two. See http://www.climate.unibe.ch/jcm/doc/emit/sres.html for more details.

4 Future Development Needs and Further Readings

Areas of future development need in AOGCMs touched upon in this paper include the following:

- Better treatment of cloud processes, particularly relating to cumulus and stratocumulus cloud formation. This will potentially lead to better precipitation projections and more constrained evaluation of cloud feedback processes in AOGCMs.
- Better understanding of aerosol physics, including both their optical properties and processes determining their formation and size distribution. This will lead to more constrained evaluation of tropospheric aerosol forcing in AOGCM attribution and projection studies.

In addition to references already cited in this paper, the following websites provide other useful information on the topics of climate change and AOGCM modeling:

- The Intergovernmental Panel and Climate Change: http://www.ipcc.ch/
- Real Climate: http://www.realclimate.org/
- Website of Professor Steven Schneider: http://stephenschneider.stanford.edu/
- Website of Professor Roger Pielke: http://climatesci.colorado.edu/

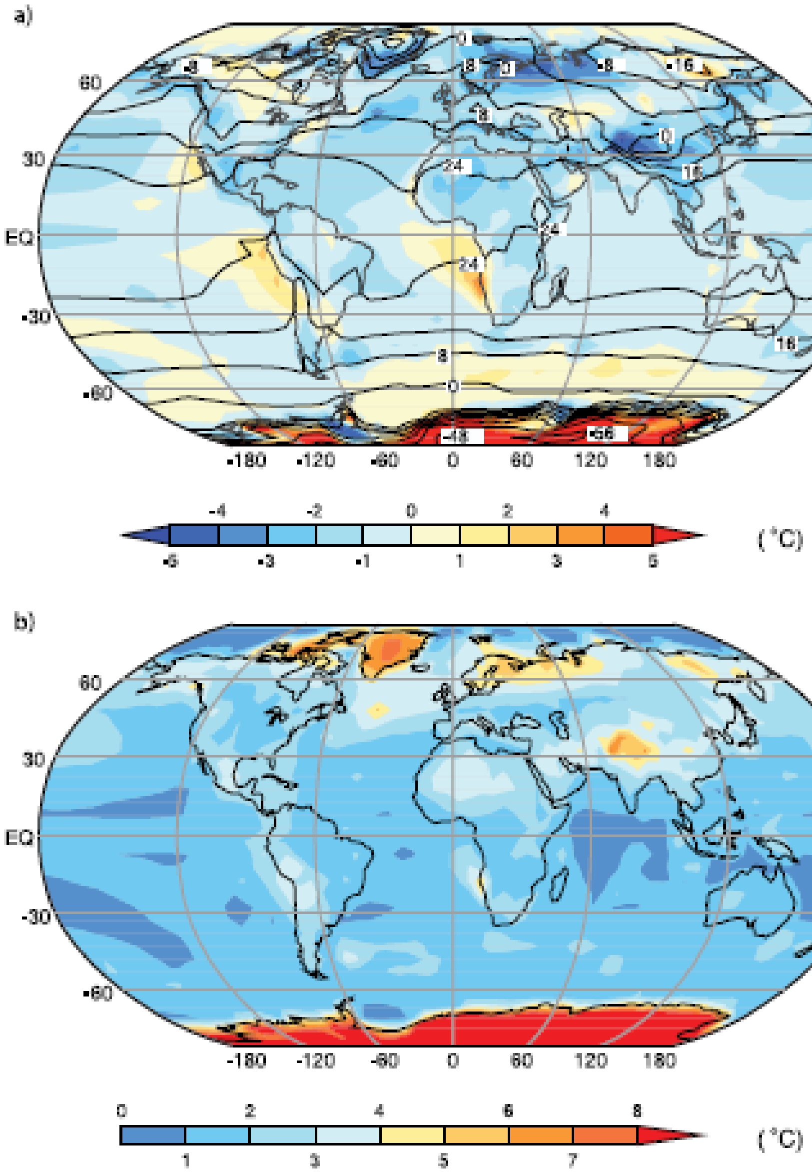

Figure 1. Figure 8.2 of AR4, showing predicted vs. observed surface temperature by the contributing AOGCMs in AR4. In (a), the solid-line contours are the observations, while the color contours are differences between the model-mean prediction vs. observations. In (b), the color contours are of the root-mean square of the difference between each model prediction vs. observations. See AR4 for more details.

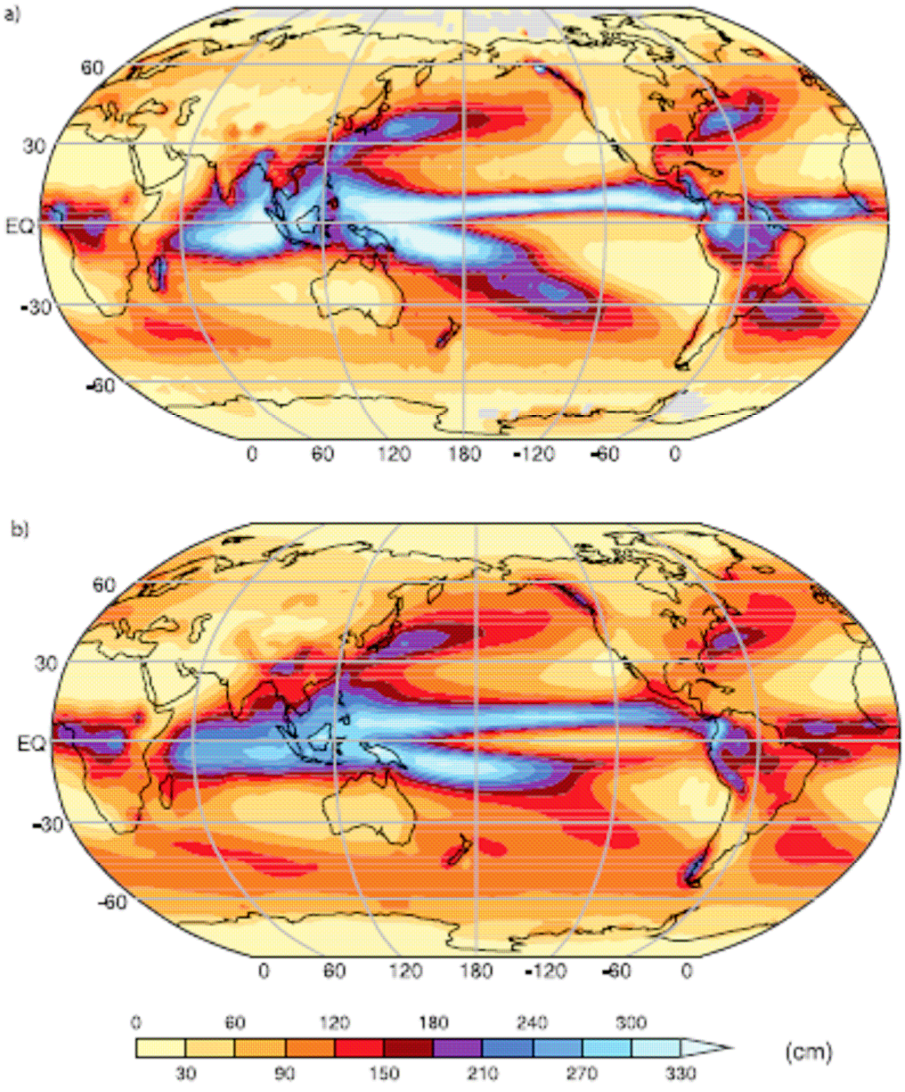

Figure 2. Figure 8.5 of AR4, showing (a) observed and (b) predicted precipitation by the contributing AOGCMs in AR4. See AR4 for more details.

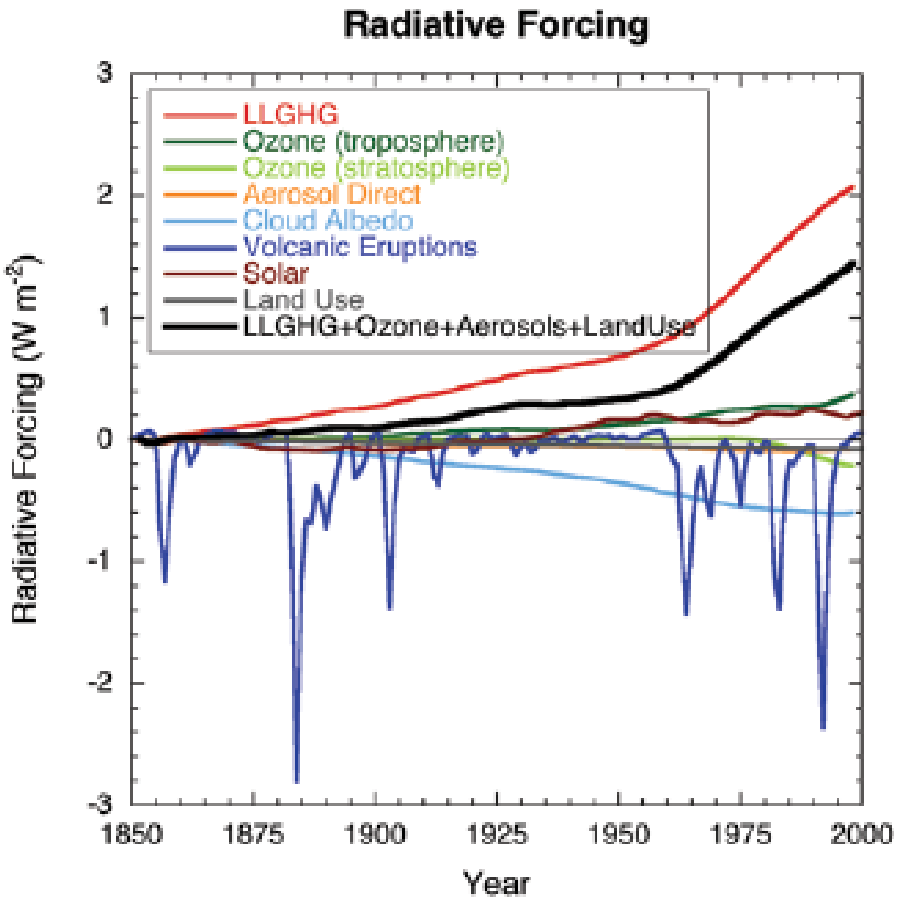

Figure 3. Figure 2.23 of AR4, showing the time-variation of radiative forcing used in one of the contributing models in AR4.

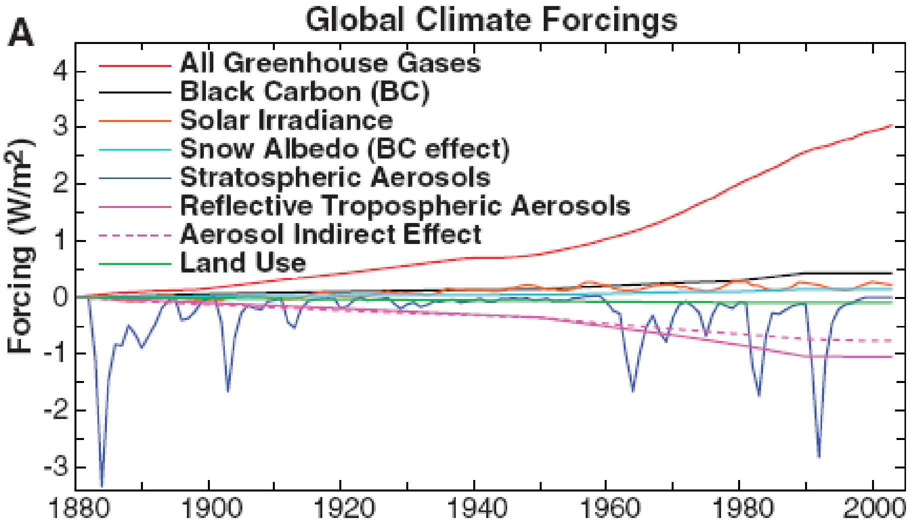

Figure 4. Figure 1 of Hansen et al. (2005, see footnote 18), showing the time-variation of climate forcing used in their AOGCM simulation.

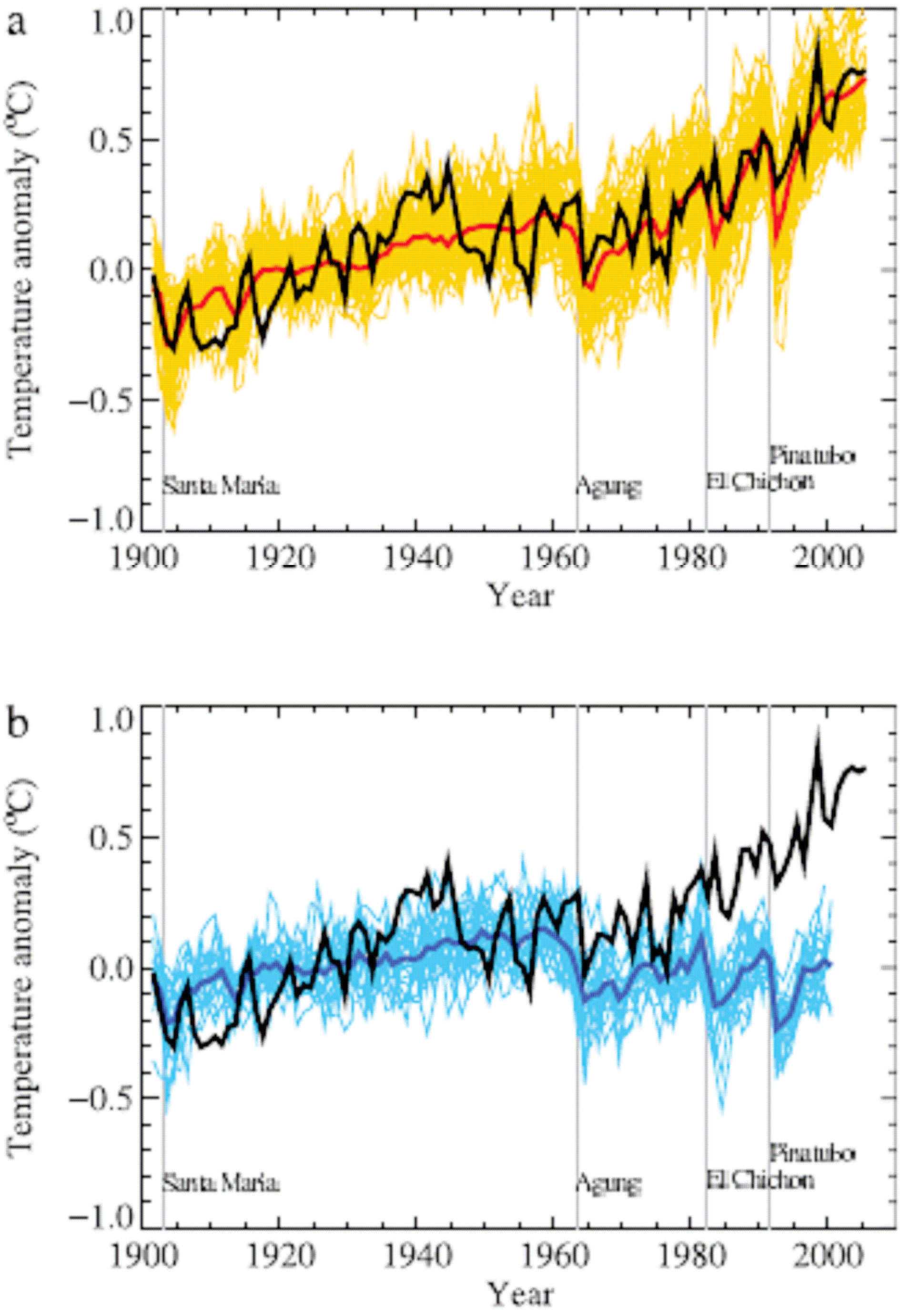

Figure 5. Figure 9-5 of AR4, showing the temperature anomaly relative to 1901-1950 mean versus year for runs of the contributing AOGCMs employing anthropogenic plus natural forcing (top) and natural forcing only (bottom). The black solid line is the observations. The thick red and blue lines are the multi-model mean, while the thin yellow and blue lines are the results of individual model runs (14 models and 58 runs). The vertical grey lines denote major volcanic eruptions. See AR4 for more details.

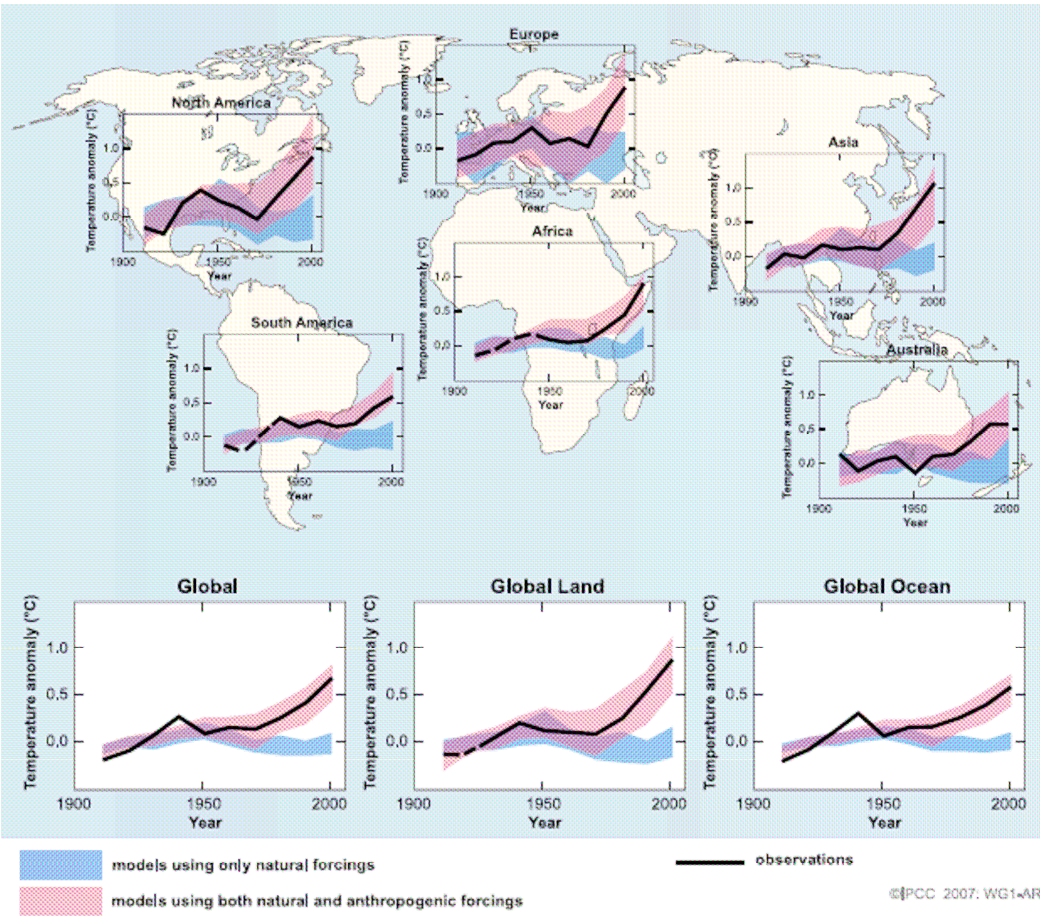

Figure 6. FAQ 9.2, Figure 1 of AR4, showing simulated vs. observed surface temperature trends over individual continents, land and ocean by the contributing AOGCMs in AR4. Blue, natural forcing only; red, anthropogenic and natural forcing. See AR4 for more details.

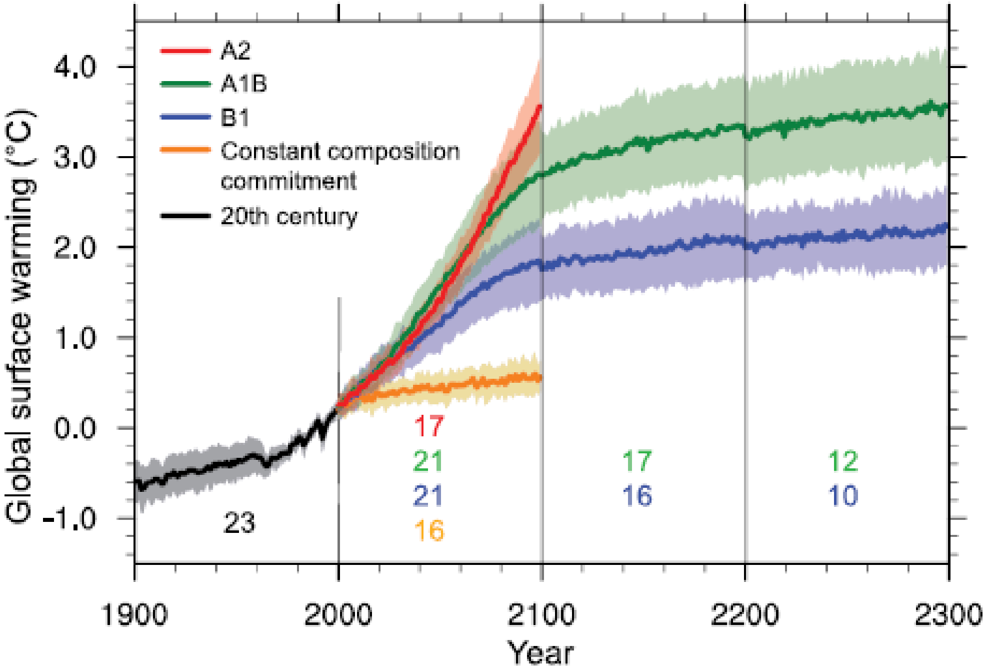

Figure 7. Figure 10-4 of AR4, showing projected surface temperature warming relative to the 1980-1999 mean value by the contributing AOGCMs to AR4. Trends for different future GHG concentration scenarios are shown. The yellow line is for CO_2 concentration held fixed at its current-day value, while the blue, green and red lines are for "low", "medium" and "high" future GHG emission trends, respectively. The shading denotes plus and minus one standard deviation in the individual model runs, while the numbers denote the number of contributing AOGCMs to each scenario. See text and AR4 for more details.

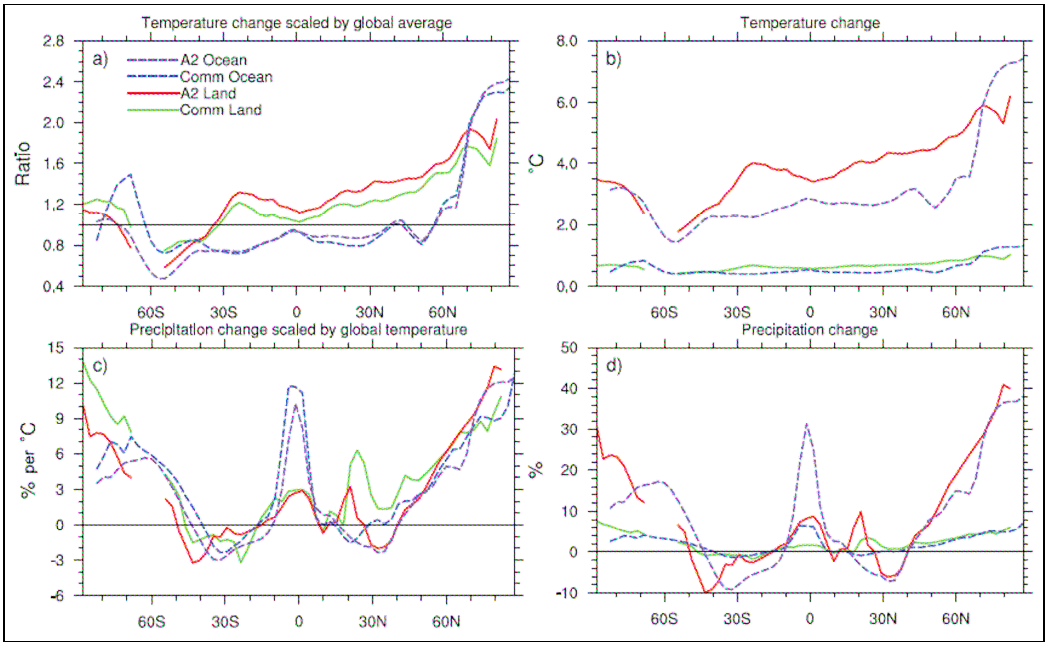

Figure 8. Figure 10-6 of AR4, showing the latitudinal variation of average surface temperature and precipitation change from 2080-2099 relative to 1980-1999 projected by the contributing AOGCMs to AR4. Results are shown for case of high future GHG emissions (A2) and constant concentrations at current-day levels ("Comm"). See AR4 for more details.