4

Validation of Climate Models

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Executive Summary

1 The validation of the present day climate simulated by atmospheric general circulation models shows that there is considerable skill in the portrayal of the large-scale distribution of the pressure, temperature, wind and precipitation in both summer and winter, although this success is in part due to the constraints placed on the sea surface temperature and sea-ice

2 On regional scales there are significant errors in these variables in all models Validation for five selected regions shows mean surface air temperature errors of 2 to 3°C, compared with an average seasonal variation of 15°C Similarly, the simulation of precipitation exhibits errors on sub continental scales (1000-2000 km) which differ in location between models Validation on these scales for the five selected regions shows mean errors of from 20% to 50% of the average rainfall depending on the model

3 The limited soil moisture data available show that the simulated middle latitude summer and winter distributions qualitatively reflect most of the observed large-scale characteristics

4 Snow cover can be well simulated in winter apart from errors in regions where the temperature is poorly simulated. Though comparison is difficult in other seasons because of the different forms of model and observed data, it is evident that the broad seasonal variation can be simulated, although there are significant errors on regional scales

5 The radiative fluxes at the top of the atmosphere, important for the response of climate to radiative perturbations, are simulated well in some models, indicating some skill in cloud parameterization Errors averaged around latitude circles are mostly less than 20 Wm^{-2} with average error magnitudes as low as 5 Wm^{-2} or about 2% of the unperturbed values, however, there are substantial discrepancies in albedo, particularly in middle and high latitudes due to the sensitivity of the parameterization schemes

6. There has been a general reduction in the errors in more recent models as a result of increased resolution, changes in the parameterization of convection, cloudiness and surface processes and the introduction of parameterizations of gravity wave drag

7 Although the daily and interannual variability of temperature and precipitation have been examined only to a limited extent, there is evidence that they are overestimated in some models, especially during summer The daily variability of sea-level pressure can be well simulated, but the eddy kinetic energy in the upper troposphere tends to be underestimated

8 Our confidence that changes simulated by the latest atmospheric models used in climate change studies can be given credence is increased by their generally satisfactory portrayal of aspects of low-frequency variability, such as the atmospheric response to sea surface temperature anomalies associated with the El Niño and with wet and dry periods in the Sahel, and by their ability to simulate aspects of the climate at selected times during the last 18,000 years

9 Models of the oceanic general circulation simulate many of the observed large scale features of ocean climate, especially in lower latitudes, although their solutions are sensitive to resolution and to the parameterization of sub-gridscale processes such as mixing and convective overturning

10 Atmospheric models have been coupled with simple mixed layer ocean models in which a flux adjustment is often made to compensate for the omission of heat advection by ocean currents and for other deficiencies Confidence in these models is enhanced by their ability to simulate aspects of the climate of the last ice age

11 Atmospheric models have been coupled with multi-layer oceanic general circulation models, in which an adjustment is sometimes made to the surface heat and salinity fluxes Although so far such models are of relatively coarse resolution, the large scale structure of the ocean and atmosphere can be simulated with some skill

12 There is an urgent need to acquire further data for climate model validation on both global and regional scales, and to perform validation against data sets produced in the course of operational weather forecasting

4.1 INTRODUCTION

Climate models, and those based on general circulation models (GCMs) in particular, are mathematical formulations of atmosphere, ocean and land surface processes that are based on classical physical principles They represent a unique and potentially powerful tool for the study of the climatic changes that may result from increased concentrations of CO_2 and other greenhouse gases in the atmosphere Such models are the only available means to consider simultaneously the wide range of interacting physical processes that characterize the climate system, and their objective numerical solution provides an opportunity to examine the nature of both past and possible future climates under a variety of conditions In order to evaluate such model estimates properly however, it is necessary to validate the simulations against the observed climate, and thereby to identify their systematic errors, particularly errors common to several models These errors or model biases must be taken into account in evaluating the estimates of future climate changes Additional caution arises from the GCMs' relatively crude treatment of the ocean and their neglect of other potentially-important elements of the climate system such as the upper atmosphere and atmospheric chemical and surface biological processes While it is to be expected that GCMs will gradually improve there will always be a range of uncertainty associated with their results, the scientific challenge to climate modelling is to make these uncertainties as small as possible

The purpose of this section is to present an authoritative overview of the accuracy of current GCM based climate models, although space limitations have not allowed consideration of all climate variables We have also not considered the simpler climate models since they do not allow assessment of regional climate changes and have to be calibrated using the more complex models We begin this task by evaluating the models' ability to reproduce selected features of the observed mean climate and the average seasonal climate variations, after which we consider their ability to simulate climate anomalies and extreme events We also consider other aspects which increase our overall confidence in models such as the performance of atmospheric models in operational weather prediction and of atmospheric and coupled atmosphere-ocean models in the simulation of low-frequency variability and palaeo-climates

4.1.1 Model Overview

The models that have been used for climate change experiments have been described in Section 3 5 and are discussed further below Because of limitations in computing power, the higher resolution atmospheric models have so far been used only in conjunction with the simple mixed-layer ocean models, as in the equilibrium experiments in Section 5 Many of these models give results similar to those from experiments with prescribed sea surface temperature (SST) and sea-ice, because these variables are constrained to be near the observed values by use of prescribed advective heat fluxes This assessment places an upper bound on the expected performance of models with more complete representations of the ocean, whose results are discussed in Section 6

Although the atmospheric models that have been developed over the past several decades have many differences in their formulations and especially in their physical parameterizations, they necessarily have a strong family resemblance It can therefore be understood that though they all generate simulations which are to a substantial degree realistic, at the same time they display a number of systematic errors in common, such as excessively low temperatures in the polar lower stratosphere and excessively low levels of eddy kinetic energy in the upper troposphere On a regional basis atmospheric GCMs display a wide variety of errors, some of which are related to the parameterizations of sub-grid-scale processes and some to the models' limited resolution Recent numerical experimentation with several models has revealed a marked sensitivity of simulated climate (and climate change) to the treatment of clouds while significant sensitivity to the parameterization of convection, soil moisture and frictional dissipation has also been demonstrated These model errors and sensitivities and our current uncertainty over how best to represent the processes involved require a serious consideration of the extent to which we can have confidence in the performance of models on different scales

As anticipated above, the first part of this validation of climate models focuses on those models that have been used for equilibrium experiments with increased CO_2 as discussed in Section 5 Many of the models considered (Table 3 2(a) - see caption to Figure 4 1(a) for models reference numbers) are of relatively low resolution since until recently it is only such models that could be integrated for the long periods required to obtain a clear signal To represent the seasonal cycle realistically and to estimate equilibrium climate change the ocean must be represented in such a way that it can respond to seasonal forcing with an appropriate amplitude All the models in Table 3 2(a) have been run with a coupled mixed-layer or slab ocean The period used for validation of these models is typically about ten years this is believed to be sufficient to define the mean and standard deviation of atmospheric variables for validation purposes Additionally some of these models (versions listed in Table 3 2(b)) have been coupled to a dynamic model of the deeper ocean (see Section 6)

4.1.2 Methods and Problems of Model Validation

The questions we need to answer in this assessment concern the suitability of individual models for estimating climate change. The response of modelled climate to a perturbation of the radiative or other forcing has been shown to depend on the control climate. How serious can a model's errors be for its response to a perturbation still to be credible? Mitchell et al. (1987) pointed out that it may be possible to allow for some discrepancies between simulated and observed climates, provided the patterns are sufficiently alike that relevant physical mechanisms can be identified. For example, they found that with increased CO_2 and increased surface temperatures, precipitation tended to increase where it was already heavy, so that if a rainbelt was differently located in two models, the response patterns could differ but still have the same implications for the real climate change. However, although a perfect simulation may not be required, it is clear that the better the simulation the more reliable the conclusions concerning climate change that may be made. Also, since, as discussed in Section 3, the magnitude of the response depends on the feedbacks, these feedbacks should be realistically represented in the models. Thus, in selecting model variables with which to validate atmospheric components of the climate models, we considered the following:

a) Variables that are important for the description of the atmospheric circulation and which therefore ought to be realistically portrayed in the control simulations if the modelled changes are to be given credence. Examples include sea-level pressure and atmospheric wind and temperature, and their variability as portrayed by the kinetic energy of eddies.

b) Variables that are critical in defining climate changes generated by greenhouse gases. These data also need to be realistic in control simulations for the present climate if the model predictions are to be credible. Examples include surface air temperature, precipitation, and soil moisture, along with their day-to-day and year-to-year variability.

c) Variables that are important for climate feedbacks. If they are poorly simulated, we cannot expect changes in global and regional climate to be accurately estimated. Examples are snow cover, sea-ice, and clouds and their radiative effects.

In general, the assessments made can only be relative in character. It is not usually possible to specify a critical value that errors must not exceed. Thus temperature changes may be realistically simulated even when the modelled temperatures are in error by several degrees, for example, the error may be due to excessive night time cooling of air near the surface which may have little effect on other aspects of the simulation. On the other hand it may be obvious that an error is too serious for much credence to be given to changes in a particular region. For example, a prediction of changes in temperature in a coastal region with observed winds off the ocean, if the simulated winds blow off the land. To allow the reader to make such assessments, maps are shown for a number of key variables and models for which detailed changes are depicted in Section 5.

The validation of climate models requires, of course, the availability of appropriate observed data. For some variables of interest, observed data are unavailable, or are available for only certain regions of the world. In addition to traditional climatological data, useful compilations of a number of variables simulated by climate models have been provided by Schutz and Gates (1971, 1972), Oort (1983) and Levitus (1982), and more recent compilations of atmospheric statistics have been made using analyses from operational weather prediction (see, for example, Trenberth and Olson, 1988). Rather than attempting to provide a comprehensive summary of observed climatic data, we have used what appear to be the best available data in each case, even though the length and quality of the data are uneven. Satellite observing systems also provide important data sets with which to validate some aspects of climate models, and when fully incorporated in the data assimilation routines of operational models such data are expected to become an important new source of global data for model validation.

A wide range of statistical methods has been used to compare model simulations with observations (Livezey, 1985, Katz, 1988, Wigley and Santer, 1990, Santer and Wigley, 1990). No one method, however, is "ideal" in view of the generally small samples and high noise levels involved and the specific purposes of each validation. Other factors that can complicate the validation process include variations in the form in which variables are represented in different models, for example, soil moisture may be expressed as a fraction of soil capacity or as a depth, and snowcover may be portrayed by the fractional cover or by the equivalent mass of liquid water. Another problem is the inadequate representation of the distribution of some climatic variables obtainable with available observations, such as precipitation over the oceans and soil moisture.

Another method of validation which should be considered is internal validation where the accuracy of a particular model process or parameterization is tested by comparison with observations or with results of more detailed models of the process. This approach has only been applied to a very limited extent. The best example is the validation of radiative transfer calculations conducted under the auspices of the WCRP programme for Intercomparison of Radiation Codes in Climate Models (ICRCCM). This intercomparison established the relative accuracy of radiation codes for clear sky conditions against line-by-line calculations, and has led to improvements in several climate models Similarly, the intercomparison of simulated cloud-radiative forcing with satellite observations from the Earth Radiation Budget Experiment (ERBE) should result in improvements in the representation of clouds in climate models

In addition to validation of the present climate, it is instructive to consider the evidence that climate models are capable of simulating climate changes Important evidence comes from atmospheric models when used in other than climate simulations, since the ocean surface temperature is often constrained in similar ways Relevant experiments in this regard for atmospheric models are those with variations of tropical sea-surface temperature (SST) in the El Niño context Numerical weather prediction, which uses atmospheric models that are similar in many respects to those used in climate simulation, provides an additional source of validation The simulation of climate since the last glacial maximum, for which we have some knowledge of the land ice, trace gas concentrations and ocean surface

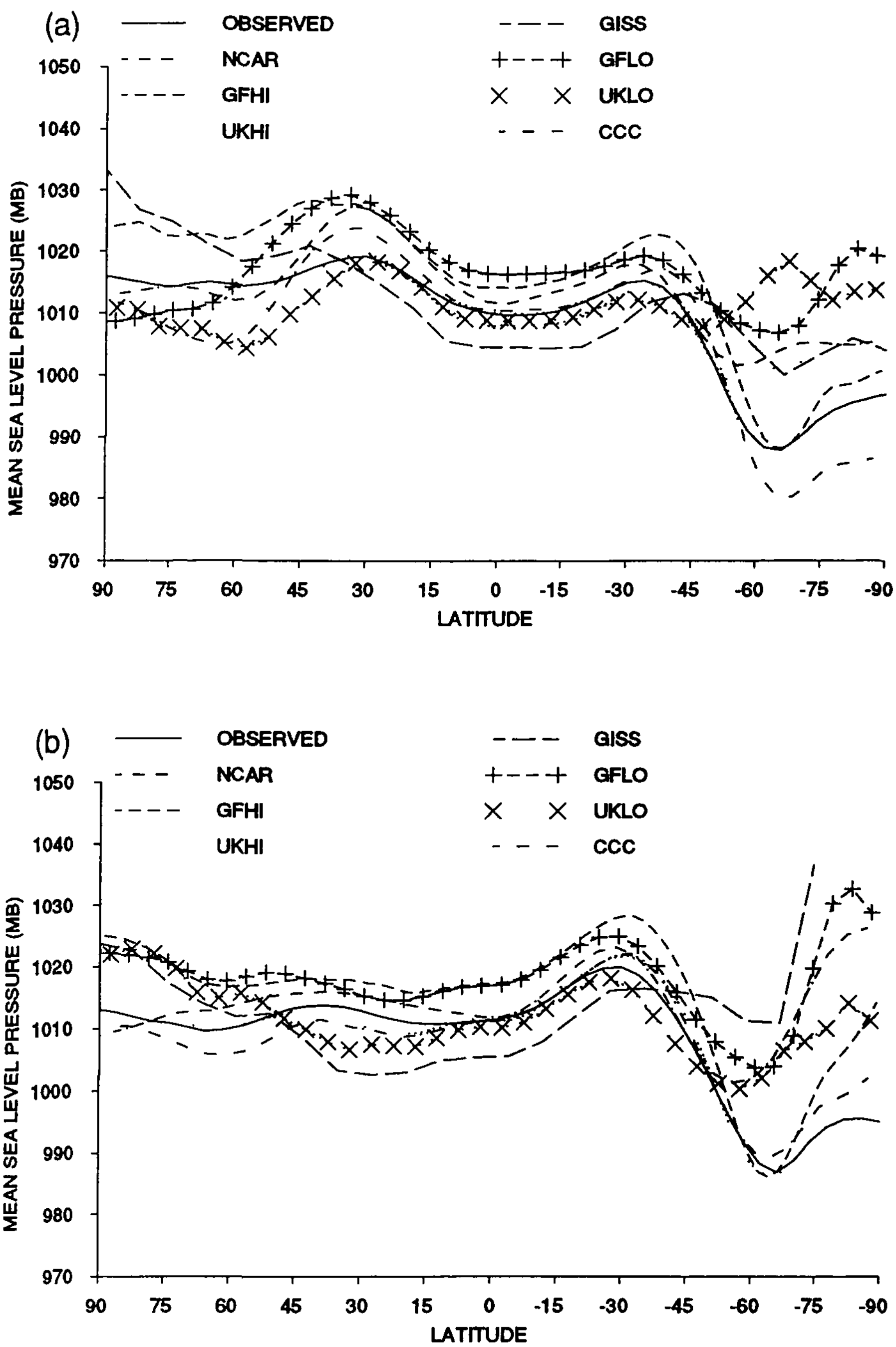


Figure 4.1: Zonally averaged sea-level pressure (hPa) for observed (Schutz and Gates, 1971, 1972) and models (a) December-January-February, (b) June-July-August Model reference numbers (Table 3 2 (a)) are CCC (20), GFHI (21), GFLO (13), GISS (11), NCAR (7) UKHI (22), UKLO (15)

temperatures, also provides a useful test of climate models Finally for validation of the experiments on transient climate change discussed in Section 6, it is important to consider the validation of ocean and coupled ocean-atmosphere models

4.2 Simulation of the Atmospheric Circulation

In this section we consider a number of basic atmospheric variables for which validation data are readily available and whose satisfactory simulation is a prerequisite for confidence in the models ability to portray climate change

4.2.1 Sea-Level Pressure

The sea-level pressure pattern provides a useful characterization of the atmospheric circulation near the surface and is closely related to many aspects of climate A simple but revealing measure of the pressure pattern is the north-south profile of the zonal average (average around a latitude circle) (Figure 4 1) In both solstitial seasons the structure is rather similar, with a deep Antarctic trough subtropical ridges with a near-equatorial trough between and a rather weak and asymmetric pattern in northern middle and high latitudes The models approximate the observed pattern with varying degrees of success all simulate to some extent the subtropical ridges and Antarctic trough The ridges are in some cases displaced poleward and there is a considerable range in their strength particularly in the NH (Northern Hemisphere) In the lower resolution models the Antarctic trough is generally too weak and sometimes poorly located

The dependence of the simulation of the Antarctic trough on resolution evident here for the GFDL and UKMO models has been found in several previous studies (Manabe et al 1978 Hansen et al 1983 Dyson 1985) While Manabe et al found it to be marked in the GFDL spectral models only in July the similar GFDL model considered here shows it clearly in January also The earlier GFDL result is consistent with experiments with the CCC model by Boer and Lazare (1988) showing only a slight deepening of an already deep Antarctic trough as resolution was increased The important result in the present context is that the more realistic models used in CO_2 experiments are those with higher resolution (CCC GFHI and UKHI)

The NH winter subtropical ridge is too strong in most models while the decrease in pressure from this ridge to the mid-latitude trough is generally excessive this is associated with excessively deep oceanic lows in some models and with spurious westerlies over the Rockies in others The westerlies in high resolution models are very sensitive to the representation of the drag associated with gravity waves induced by mountains without it a ring of strong westerlies extends around middle latitudes during northern winter (Slingo and Pearson 1987)

The models simulate the seasonal reversal from northern summer to winter (for example Figure 4 2) To some degree this reflects the dominance of thermal forcing of the pressure pattern and the fact that most of the models have ocean temperatures which are kept close to climatology Summer temperatures over land are strongly affected by the availability of soil moisture (see Section 4 3 3), the absence of evaporative cooling generates higher surface temperature and lower pressure as in the "dry land" experiment of Shukla and Mintz (1982) This effect is evident in some of the models simulations of pressure over land in the summer A serious shortcoming of the lower resolution models in the northern summer is the tendency to develop too strong a ridge between the Azores high and the Arctic, this error shows up as the absence of a trough near 60°N in Figure 4 1(b) and was also found in previous assessments (e g , Manabe et al 1978, Dyson, 1985)

The variability of the pressure pattern can usefully be separated into the daily variance within a month and the interannual variability of monthly means Both are simulated with some skill by models, especially the daily variance (e g Figure 4 3) in particular, the variability maxima over the eastern Atlantic and northeast Pacific are well simulated and in the Southern Hemisphere high values are simulated near 60°S as observed These results indicate that the models can successfully simulate the major storm tracks in middle latitudes On smaller scales, however there are regionally important errors, associated for example with the displacements of the variability maxima in the Northern Hemisphere

In summary the recent higher resolution models are capable of generally realistic simulations of the time averaged sea level pressure and of the temporal pressure variability

4.2 2 Temperature

While models successfully simulate the major features of the observed temperature structure of the atmosphere, all models contain systematic errors such as those shown in the simulated zonally averaged temperatures in Figure 4 4 Of errors common to many models, the most notable is the general coldness of the simulated atmosphere, simulated temperatures in the polar upper troposphere and lower stratosphere are too low in summer by more than 10°C while the lower troposphere in tropical and middle latitudes is too cold in both summer and winter The latter error may in some cases be alleviated by increasing the horizontal resolution (Boer and Lazare 1988, Ingram, personal communication) The existence of such common deficiencies despite the considerable differences in the models resolution numerical treatments and physical parameterizations implies that all models may be misrepresenting (or indeed omitting) some physical mechanisms In contrast in some regions of the

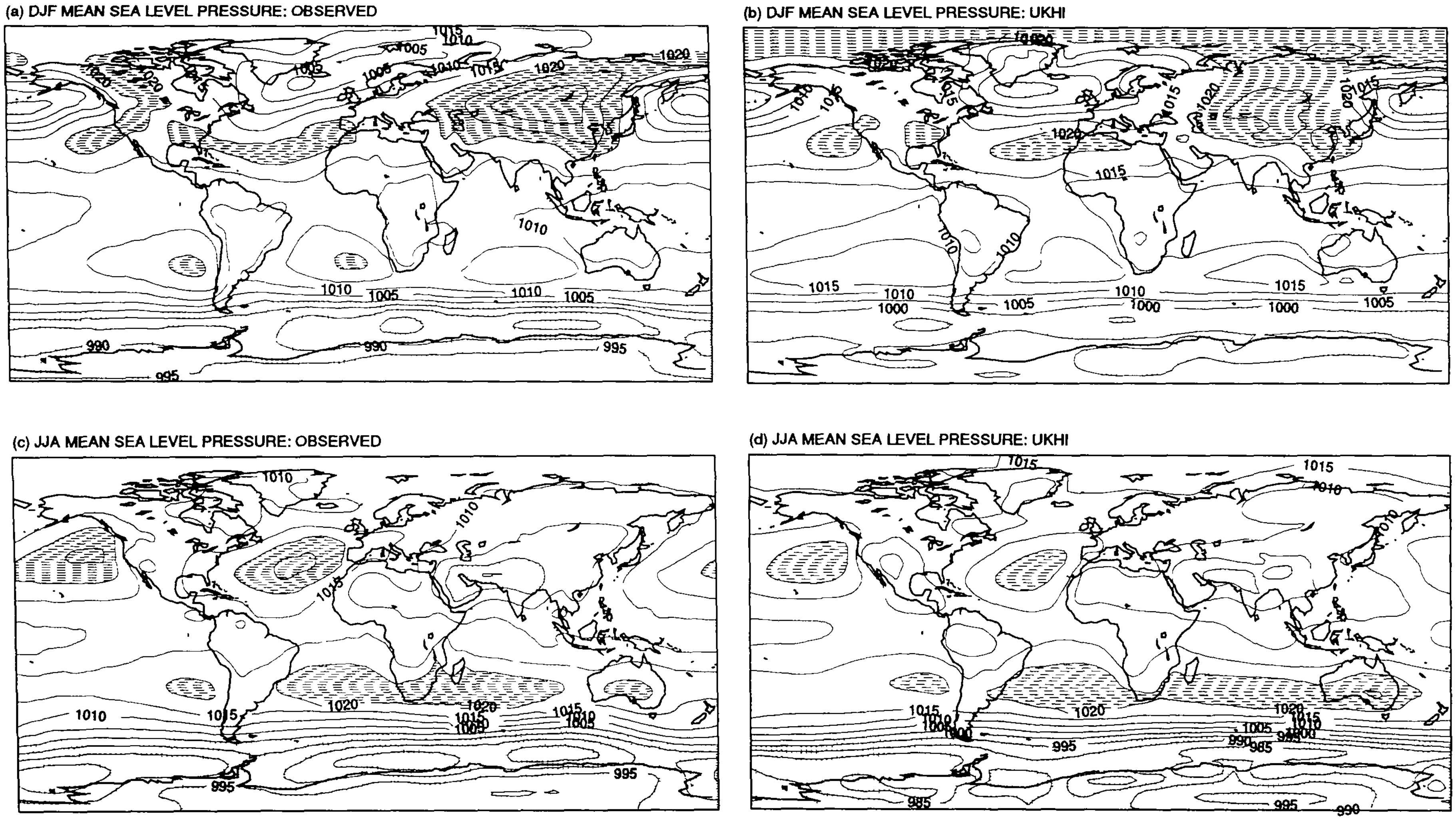


Figure 4.2: Sea-level pressure (hPa) for December-January-February (a,b) and June-July-August (c,d) for: (a,c) Observed (Schutz and Gates 1971, 1972) and (b,d) the UKHI model (No. 22, Table 3.2(a))

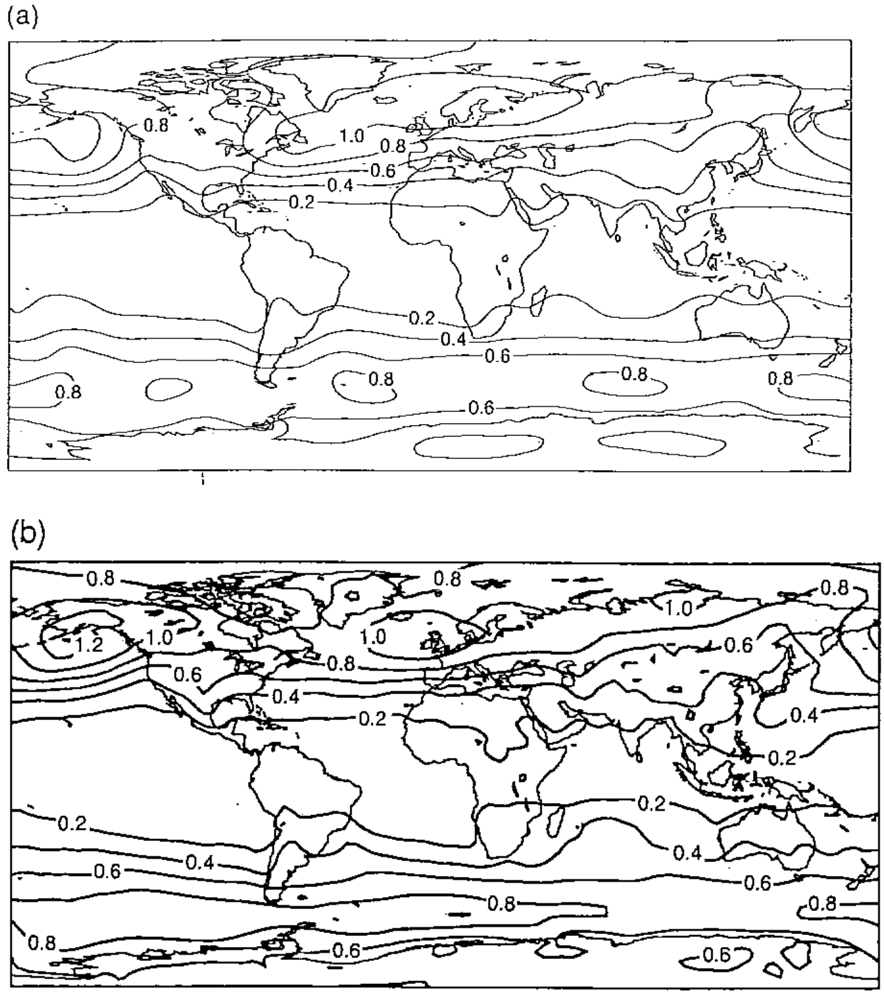


Figure 4.3: Daily standard deviation of 1000 hPa height (hm) for December-January-February for: (a) Observed (Trenberth and Olson, 1988), (b) For CCC model (No. 20 Table 3.2(a)).

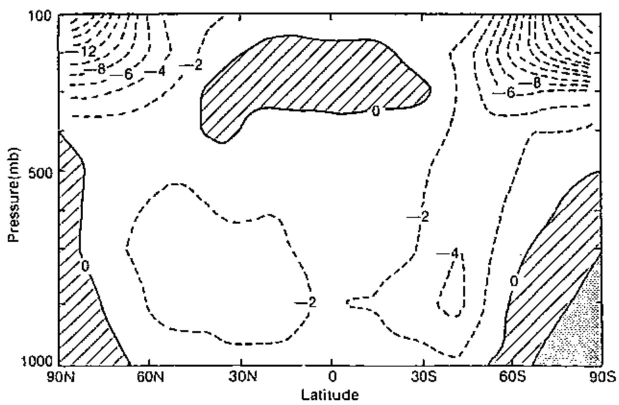


Figure 4.4: Zonally averaged temperature errors (°C) for an early version of the CCC model (not shown in Table 3.2(a)) for December-January-February. Contours every 2°C with negative errors dashed.

atmosphere, the simulated temperatures do not have a consistent bias and are warmer than observed in some models and cooler than observed in others.

In summary, the major features of the observed zonally averaged temperature structure are successfully simulated by modern general circulation models. There are, however, characteristic errors in specific regions, notably the polar upper troposphere and lower stratosphere in summer and much of the lower troposphere where temperatures are colder than observed in all models.

4.2.3 Zonal Wind

The winds are closely linked to the pressure and temperature distributions. The general poleward decrease of temperature in most of the troposphere leads to westerly flow, at least in the zonal mean (Figure 4.5). The major features in both solstitial seasons are the closed-off jets in each hemisphere and the easterlies in the tropics, especially near the surface and in the lower stratosphere. While most of the models represent these features to some extent, there

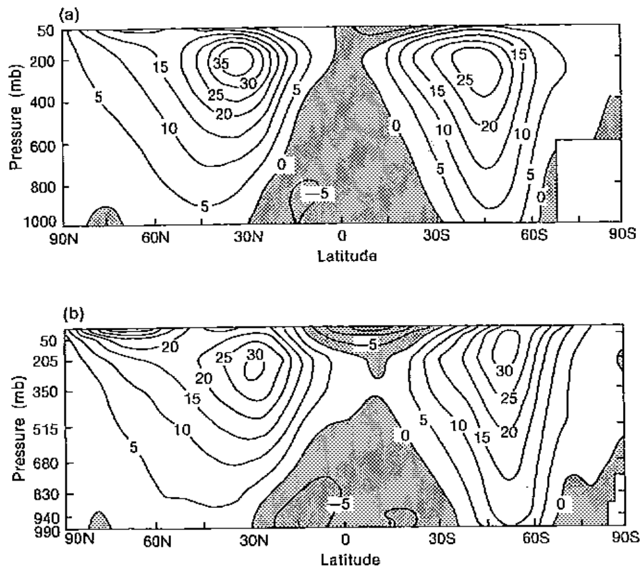


Figure 4.5: Zonally averaged zonal wind (ms^{-1}) for December-January-February for: (a) Observed (Arpe, personal communication), based on ECMWF analyses; (b) GFHI model (No. 21 Table 3.2(a)).

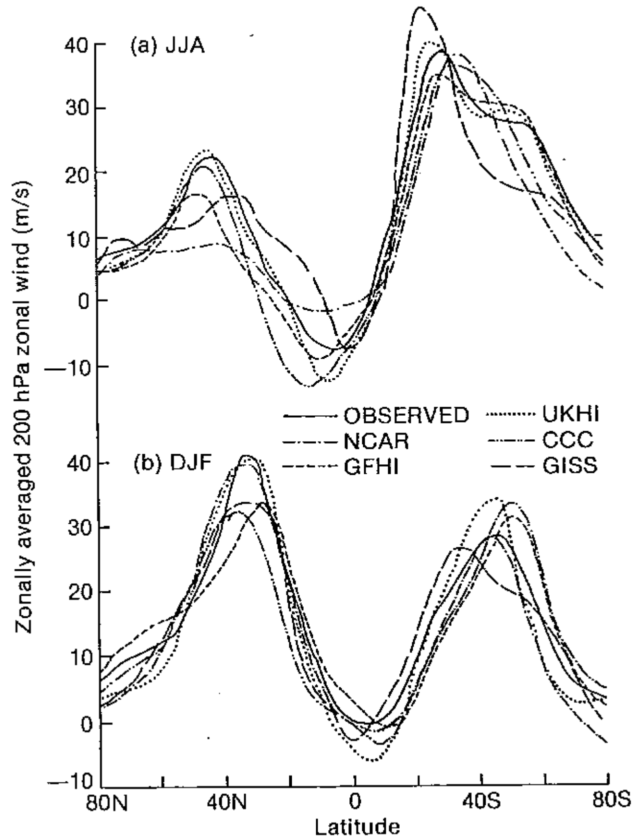


Figure 4.6: Zonally averaged 200 hPa zonal wind (ms^{-1}) for various models and as observed (Trenberth, personal communication) for: (a) June-July-August, (b) December-January-February.

are a number of errors in common. The most prominent of these are excessive westerlies above the summer jet, especially in the SH, and above and poleward of the winter jet. In consequence, some models fail to close the winter subtropical jet (i.e., separate it from the stratospheric polar night jet). This problem can also be alleviated by improving the vertical resolution (Cariolle et al., (1990)). In the NH the closure error is smallest in the more recent simulations using higher resolution models (e.g., Figure 4.5(b)), although this improvement may owe more to the inclusion of gravity wave drag than to the improvement in resolution. Dyson (1985) found that improved resolution helped to intensify the NH summer jet; this result is also evident here, as shown by Figure 4.6, which allows comparison of the observed and modelled meridional profiles of wind at 200 hPa. At this level the June-July-August jet in the SH is realistically simulated in most models, but again most fail to close it.

In summary, although most models represent the broad features of the observed zonal wind structure, only the more recent models with the more realistic simulations of sea-level pressure succeed in closing the winter jets and in providing a sufficiently strong NH summer jet.

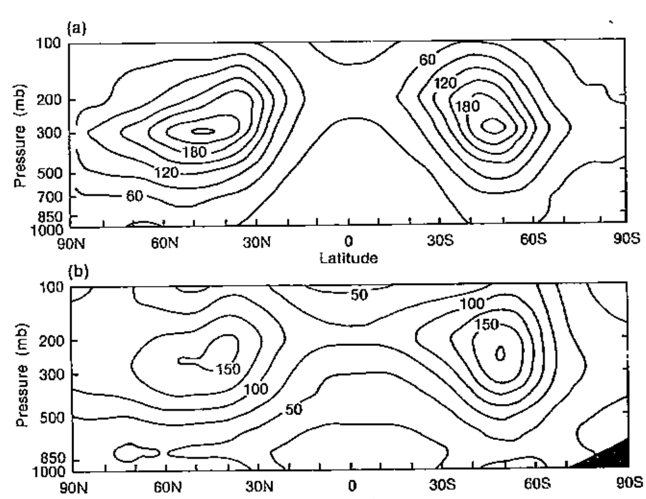


Figure 4.7: Zonally averaged transient eddy kinetic energy (m^2s^{-2}) for December-January-February for (a) Observed (Trenberth and Olson, 1988) based on ECMWF analyses; (b) T30 version of the CCC model (not listed in Table 3.2(a)) (from Boer and Lazare, 1988).

4.2.4 Eddy Kinetic Energy

A realistic climate model should simulate correctly not only the zonally-averaged atmospheric variables but also their space-time variability. Nearly half the atmospheric kinetic energy resides in "eddies", by which meteorologists understand deviations of the flow from zonally-averaged

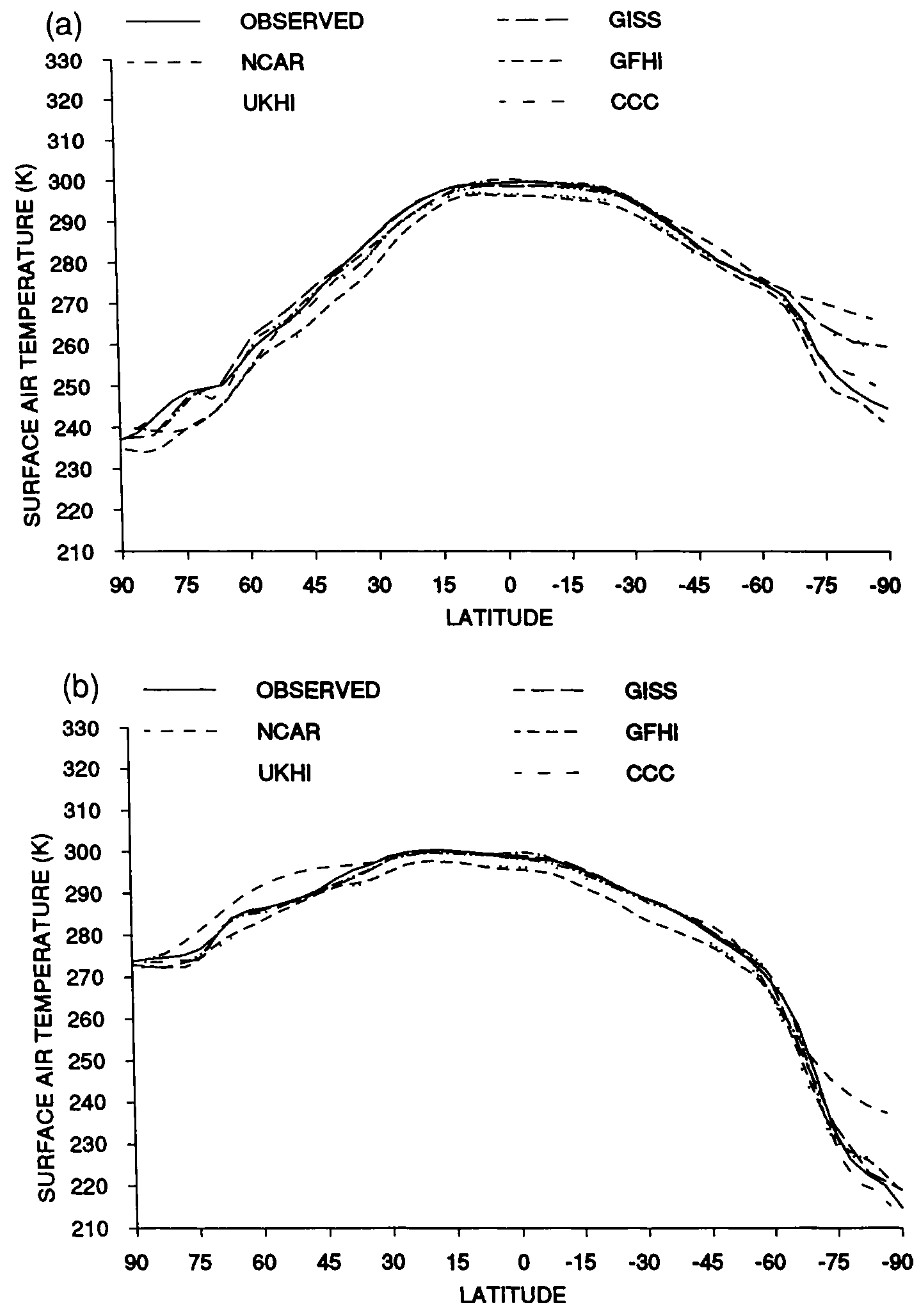
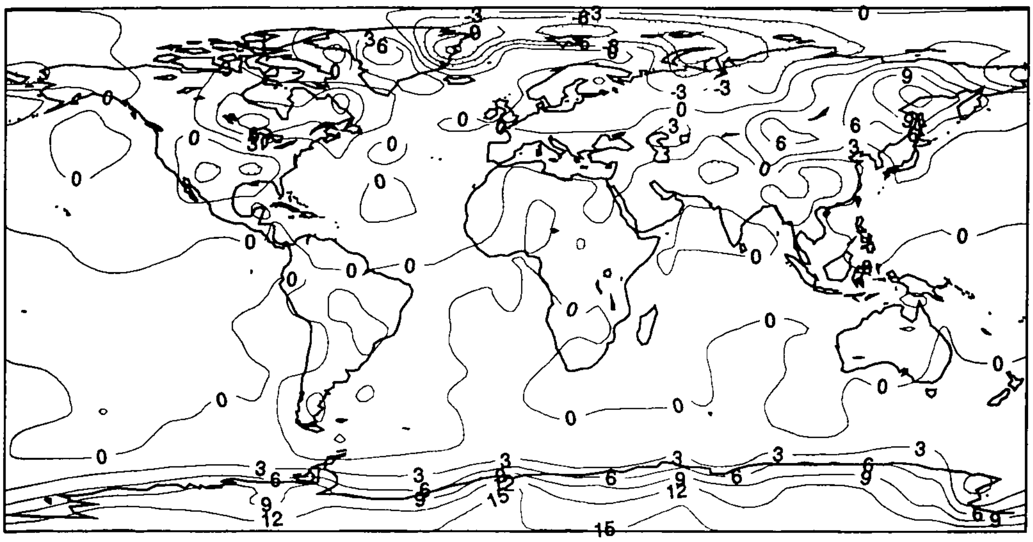


Figure 4.8: Zonally averaged surface air temperatures (K) for various models and as observed (Schutz and Gates, 1971, 1972) for (a) December-January-February, (b) June-July-August

conditions, as caused, for example, by cyclones and meanders of the jet stream A measure of the intensity of the eddies is the "eddy kinetic energy" (EKE), which is observed to be largest in the extratropical latitudes in the upper troposphere

A persistent error of atmospheric general circulation models is their tendency to underestimate the EKE particularly the transient part representing variations about the time-averaged flow When integrated from real initial conditions the models tend to lose EKE in the course of the integration until they reach their own characteristic climate For example, Figure 4 7 compares the transient EKE for December-January-February in a version of the CCC model (Boer and Lazare, 1988) with the corresponding observed EKE (Trenberth, personal communication), and shows a significant underestimate of the EKE maxima in middle latitudes There is a suggestion of overestimation in the tropics Similar results have been obtained for forecast models (WGNE 1988 see also Section 4 7) Since recent experiments have indicated that resolution is not the basic reason for this systematic EKE error (Boer and Lazare 1988 Tibaldi et al , 1989), it is

(a) DJF GISS - OBSERVED SURFACE AIR TEMPERATURE



(b) JJA GISS - OBSERVED SURFACE AIR TEMPERATURE

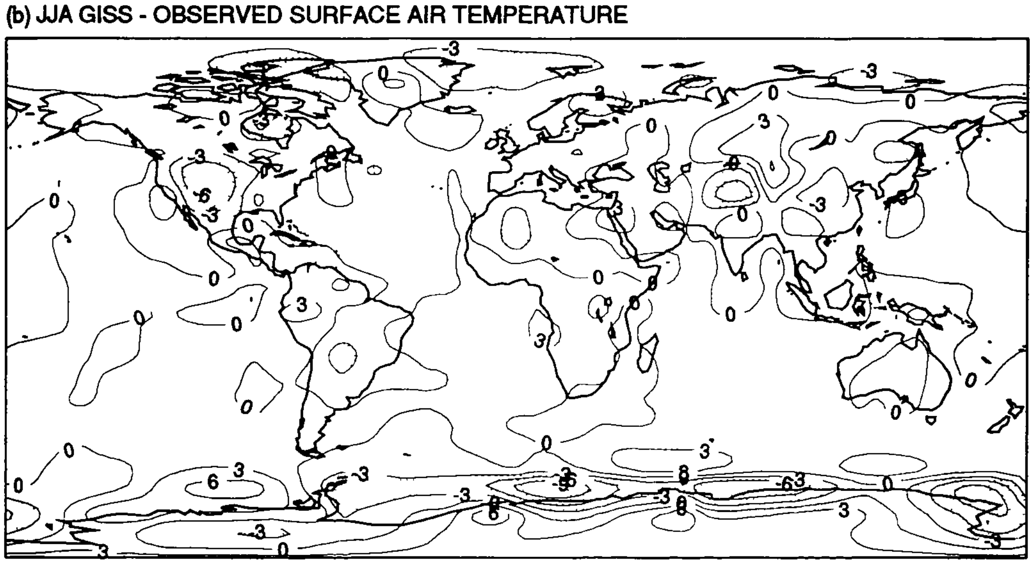


Figure 4.9: Surface air temperature errors for December-January-February (a) and June-July-August (b) for GISS model (No. 11, Table 3.2(a)). Errors calculated relative to Schutz and Gates (1971, 1972). Areas less than -3°C shaded.

probably caused by the models' treatment of physical processes.

In summary, models suffer from a deficiency of transient eddy kinetic energy, an error which appears most marked in the upper extratropical troposphere and which may be reversed in the tropics.

4.3 Simulation of Other Key Climate Variables

In this section we assess the global distribution of variables involved in the energy and hydrological balances whose satisfactory simulation is important for determining the climate's response to increased greenhouse gases.

4.3.1 Surface Air Temperature

The temperature of the air near the surface is an important climatic parameter. The global pattern is dominated by large pole to equator gradients which models simulate well (Figure 4.8) though it should be recalled that in most of the models shown, the ocean surface temperatures are maintained near the correct level by 'flux adjustment' techniques. Because of the dominance of the pole-to-equator gradient, the maps shown (Figure 4.9) are of departures of temperature from the observed. Validation of this quantity from atmospheric GCMs is complicated by the models' low vertical resolution and by the relatively large diurnal variation of temperature near the surface.

A principal conclusion from the comparison of simulated with observed near-surface air temperature is that while each model displays systematic errors, there are few errors common to all models One characteristic error is that temperatures over eastern Asia are too cold in winter (e g , Figure 4 9(a) over southeast Asia) Another, common to most models, is that temperatures are too high over the Antarctic ice sheet (Figure 4 8), in winter at least, this can be attributed to the models' difficulty in resolving the shallow cold surface layer In summer, errors in the simulated ground wetness appear to be responsible for many of the temperature errors over the continents (compare Figures 4 8 and 4 12) this error being less marked in models with more complete representations of the land surface (e g , Figure 4 9) (See Section 4 4 for a detailed assessment for five selected areas)

The variability of surface air temperature can, like sea-level pressure, be considered in terms of the day-to-day variations within a month or season, and the interannual variations of monthly or seasonal means Detailed validations of these quantities for selected regions in North America in relatively low resolution models have been made by Rind et al (1989) and Mearns et al , (199) Both found variances to be too high on a daily time-scale, while for interannual timescales, the results differed between the models An earlier study by Reed (1986) with a version of the UKMO model (not in Table 3 2(a)) also revealed too high variability on a daily time-scale in eastern England On the other hand, for the models reviewed in this assessment for which data were available, the daily variance appeared to be capable of realistic simulation though it tended to be deficient over northern middle latitudes, especially in summer

In summary, the patterns of simulated surface air temperature are generally similar to the observed Errors common to most models include excessively cold air over eastern Asia in winter and too warm conditions over Antarctica Errors over the continents in summer are often associated with errors in ground wetness

4.3.2 Precipitation

A realistic simulation of precipitation is essential for many if not all studies of the impact of climate change A number of estimates of the distributions of precipitation from observations are available, some of these are derived from station observations, which are generally considered adequate over land, one is derived from satellite measurements of outgoing longwave radiation (Arkin and Meisner, 1987, Arkin and Ardanuy 1989) while another is from ship observations of current weather coupled with estimated equivalent rainfall rates (e g Dorman and Bourke 1979) The differences among these analyses are not insignificant but are mostly smaller than the differences between the analyses and model simulations

While all models simulate the broad features of the observed precipitation pattern, with useful regional detail in some regions, (see, for example the zonally averaged patterns in Figure 4 10 and the patterns for the higher resolution models in Figure 4 11), significant errors are present, such as the generally inadequate simulation of the southeast Asia summer monsoon rainfall (see also Section 4 5 3), the zonal rainfall gradient across the tropical Pacific, and the southern summer rains in the Zaire basin These errors reduce the correlation between observed and modelled patterns over land to about 0 75 (model 22, Table 3 2(a)) A similar level of skill is evident in the assessment in Section 4 4 2 Some of the earlier models underestimate the dryness of the subtropics (Figure 4 10), while several models are much too wet in high latitudes in winter Models that do not use a flux correction to ensure an approximately correct SST fail to simulate the eastern and central equatorial Pacific dry zone (not shown) There are also large differences between the recent model simulations of the intensity of the tropical oceanic rainbelts though the (inevitable) uncertainties in the observed ocean precipitation can make it unclear which models are nearer reality

Rind et al (1989) and Mearns et al (1990) have found that over the USA interannual variability of simulated precipitation in the GISS and NCAR models is generally excessive in both summer and winter, while daily variability is not seriously biased in either season, at least relative to the mean precipitation The NCAR study also revealed considerable sensitivity of the daily precipitation to the model formulation, particularly to aspects of the parameterization of evaporation over land Analyses of the UKMO model (Reed, 1986, Wilson and Mitchell, 1987) over western Europe showed that there were too many rain days, although occurrences of heavy rain were underpredicted

In summary, current atmospheric models are capable of realistic simulations of the broadscale precipitation pattern provided the ocean surface temperatures are accurately represented All the models assessed, however, have some important regional precipitation errors

4.3.3 Soil Moisture

Soil moisture is a climatic variable that has a significant impact on ecosystems and agriculture Some model experiments on the impact of increasing greenhouse gases on climate have shown large decreases in soil moisture over land in summer, this can provide a positive feedback with higher surface temperatures and decreased cloud cover Since there is no global coverage of observations of soil moisture its validation is difficult Estimates of soil moisture have been made by Mintz and Serafini (1989) from precipitation data and estimates of evaporation but comparison with a recent analysis of observations over the

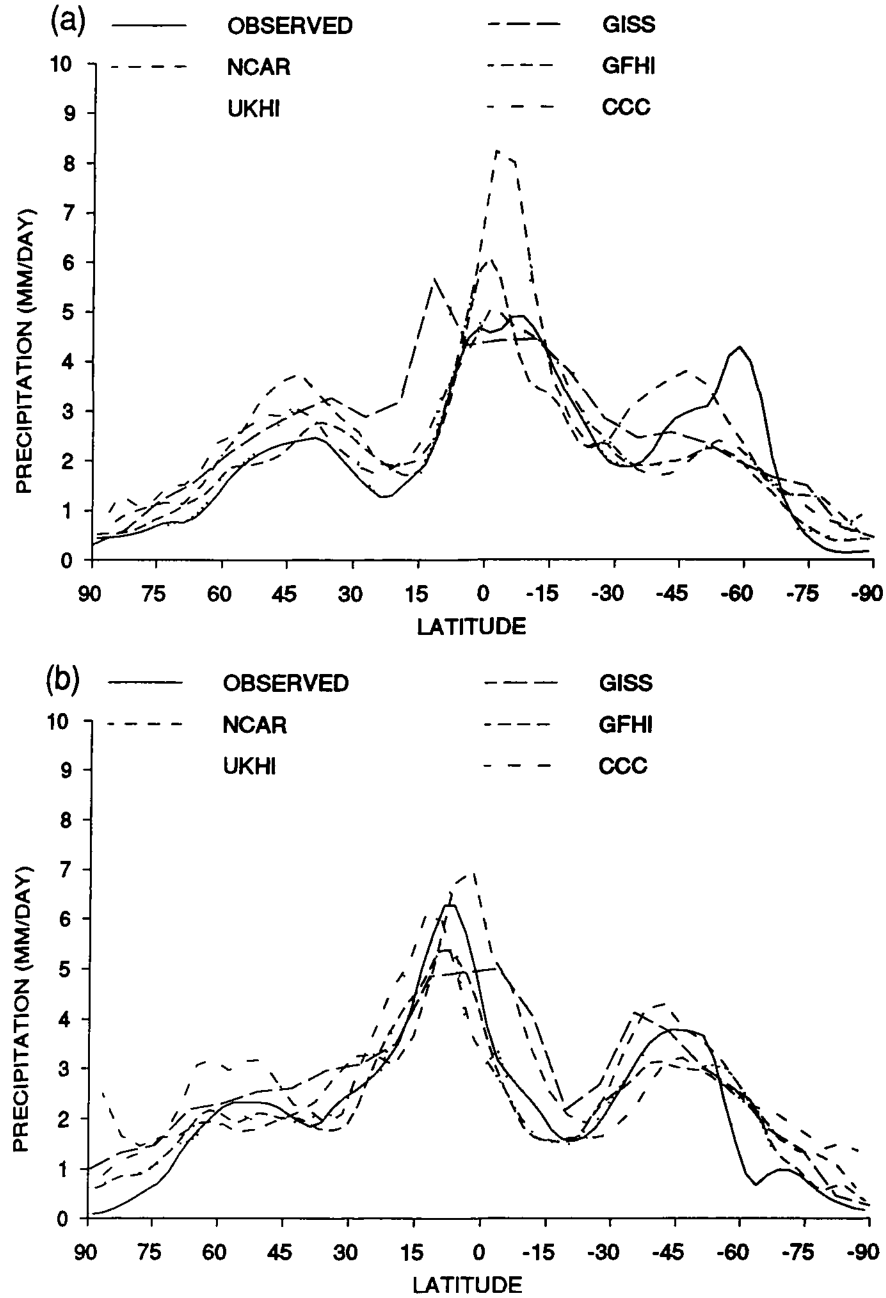


Figure 4.10: Zonally averaged precipitation (mm day [1]) for various models and as observed (Jaeger, 1976) for (a) December January February, (b) June-July-August

western USSR (Vinnikov and Yeserkepova, 1990) suggests the estimates are too low in high latitudes in summer (Table 4 1)

Compared with the Mintz-Serafini observational estimates, model simulations generally show a greater seasonal variation, especially in the tropics In general the simulations errors in soil moisture resemble those in precipitation, and vary considerably among models, as is evident from the zonally averaged June-August data (Figure 4 12) The simulations over Eurasia and northern Africa are quite close to the "observed" in most models However the zonally averaged data and also comparison with the USSR data (e g , Table 4 1), suggests that some models become too dry in summer in middle latitudes All models have difficulty with the extent of the aridity over Australia, especially in the (southern) summer

In summary, the limited soil moisture data available show that the simulated middle latitude summer and winter distributions qualitatively reflect most of the observed large-scale characteristics However, there are large differences in the models' simulations of soil moisture, as expected from the precipitation simulations, and it should be emphasized that the representation (and validation) of soil moisture in current climate models is still relatively crude

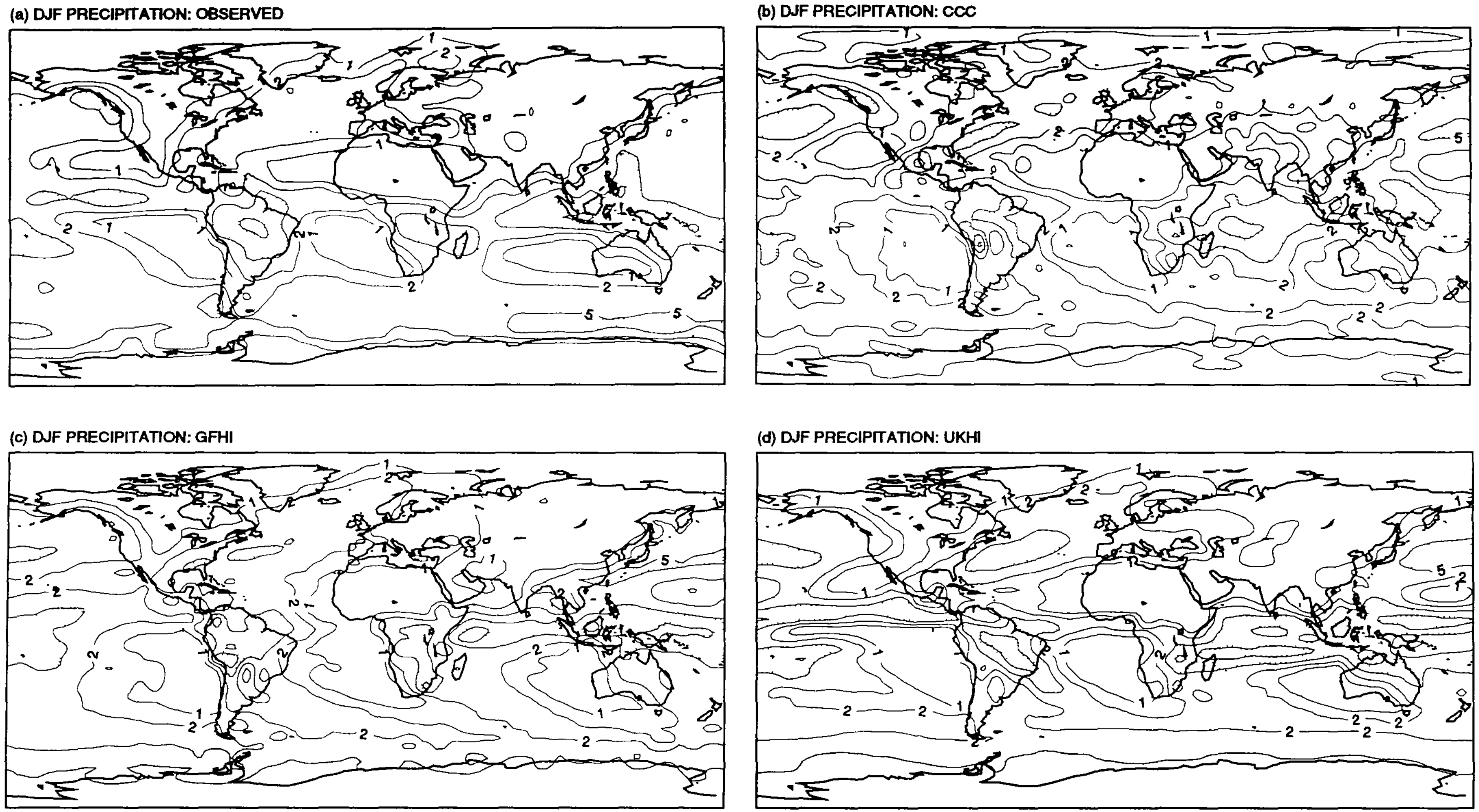


Figure 4.11: Precipitation (mm day^{-1}) for December-January-February (a, b, c, d) and June-July-August (e, f, g, h); observed (Jaeger, 1976) (a, e) and CCC model (No. 20) (b, f), GFHI model (No. 21) (c, g) and UKHI model (No. 22) (d, h) (see Table 3.2(a) for model reference numbers).

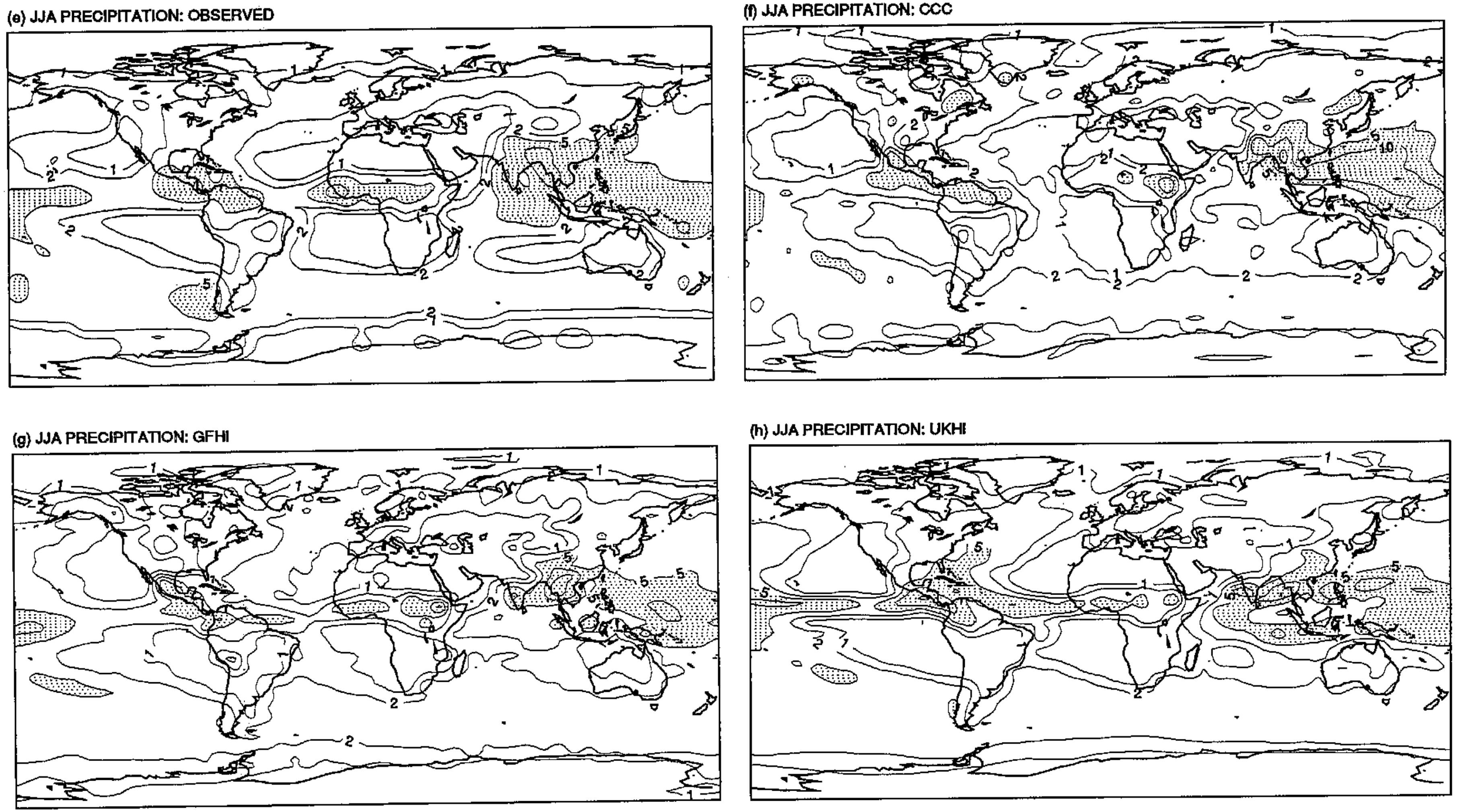


Figure 4.11 (continued)

Table 4.1 Averages of available soil moisture as percentage of capacity for 30 60°E as observed (Vinnikov and Yeserkepova 1990) estimated from observations (Mintz and Serafini 1989) and for three models (CCC, GFHI and UKHI) for December February (DJF) and June August (JJA)

Model or Data	Vinnikov & Yeserkepova		Mintz & Serafini		CCC		GFHI		UKHI	
Seasons	DJF	JJA	DJF	JJA	DJF	JJA	DJF	JJA	DJF	JJA
62°N	100	100	100	55	>90	88	56	54	93	97
58°N	100	98	97	41	>90	85	32	22	90	93
54°N	85	57	83	27	78	77	25	13	81	67
50°N	63	24	57	12	35	22	28	10	70	30

NOTE The capacities vary between the data sets For Mintz and Serafini and GFHI, they are 15cm For UKHI, there is no fixed capacity, but the runoff parameterization leads to an effective capacity close to 15cm, as used for the above results CCC and Vinnikov and Yeserkepova have larger capacities, their data were provided as actual fractions of capacity

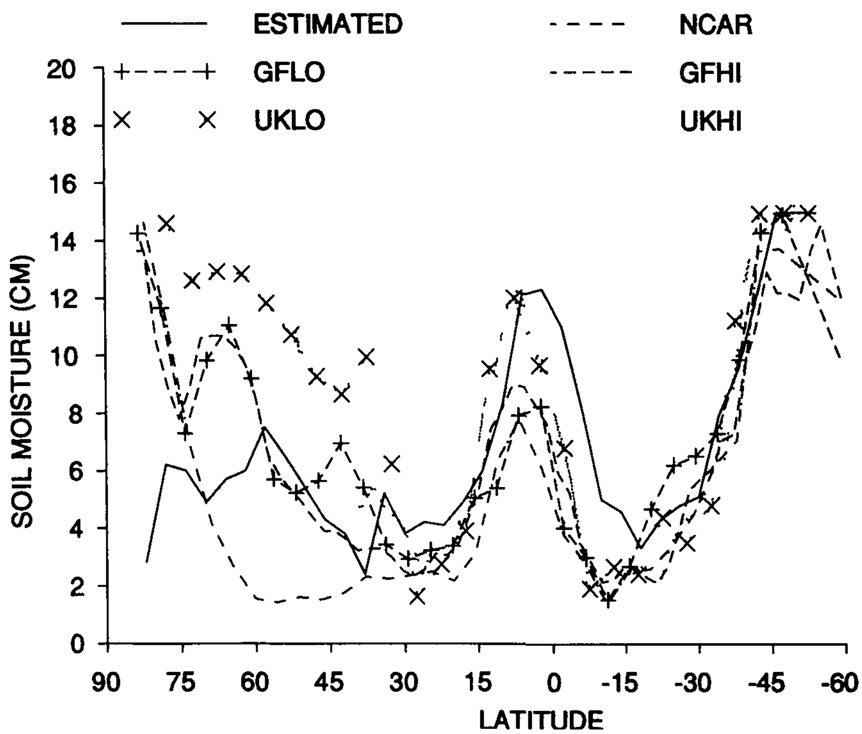


Figure 4.12: Zonally averaged soil moisture (cm) for land points as estimated by Mintz and Serafini (1989) for July and as modelled for June-July-August

4.3.4 Snow Cover

Snow is an important climate element because of its high reflectivity for solar radiation and because of its possible involvement in a feedback with temperature The correct simulation of snow extent is thus critical for accurate prediction of the response to increasing greenhouse gases

Snow cover observations used for model validation were a 15 year satellite-derived data set of the frequency of cover (Matson et al , 1986) and an earlier snow depth data set (Arctic Construction and Frost Effects Laboratory, 1954) These observations document the expected maximum snow cover in the Northern Hemisphere winter, with Southern Hemisphere snow confined mainly to Antarctica

Detailed assessments of the simulations, especially for seasons other than winter, are hindered by the different forms of the model data (mostly seasonal mean liquid water content) and the observed data (either frequency of cover or maps of depth at ends of months) While all models capture the gross features of the seasonal cycle of snow cover, some models exhibit large errors Otherwise, except over eastern Asia where snow extents are mostly excessive (consistent with the low simulated temperatures (e g , Figure 4 9)), the models' average winter snow depths can be near those observed, this is illustrated for North America in Figure 4 13, which compares the observed 5cm snowdepth contour at the end of January with the modelled 1cm liquid water equivalent contour averaged for December to February Comparable results are obtained over Europe and western Asia

In summary, several models achieve a broadly realistic simulation of snow cover Provided snow albedos are realistic, the simulated snow extent should thus not distort simulated global radiative feedbacks However, there are significant errors in the snow cover on regional scales in all models

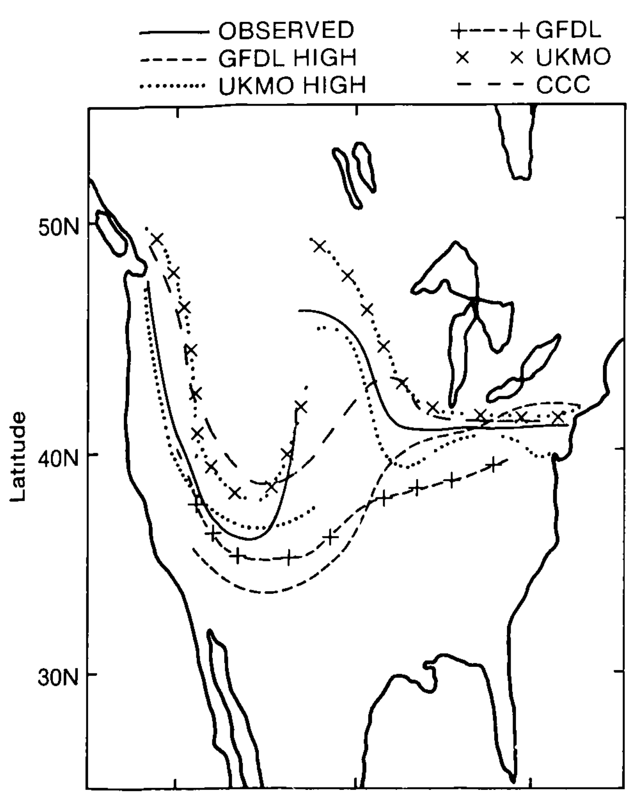


Figure 4.13: Winter snow cover over North America as defined for various models by the minimum latitude at which the December-January February simulated snow cover had a 1 cm liquid water equivalent contour, and as observed by the minimum latitude of the end-of-January average 2 inch (5 cm) depth contour (GFDL HIGH = GFHI, UKMO HIGH = UKHI GFDL = GFLO UKMO = UKLO)

4.3.5 Sea-Ice

An accurate simulation of sea-ice is important for a model's ability to simulate climate change by virtue of its profound effect on the surface heat flux and radiative feedbacks in high latitudes An attempt is made to ensure a good simulation of sea-ice extent by including a prescribed ocean heat flux in many current models, this flux is assumed to be unchanged when the climate is perturbed Without it, models tend to simulate excessive temperature gradients between pole and equator, particularly in the Northern Hemisphere winter, with a consequent excess of sea-ice Sea-ice in the Arctic Ocean is constrained to follow the coast in winter, but in summer and autumn the ice separates from the coast in many places, this behaviour is simulated by some models Experiments with relatively sophisticated dynamic-thermodynamic sea-ice models (Hibler, 1979, Hibler and Ackley, 1983, Owens and Lemke, 1989) indicate that a realistic simulation of sea-ice variations may require the inclusion of dynamic effects, although the optimal representation for climate applications has not yet been determined Although the thickness of sea-ice is not readily validated due to the inadequacy of observational data, models display substantial differences in simulated sea-ice thickness

In summary, considerable improvement in the representation of sea ice is necessary before models can be expected to simulate satisfactorily high-latitude climate changes

4.3.6 Clouds and Radiation

The global distribution of clouds has been analysed from satellite data over recent years in ISCCP, and the diagnosed cloud cover can be compared with modelled cloud For example, Li and Letreut (1989) showed that the patterns of cloud amounts in a 10-day forecast were similar to those diagnosed in ISCCP over Africa in July, but were deficient over the southeast Atlantic However, the definition of cloud may differ from model to model and between model and observations so, as discussed by Li and Letreut, it is often easier and more satisfactory to compare measurable radiative quantities A useful indication of cloud cover can be obtained from top-of-the-atmosphere satellite measurements of the outgoing longwave radiation (OLR) and planetary albedo, as provided by Nimbus 7 Earth Radiation budget measurements (Hartmann et al , 1986 Ardanuy et al 1989) These quantities describe the exchange of energy between the whole climate system (ocean, ground ice and atmosphere) and outer space, and in that sense constitute the net forcing of the climate At the same time

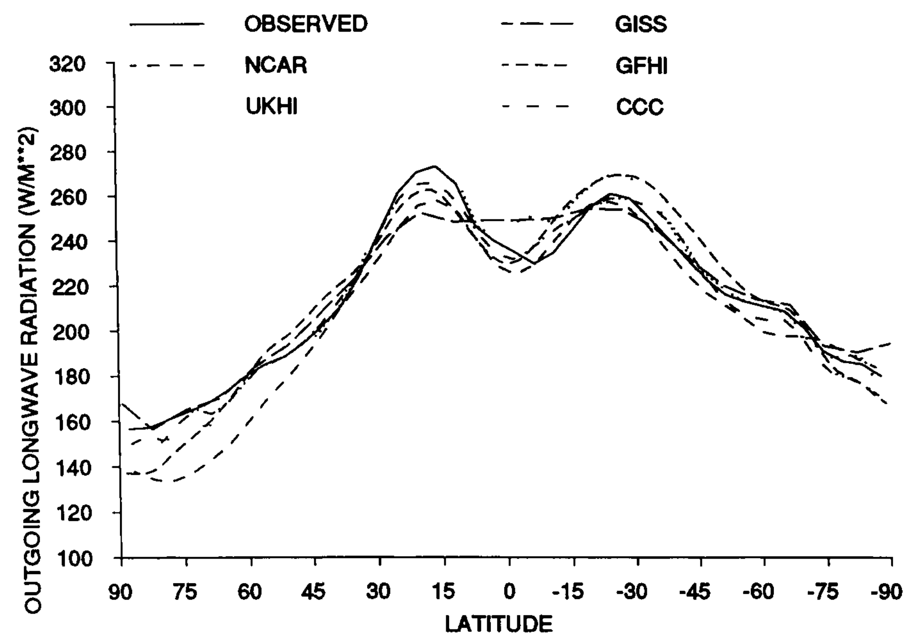


Figure 4.14: Zonally averaged OLR (Wm^{-2}) for December-January-February (models) and for January (observed, Nimbus-7 NFOV)

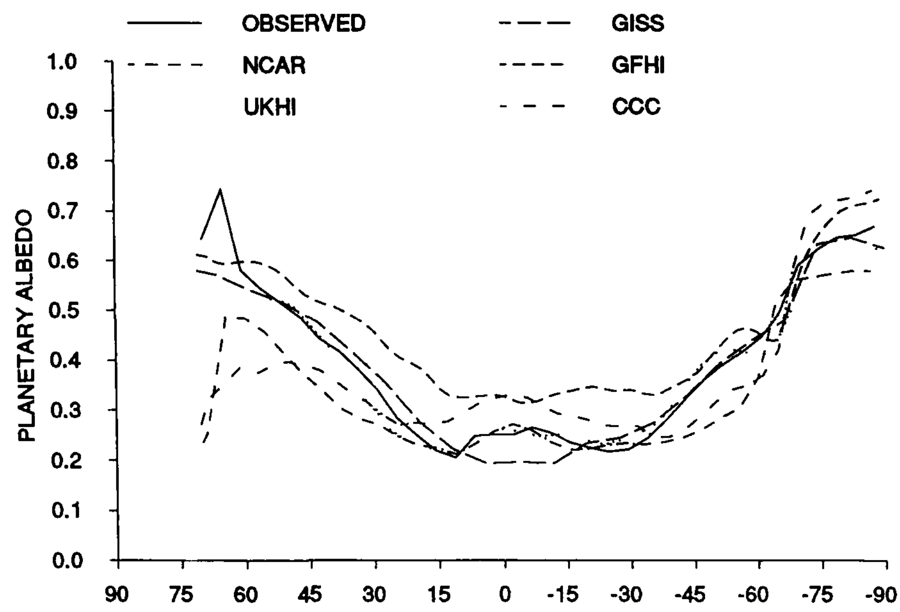


Figure 4.15: Zonally averaged planetary albedo for December-January-February (models) and for January (observed, Nimbus-7 NFOV)

they depend critically on many mechanisms that are internal to the climate system, and in particular the hydrological cycle As a result, the ability of models to simulate the OLR and planetary albedo properly depends not only on the algorithms used to compute the radiative transfers within the atmosphere but also on the simulated snow cover, surface temperature and clouds

The zonally averaged OLR (Figure 4 14) is dominated by maxima in low latitudes and minima in high latitudes Clouds generate minimum OLR near the tropical convergence zones, which are also evident as maxima in the albedo (Figure 4 15) The increase in albedo toward high latitudes, on the other hand, can be associated with clouds, snow and ice, or changes in land surface type and solar zenith angle

Because of the important radiative effects of clouds and their association with precipitation, observed tropical and subtropical OLR extremes are highly correlated with those of precipitation. In general, in tropical regions the models' OLR values are realistic, and models successfully simulate the correlation of precipitation with planetary albedo. At higher latitudes in winter, there is considerable disparity among models in the simulated values of planetary albedo, evidently due to the differing simulations of snow cover and/or clouds and the different specifications of albedo for particular surfaces or cloud types. In general, the models simulate polar OLR minima which are below the observed values, probably because of the temperature errors there (Figure 4.4, 4.8). Apart from these high latitude regions, the zonally averaged OLR is generally within 20 Wm^{-2} of the observed. The mean error magnitudes for individual models are as low as 5 Wm^{-2} (Model 20, Table 3.2(a)) or 2% of the climatological values. For absorbed solar radiation, errors are mostly below 20 Wm^{-2} with albedo errors less than 0.1 except in northern middle and high latitudes.

In summary, this assessment has shown that although the latitudinal variation of top of the atmosphere radiative parameters can be well simulated, there are some discrepancies, particularly in the albedo in middle and high latitudes due to the sensitivity of the parameterization schemes. Most models underestimate the OLR in high latitudes.

4.4 Simulation of the Regional Seasonal Cycle

The seasonal cycle constitutes the largest regularly observed change of the atmosphere-ocean system, and provides an important opportunity for model validation. In general, all GCMs simulate a recognizable average seasonal variation of the principal climate variables, as measured by the phase and amplitude of the annual harmonic. The seasonal variation of the amplitudes of the transient and stationary waves can also be simulated with reasonable fidelity (e.g., the GLA GCM; see Straus and Shukla, 1988 and Section 4.2.1).

A more detailed summary of GCMs simulations of the seasonal cycle and a comparison with observational estimates for five selected regions is given in Table 4.2 in terms of the surface air temperature and precipitation. In this statistical summary, each model's grid-point data over land areas within the selected region have been averaged without interpolation or area-weighting; the areas are bounded as follows: Region 1 (35-50N, 85-105W), Region 2 (5-30N, 70-105E), Region 3 (10-20N, 20W-40E), Region 4 (35-50N, 10W-45E), Region 5 (10-45S, 110-155E). Similar areas are used in analysing regional changes in Section 5.

4.4.1 Surface Air Temperature

The surface temperature data in Table 4.2 are for the bottom model layer except for the CCC model, for which an estimate of screen temperature at 2m was supplied. For the UKMO models, 00GMT data were adjusted to daily means using detailed data for selected points. The differences between the model simulations are generally much larger than those between the observed data sets, with the best agreement among the models' surface air temperature occurring over southeast Asia in summer, and the poorest agreement over the Sahel in winter. In general, the seasonal differences for each of the regions show that the models are, on average, capable of a good representation of the seasonal variation of surface air temperature.

The magnitudes of the average errors of the individual models lie in the range 2.6±0.8°C, with larger values in winter (3.1°C) than in summer (2.1°C). For the high resolution models, the average is 2.3°C. These figures may be compared with the mean seasonal variation of 15.5°C. There appears to be no surface air temperature bias common to all the models, although the models with higher resolution (of the eight assessed) show an average temperature below that observed. Average regional errors are generally small, with only southeast Asia in winter having a mean error (-2.6°C) of more than 1.5°C; the models' average estimates of the seasonal range are within 1°C of that observed for each region except southeast Asia.

In summary, climate models simulate the regional seasonal cycle of surface air temperature with an error of 2 to 3°C, though this error is in all cases a relatively small fraction of the seasonal temperature range itself.

4.4.2 Precipitation

Average values of the simulated and observed precipitation over the five regions are presented in Table 4.2. Most models succeed in identifying southeast Asia in summer as the wettest and the Sahel in winter as the driest seasonal precipitation regimes of those assessed; the region and season which gives the most difficulty appears to be southeast Asia in winter, where several of the models are much too wet. Indeed, all four northern winter validations reveal a preponderance of positive errors, and Australia also tends to be too wet. The mean magnitude of model error varies quite widely between models, from 0.5 to 1.2 mm day^{-1}, or from 20 to 50% of the observed; the three higher resolution models have the smallest mean errors. The relatively large differences among the models indicate the difficulty of accurately simulating precipitation in a specific region (even on a seasonal basis), and underscores the need for improved parameterization of precipitation mechanisms.

In summary, as for temperature, the range of model skill in simulating the seasonal precipitation is substantial, the mean errors being from 20% to 50% of the average precipitation. The models tend to overestimate precipitation in winter.

***Table 4.2** Regional unweighted averages of seasonal surface air temperature (℃, upper portion) and precipitation (mm day^{-1}, lower portion) as simulated in model control runs and as observed over five selected regions (see text). Here DJF is December-January-February and JJA is June-July-August (see Table 3.2(a) for model identification, where different from Figure 4.1).*

Model	Region 1 Gt. Plains		Region 2 S E Asia		Region 3 Sahel		Region 4 S Europe		Region 5 Australia	
or Data	DJF	JJA	DJF	JJA	DJF	JJA	DJF	JJA	DJF	JJA
CCC	-8.4	21.2	10.9	25.3	13.5	27.5	2.3	20.7	26.9	11.3
NCAR (#6)	-3.5	29.9	10.5	27.4	25.2	31.8	2.3	26.4	29.3	17.0
GFDL R15 (#8)	-5.7	25.9	14.1	27.3	25.9	31.7	2.0	26.7	31.9	16.1
GFHI	-7.3	23.7	9.0	25.5	18.3	26.0	-3.8	20.9	24.9	11.8
GISS	-1.2	19.5	14.7	25.4	21.3	28.6	7.5	22.9	26.5	14.3
OSU (#3)	-4.8	20.4	13.9	28.2	30.5	32.8	-1.0	20.2	30.7	22.4
UKLO	-1.7	19.5	17.7	25.8	26.0	26.9	3.7	20.1	25.2	16.3
UKHI	-11.4	20.2	13.1	25.2	21.1	28.5	-2.0	18.5	25.5	15.3
Oort	-6.3	20.8	16.2	25.9	22.7	28.8	1.5	20.8	27.3	15.3
Schutz	-7.7	22.1	15.0	25.6	22.1	28.2	0.3	21.9	27.6	14.4
CCC	1.4	3.8	2.0	8.6	0.1	2.9	2.4	1.7	2.0	0.8
NCAR (#6)	1.6	1.0	3.1	9.3	0.5	4.3	2.9	0.8	3.4	2.7
GFDL R15 (#8)	1.9	3.3	3.3	9.5	1.0	3.9	2.8	1.1	2.3	2.5
GFHI	1.3	2.1	1.6	8.6	0.5	4.5	1.6	1.4	2.9	1.0
GISS	2.0	3.1	5.9	6.0	0.9	3.2	3.0	2.0	2.6	1.6
OSU (#3)	1.4	1.7	0.8	1.4	0.2	1.5	2.2	1.1	1.3	0.9
UKLO	1.2	4.0	1.5	4.1	0.3	3.8	2.2	3.5	3.0	0.8
UKHI	1.0	2.7	0.5	4.3	0.0	2.8	2.8	1.5	4.1	1.0
Jaeger	1.1	2.5	0.6	9.0	0.1	4.4	2.1	2.0	2.4	0.8
Schutz	1.1	2.4	0.6	6.3	0.2	3.4	1.7	1.8	2.1	1.1

4.5 Simulation of Regional Climate Anomalies

4.5.1 Response to El Niño SST Anomalies

The El Niño Southern Oscillation (ENSO) phenomenon is now recognized to be an irregular oscillation of the coupled ocean/atmosphere system in the tropical Pacific, occurring approximately every three to five years. During the peak of an El Niño, sea surface temperatures (SSTs) in the eastern tropical Pacific can be several degrees warmer than the climatological mean. The convective rainfall maximum is shifted towards the warm SST anomalies, and the associated anomalous latent heat release forces changes in the large scale atmospheric circulation over the Pacific basin (and this in turn helps to maintain the anomalous SST). In addition, there is evidence that the extratropical

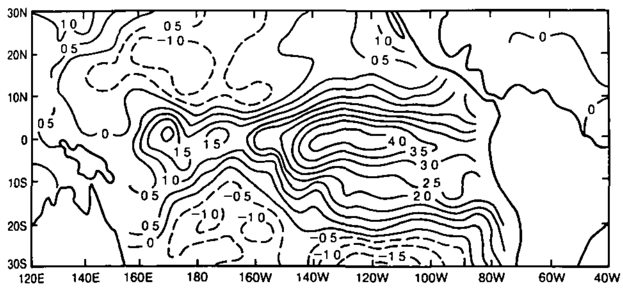


Figure 4.16: Sea surface temperature anomaly (°C) for January 1983. Dashed contours are negative. (Fennessy and Shukla 1988b)

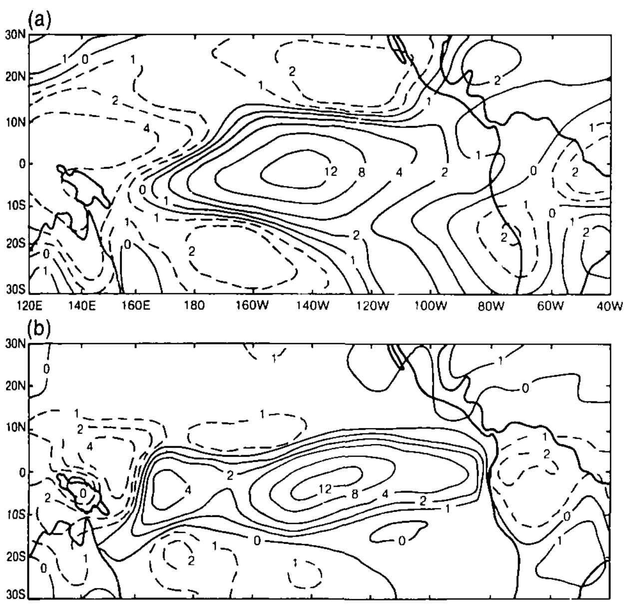


Figure 4.17: Anomalies of mean convective precipitation (mm day^{-1}) from mid-December 1982 to mid February 1983. (a) Observed, (b) Simulated. Observed precipitation anomalies are calculated from OLR data, simulated anomalies are the average of three 60-day integrations with the Goddard Laboratory for Atmospheres GCM starting from 15, 16 and 17 December (Fennessy and Shukla, 1988b)

jet streams are significantly displaced from their climatological positions during strong El Niño events, particularly over the North Pacific and North America (Fennessy and Shukla, 1988a).

Before the capability of coupled atmosphere/ocean GCMs to simulate El Niño and its teleconnections can be assessed, it is first necessary to assess whether the atmospheric component of these models can respond realistically to observed SST anomalies. There has been considerable research on this problem in recent years as part of the WCRP TOGA programme (see for example, Nihoul, 1985, WMO, 1986, 1988) following Rowntree's (1972) initial studies. Figure 4.16 shows the SST anomaly in the Pacific for January 1983, with a maximum of 4°C in the eastern Pacific. An example of the observed and simulated precipitation anomalies from mid-December 1982 to mid-February 1983 is shown in Figure 4.17 (Fennessy and Shukla, 1988b), where a close correspondence across the central and eastern Pacific as well as over Indonesia and northern Australia can be seen. The observed and simulated anomalies in the zonal departure of the 200mb stream function for this same period are shown in Figure 4.18. The strong anticyclonic couplet straddling the equator in the central and eastern Pacific and the weaker couplet to the east in the tropics are well simulated in the model though their magnitudes are too weak. In the extratropics over the Pacific and North America, an eastward-shifted PNA-like pattern (Wallace and Gutzler, 1981), with cyclonic anomaly over the North Pacific and anticyclonic anomaly over Canada, is present in both the observed and simulated anomaly fields.

While the results above indicate that atmospheric GCMs can respond realistically to El Niño SST patterns, comparison of different GCMs' responses to identical SST anomalies underscores the importance of a realistic model control climate (Palmer and Mansfield, 1986). For example, the responses of models to an identical El Niño SST anomaly are significantly different in those regions where the models control climates differ markedly. In such experiments there are also errors in the simulated anomalous surface heat flux and wind stress, which would give rise to quite different SST if used to force an ocean model.

Comparative extended-range forecast experiments using initial data from the El Niño winter of 1982/3 with both observed and climatological sea surface temperatures, showed that in the tropics the use of the observed SST led to consistent improvements in forecast skill compared with runs with climatological SST, while in the extratropics the improvements were more variable (WMO, 1986). These results suggest that, in the winter-time extratropics, the internal low-frequency variability of the atmosphere is as large as the signal from tropical forcing by El Niño, while in the tropics the influence of the El Niño forcing is dominant.

In summary, we may conclude that, given a satisfactory estimate of anomalous SST in the tropical Pacific, atmospheric GCMs can provide a realistic simulation of seasonal tropical atmospheric anomalies at least for intense El Niño episodes. This success serves to increase our confidence in these models and in their response to surface forcing. Problems associated with climate drift, particularly in relation to fluxes at the ocean-atmosphere interface,

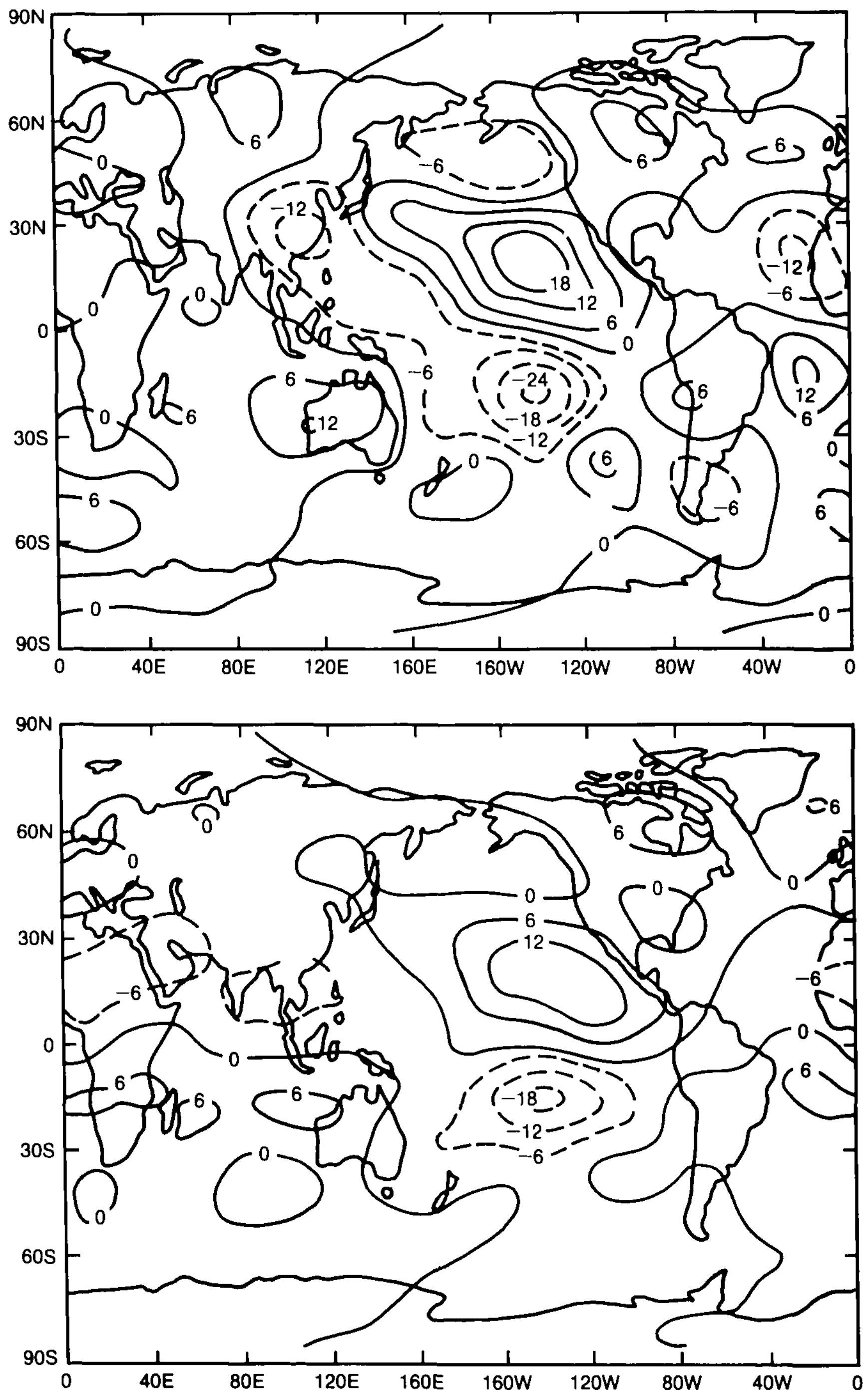


Figure 4.18: Mean departure from the zonal mean of anomalies of the 200 hPa stream-function ($10^6 m^2 s^{-1}$). Dashed contours are negative. Other details as in Figure 4.17. (Upper panel shows observed, lower panel shows simulated).

however, have so far inhibited consistently successful El Niño prediction with coupled ocean-atmosphere GCMs, although recent simulations have reproduced some aspects of observed El Niño phenomena (Sperber et al., 1987; Meehl, 1990).

4.5.2 *Sahelian Drought*

Over much of the 1970s and 1980s, sub-Saharan Africa experienced persistent drought, while in the 1950s rainfall was relatively plentiful. Climate models have been useful in determining the mechanisms responsible for the drought, although the successful prediction of seasonal rainfall anomalies requires further model development.

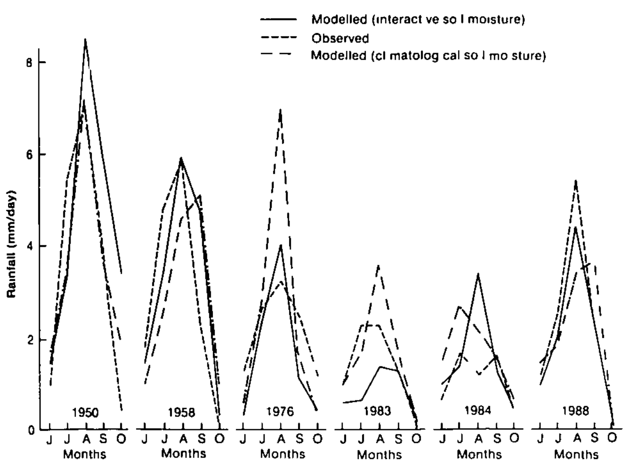


Figure 4.19: Simulated and observed Sahel rainfall in the six years for which simulations have been made Simulations were made both with climatological and interactive soil moisture in the UKMO GCM (version not shown in Table 3 2(a)) (Folland, 1990 - personal communication)

A number of GCM studies have indicated that local changes in land surface conditions have an important influence on rainfall For example, Charney et al (1977), Sud and Fennessy (1982) and Laval and Picon (1986) have shown that an increase in land albedo over the Sahel can inhibit rainfall, while Rowntree and Sangster (1986) have shown that restriction of soil moisture storage (as well as albedo increases) can also have a substantial impact on rainfall in the Sahel Other experiments indicate that the climate of the Sahel is sensitive to changes in local vegetation cover

Further GCM experimentation has been described by Folland et al (1989), the UKMO GCM has now been run from observed initial conditions in March and forced with the observed SST for seven months of each of 1950, 1958, 1976, 1983, 1984 and 1988 (Folland, personal communication) For each of these years, two experiments were performed one with an interactive soil moisture parameterization, and one with fixed climatological soil moisture Figure 4 19 shows a comparison of the observed and simulated rainfall over the Sahel It is clear that the decadal time-scale trend in Sahel rainfall has been well captured Moreover, the results suggest that soil moisture feedback is not the main cause of the large modelled differences in rain between the wet and dry years, though it does contribute to the skill of the simulations Insofar as these decadal timescale fluctuations in large-scale SST are associated with internal variability of the ocean atmosphere system, it would appear that Sahel drought is part of the natural variability of the climate, although the physical mechanisms whereby SST influences Sahel rain clearly involve remote dynamical processes (Palmer, 1986)

In summary, atmospheric model experiments exhibit an ability to simulate some of the observed interannual variations in Sahel rainfall, given the correct SST patterns

4.5.3 Summer Monsoon

The monsoon, especially the Asian monsoon, displays significant seasonal variation and interannual variability, and the onset and retreat of the summer monsoons in Asia and Australia are associated with abrupt changes in the atmospheric general circulation (Yeh et al , 1959, McBride, 1987) An earlier or later monsoon onset, or a longer or shorter duration, usually causes flood or drought Therefore, not only the accuracy of the seasonal monsoon precipitation but also the accuracy of the monsoon timing are important aspects of a model's ability to simulate regional climate anomalies

In general, most atmospheric GCMs simulate the gross features of summer monsoon precipitation patterns though there are significant deficiencies (see Section 4 3 2), although this aspect of model performance has not been extensively examined, some models have been shown to simulate the monsoon onset and associated abrupt changes (Kitoh and Tokioka, 1987, Zeng et al , 1988) Part of the interannual variability of the summer monsoon has been found to be associated with anomalies in SST, both local (Kershaw, 1988) and remote For example, there is an apparent correlation between the strength of the Indian monsoon and SST in the eastern tropical Pacific, in the sense that a poor monsoon is generally associated with a warm east Pacific (Gregory, 1989)

4.6 Simulation of Extreme Events

The occurrence of extreme events is an important aspect of climate, and is in some respects more important than the mean climate Many relatively large-scale extreme events such as intense heat and cold, and prolonged wet and dry spells, can be diagnosed from climate model experiments (e g , Mearns et al , 1984) The ability of climate models to simulate smaller-scale extreme events is not well established, and is examined here only in terms of tropical storm winds and small-scale severe storms

Krishnamurti and Oosterhof (1989) made a five-day forecast of the Pacific typhoon Hope (July 1979) using a 12-layer model, with different horizontal resolutions At a resolution of 75 km the model's forecast of strong winds was close to the observed maximum, while with a resolution of 400 km the maximum wind was less than half of the correct value and was located much too far from the centre of the storm Since most climate models have been run with a resolution of 300 km or more they do not adequately resolve major tropical storms and their associated severe winds It may be noted, however, that by using appropriate criteria, Manabe et al (1970), Haarsma et al (1990), and Broccoli and Manabe (1990), have reported that climate models can simulate some of the geographical structure that is characteristic of tropical cyclones

Neither models with resolutions of 300 - 1000 km nor current numerical weather prediction models simulate individual thunderstorms, which are controlled by mesoscale dynamical processes However, they do simulate variables that are related to the probability and intensity of severe weather such as thunderstorms, hail, wind gusts and tornadoes If the appropriate variables are saved from a climate model, it should therefore be possible to determine whether the frequency and intensity of severe convective storms will change in an altered climate

In summary, while changes in the occurrence of some types of extreme events, such as the frequency of high temperatures, can be diagnosed directly from climate model data, special techniques are needed for inferring changes in the occurrence of extreme events such as intense rainfall or severe local windstorms

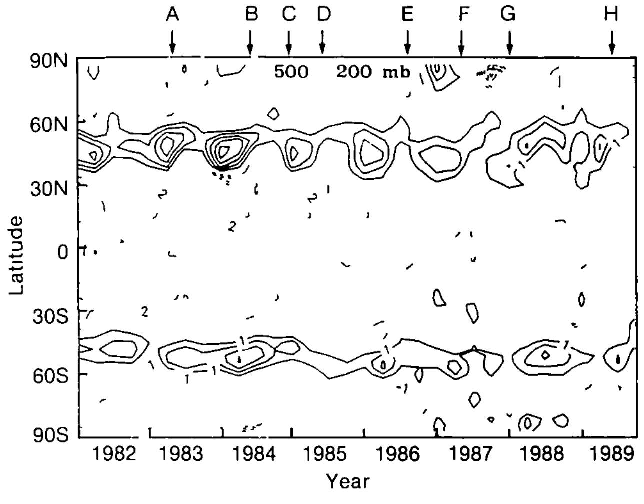


Figure 4.20: Zonal and vertical means (500-200 hPa) of zonal wind errors (forecast-analysis) of ECMWF day-10 forecasts Contours drawn from seasonal mean values at intervals of 1 ms^{-1} (zero line suppressed) The lettering at the top of the diagram indicates times of major model changes

4.7 Validation from Operational Weather Forecasting

As was recognized at the outset of numerical modelling, the climatological balance of a weather forecast model becomes of importance after a few days of prediction, while an extension of the integration domain to the whole globe becomes necessary This means that modelling problems in numerical weather prediction (NWP), at least in the medium and extended range, have become similar to those in modelling the climate on timescales of a few months (Bengtsson, 1985)

The development of numerical models over the past several decades has led to a considerable improvement in forecast skill This advance can be seen in the increased accuracy of short-range predictions, in the extension of the time range of useful predictive skill, and in the increase in the number of useful forecast products A systematic evaluation of the quality of short range forecasts in the Northern Hemisphere has been carried out by the WMO/CAS Working Group on Weather Prediction Research covering the 10-year period 1979 1988 (Lange 1989) Under this intercomparison project operational forecasts from several centres have been verified on a daily basis, considerable improvement has taken place, esp ecially in the tropics and in the Southern Hemisphere (Bengtsson, 1989)

Of particular importance for climate modelling are model errors of a systematic (or case-independent) nature Such model deficiencies give rise to a climate drift in which the model simulations generally develop significant differences from the real climate Although there has been a progressive reduction of systematic errors in NWP models as noted above a tendency to zonalization of the flow is still present Figure 4 20 shows the evolution of 10-day errors of the zonal wind component in the ECMWF model, and illustrates the global character of the model's errors (Arpe, 1989) The systematic errors typical of forecast models include the tendency for reduced variability in large-scale eddy activity, which shows up synoptically as a reduction in the frequency of blocking and quasi-stationary cut-off lows (see also Section 4 2 4)

In summary, the development and sustained improvement of atmospheric models requires long periods of validation using a large ensemble of different weather situations Confidence in a model used for climate simulation will therefore be increased if the same model is successful when used in a forecasting mode

4.8 Simulation of Ocean Climate

The ocean influences climate change on seasonal, decadal and longer timescales in several important ways The large-scale transports of heat and fresh water by ocean currents are important climate parameters, and affect both the overall magnitude as well as the regional distribution of the response of the atmosphere-ocean system to greenhouse warming (Spelman and Manabe, 1985) The circulation and thermal structure of the upper ocean control the penetration of heat into the deeper ocean and hence also the timescale by which the ocean can delay the atmospheric response to CO_2 increases (Schlesinger et al , 1985) Vertical motions and water mass formation processes in high latitudes are controlling factors (besides chemical and biological interactions) for the oceanic uptake of carbon dioxide through the sea surface, and thus influence the radiative forcing in the atmosphere To be a credible tool for the prediction of climate change, ocean models must therefore be capable of simulating the present circulation and water mass distribution, including their seasonal variability

4.8.1 Status of Ocean Modelling

The main problems in ocean modelling arise from uncertainties in the parameterization of unresolved motions, from insufficient spatial resolution, and from poor estimates of air-sea fluxes In general, ocean modelling is less advanced than atmospheric modelling, reflecting the greater difficulty of observing the ocean, the much smaller number of scientists/institutions working in this area, and the absence until recently of adequate computing resources and of an operational demand equivalent to numerical weather prediction Global ocean models have generally followed the work by Bryan and Lewis (1979), they mostly have horizontal resolutions of several hundred kilometres and about a dozen levels in the vertical Coarse grid models of this type have also been used in conjunction with atmospheric GCMs for studies of the coupled ocean-atmosphere system (see Section 4 9)

The performance of ocean models on decadal and longer timescales is critically dependent upon an accurate parameterization of sub-gridscale mixing The main contribution to poleward heat transport in ocean models arises from vertical overturning whereas the contribution associated with the horizontal circulation is somewhat smaller Most models underestimate the heat transport and simulate western boundary currents which are less intense and broader than those observed The need for eddy-resolving models (e g , Semtner and Chervin, 1988) in climate simulations is not yet established Coarse vertical resolution, on the other hand can significantly alter the effective mixing and thus influence the overturning and heat transport in a model The main thermocline in most coarse-resolution simulations is considerably warmer and more diffuse than observed a result probably due to a deficient representation of lateral and vertical mixing

An important component of the deeper ocean circulation is driven by fluxes of heat and fresh water at the sea surface In the absence of reliable data on the surface fluxes of heat and fresh water, many ocean modellers have parameterized these in terms of observed sea surface temperature and salinity The fluxes diagnosed in this way vary considerably among models While surface heat flux and surface temperature are strongly related there is no correspondingly strong connection between surface fresh water flux and surface salinity a consequence is the possible existence of multiple equilibrium states with significant differences in oceanic heat transport (Manabe and Stouffer, 1988)

4.8.2 Validation of Ocean Models

The distribution of temperature, salinity and other water mass properties is the primary information for the validation of ocean models Analysed data sets (e g , Levitus, 1982) have been very useful although the use of original hydrographic data is sometimes preferred The distributions of transient tracers, in particular tritium/helium-3 and C-14 produced by nuclear bomb tests, and CFCs, place certain constraints on the circulation and are also useful diagnostics for model evaluation (Sarmiento 1983, Toggweiler et al , 1989) The poleward transport of heat in the ocean zonal hydrographic sections (e g the annual mean of 1 0-1 2 PW at 25N in the North Atlantic found by Bryden and Hall, 1980) appears to have high reliability, and zonal sections planned in the World Ocean Circulation Experiment could significantly improve ocean heat transport estimates

Direct observations of the fluxes of heat, fresh water and momentum at the sea surface are not very accurate, and would not appear to be viable in the near future However monitoring upper ocean parameters, in particular the heat and fresh water content in connection with ocean circulation models, can contribute to an indirect determination of the surface fluxes The validation of ocean models using large data sets can in general be made more efficient if appropriate inverse modelling and/or data assimilation procedures are employed

The validation of ocean models may conveniently be considered separately on the time-scales of a season, a decade and a century The goal is a model which will correctly sequester excess heat produced by greenhouse warming and produce the right prediction of changing sea surface temperatures when it is run in coupled mode with an atmospheric model

Seasonal timescales in the upper ocean are important for a simulation of greenhouse warming both because seasonal variations are a fundamental component of climate and because of the seasonal variation of vertical mixing in the ocean Sarmiento (1986) has demonstrated that the seasonal variation of mixed layer depths can be simulated with a sufficiently detailed representation of the upper ocean

Perhaps the best way to check ocean models on decadal time scales is to simulate the spread of transient tracers Data sets based on these tracers provide a unique picture of the downward paths from the surface into the ocean thermocline and deep water The invasion of tritium into the western Atlantic about a decade after the peak of the bomb tests is compared with calculations by Sarmiento (1983) in Figure 4 21 The data show that the tritium very rapidly invades the main thermocline but only a small fraction gets into deep water The model succeeds in reproducing many of the important features of the data such as the shallow equatorial penetration and the deep penetration in high latitudes The main failure is the lack of

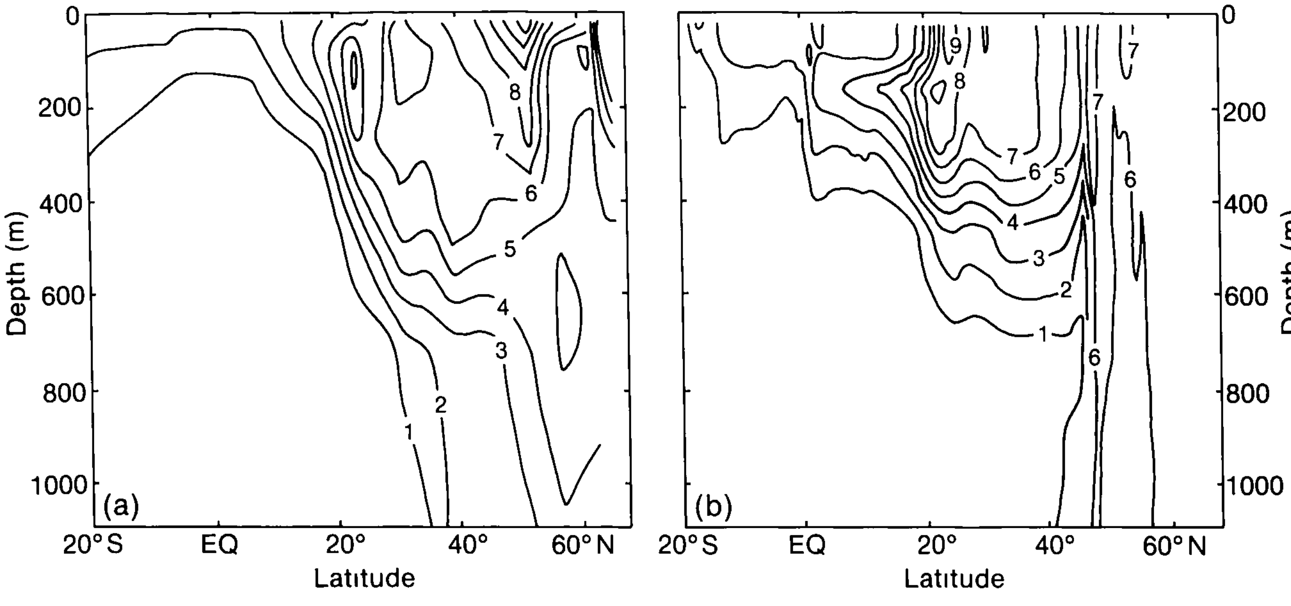


Figure 4.21: Tritium in the GEOSECS section in the western North Atlantic approximately one decade after the major bomb tests (a) GEOSECS observations, (b) as predicted by a 12-level model (Sarmiento, 1983) In Tritium units

penetration at 30-50°N, which may be related to some inadequacy in simulating cross-Gulf Stream/North Atlantic Current exchange (Bryan and Sarmiento, 1985) A notable result is the importance of seasonal convection for vertical mixing An obvious difficulty in using transient tracer data to estimate the penetration of excess heat from greenhouse warming is the feedback caused by changes in the density field A very small temperature perturbation should behave like a tracer, but as the amplitude increases, the perturbation will affect the circulation (Bryan and Spelman 1985)

In many parts of the ocean, salinity is an excellent tracer of ocean circulation The salinity field of the ocean is extremely difficult to simulate The reason for this is that sources and sinks of fresh water at the ocean surface have a rather complex distribution, much more so than the transient tracers Water masses with distinctive salinity signatures lie at the base of the thermocline in all the major oceans In the Southern Ocean and the Pacific, these water masses are characterized by salinity minima and relatively weak stability The characteristic renewal timescale of these water masses is greater than a decade but less than a century a range very important for greenhouse warming At present, these water masses have not been simulated in a satisfactory way in an ocean circulation model

In summary, oceanic processes are expected to play a major role in climate change The satisfactory representation of vertical and horizontal transport processes (and of sea-ice) are thus of particular importance There is encouraging evidence from tracer studies that at least some aspects of these mixing processes are captured by ocean models However, at present, ocean models tend to underestimate heat transport

4.9 Validation of Coupled Models

While much has been learned from models of the atmosphere and ocean formulated as separate systems, a more fundamental approach is to treat the ocean and atmosphere together as a coupled system This is unlikely to improve on the simulation of the time-meaned atmosphere and ocean when treated as separate entities (with realistic surface fluxes), since the average SST can only become less realistic, however, it is the only way in which some of the climate system's long-term interactions, including the transient response to progressively increasing CO_2, can be realistically studied (see Section 6)

Typical of the current generation of coarse-grid coupled GCMs is the simulation shown in Figure 4 22 from Washington and Meehl (1989) The general pattern of zonal mean temperature is reproduced in both atmosphere and ocean in this freely interacting coupled model, although during the time period simulated the temperature in the deeper ocean is still strongly related to the initial conditions On closer inspection, comparison of the simulated near-surface temperatures in the ocean with observed values from Levitus (1982) shows warmer-than-observed temperatures in the high latitude southern oceans, colder-than-observed temperatures in the tropics, and colder-than-observed temperatures at high northern latitudes The latter can be traced to the North Atlantic where the lack of a well-defined Gulf Stream and associated thermohaline circulation inhibits the transport of

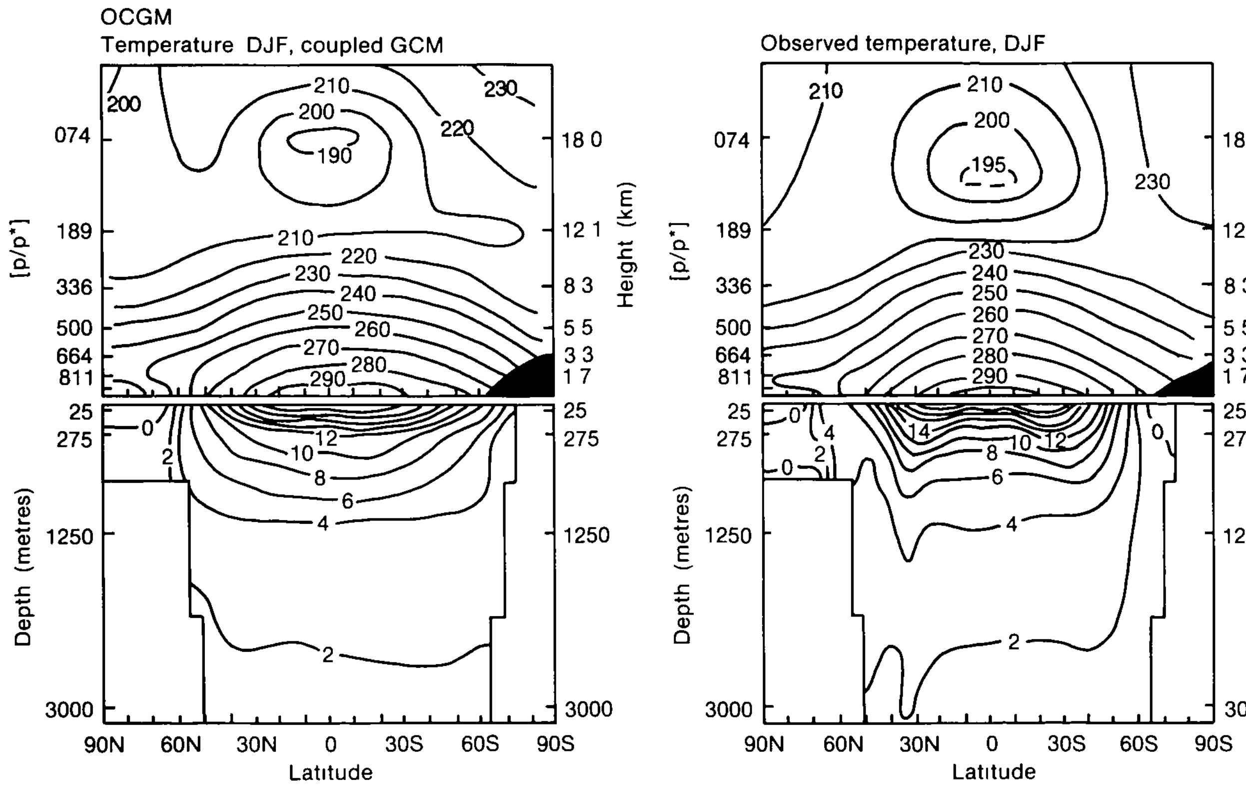


Figure 4.22: Zonal mean temperatures for December-January February for atmosphere and ocean as simulated in a 30 year integration with (left) the NCAR coupled model (Washington and Meehl, 1989) and (right) from observations Observed atmospheric temperatures are from Newell et al (1972) observed ocean temperatures are from Levitus (1982) The unlabelled contour in the observed near the tropical surface is 295K The maximum ocean temperatures in this same region are 27°C (observed) and 25°C (computed)

heat to those latitudes Similar patterns of systematic sea-surface temperature errors have been found in other coupled models (Gates et al , 1985, Manabe and Stouffer 1988), and their effects on the simulated surface heat flux have been examined by Meehl (1989)

In view of such errors, a practical decision faces those designing coupled models On the one hand they can decide that the systematic errors, while serious in terms of the control integration do not prevent the useful interpretation of results from sensitivity experiments On the other hand, they may consider that the systematic errors represent a significant bias in the control run and would affect the results of sensitivity experiments to an unacceptable degree The alternative then is to somehow adjust for the errors in the control run to provide a more realistic basic state for sensitivity experiments Such techniques have been devised and are variously called flux correction" (Sausen et al 1988) or flux adjustment (Manabe and Stouffer, 1988) These methods effectively remove a large part of the systematic errors and such coupled simulations are closer to observed conditions However, since the correction terms are additive the coupled model can still exhibit drift and the flux correction terms cannot change during the course of a climate change experiment (i e , it is effectively assumed that the model errors are the same for both the control and perturbed climates)

One way to validate coupled models is to analyse the simulated interannual variability, a fundamental source of which is associated with the El Niño - Southern Oscillation (ENSO) (see also Section 4 5 1) The current generation of coarse-grid coupled models has been shown to be capable of simulating some aspects of the ENSO phenomenon (Sperber et al 1987 Meehl 1990 Philander et al 1989) although the simulated intensity is in general too weak Ultimately a coupled climate model should be verified by its simulation of the observed evolution of the atmosphere and ocean over historical times For hypothetical future rates of CO_2 increase current coupled GCMs at least indicate that the patterns of the climate s transient response are likely to be substantially different in at least some ocean regions from those given in equilibrium simulations without a fully interacting ocean (Washington and Meehl 1989 Stouffer et al , 1989 see also Section 6)

In summary coupled models of the ocean atmospheric system are still in an early stage of development and have so far used relatively coarse resolution Nevertheless, the large scale structures of the ocean and atmosphere can be simulated with some skill using such models and current simulations give results that are generally similar to those of equilibrium models (see Sections 5 and 6)

4.10 Validation from Palaeo-Climate

Studies of palaeo-climatic changes are an important element in climate model validation for two reasons

1) they improve our physical understanding of the causes and mechanisms of large climatic changes so that we can improve the representation of the appropriate processes in models, and
2) they provide unique data sets for model validation

4.10.1 Observational Studies of the Holocene

The changes of the Earth's climate during the Holocene and since the last glacial maximum (the last 18,000 years) are the largest and best documented in the palaeo climatic record, and are therefore well-suited for model validation, the data sets are near-global in distribution, the time control (based upon radiocarbon dating) is good, and estimates of palaeo-climatic conditions can be obtained from a variety of palaeo-environmental records, such as lake sediment cores, ocean sediment cores, ice cores, and soil cores At the last glacial maximum there were large ice sheets in North America and northern Eurasia, sea-level was about 100m below present, the atmospheric CO_2 concentration was around 200ppm, sea-ice was more extensive than at present, and the patterns of vegetation and lake distribution were different from now During the last 18,000 years, we therefore have the opportunity to observe how the climate system evolved during the major change from glacial to present (interglacial) conditions CLIMAP Project Members (1976 1981) and COHMAP Members (1988) have assembled a comprehensive data set for the climate of the last 18,000 years as summarized in Figure 4 23

The period from 5 5-6kbp (thousand years before present) is probably the earliest date in the Holocene when the boundary conditions of ice-sheet extent and sea level were analogous to the present There is also general agreement that vegetation was close to equilibrium with the climate at this time Radiocarbon dating of most of the sources of stratigraphic data allows an accuracy of better than plus-or-minus 1000 years in the selection of data for the purposes of making reconstructions The earlier period around 9kbp is of particular interest because the differences of the radiative forcing from the present were particularly large (Berger, 1979), although there was still a substantial North American ice sheet

4 10.2 Model Studies of Holocene Climate

Several atmospheric GCMs have been used to simulate the climate of the 18kbp glacial maximum, and have helped to clarify the relative roles of continental ice sheets, sea-ice, ocean temperature and land albedo in producing major shifts in circulation, temperature and precipitation patterns (Gates, 1976a, b, Manabe and Hahn, 1977, Kutzbach and Guetter, 1986, Rind 1987) In addition to specifying land-based ice sheets and changed land albedos, these models also prescribed SSTs and sea-ice extents Manabe and Broccoli (1985) successfully simulated the SSTs and sea-ice during the Last Glacial Maximum using an atmospheric GCM coupled to a mixed-layer ocean model, this

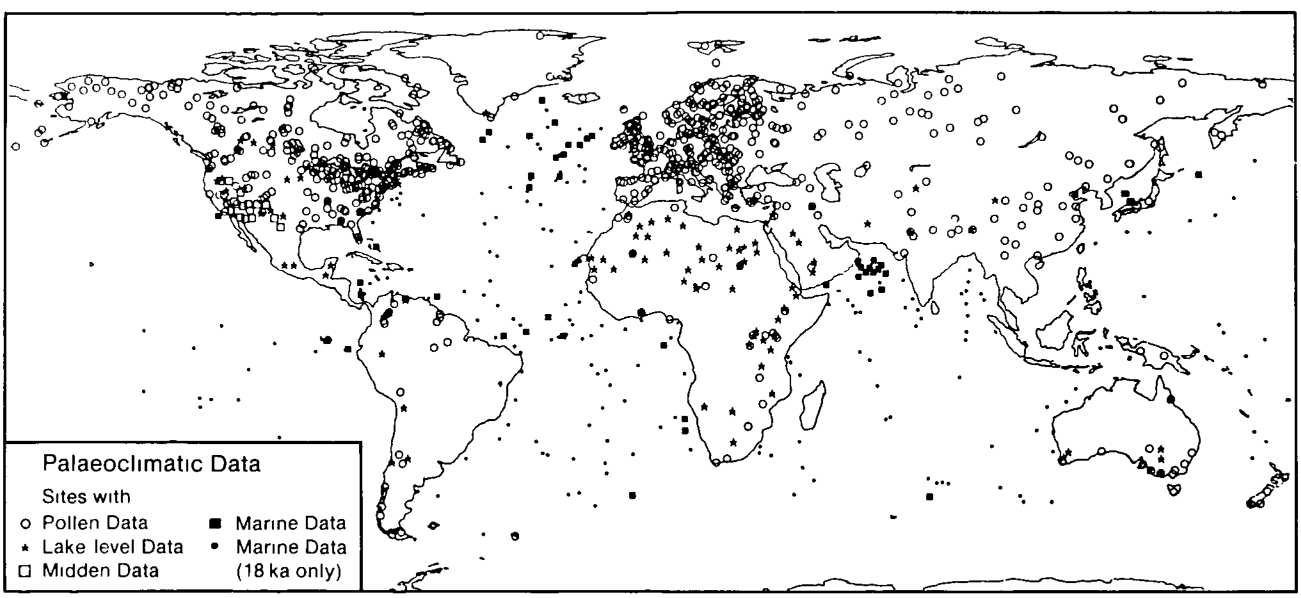


Figure 4.23: Data sites in the CLIMAP/COHMAP global palaeo-climatic data base (COHMAP Members, 1988)

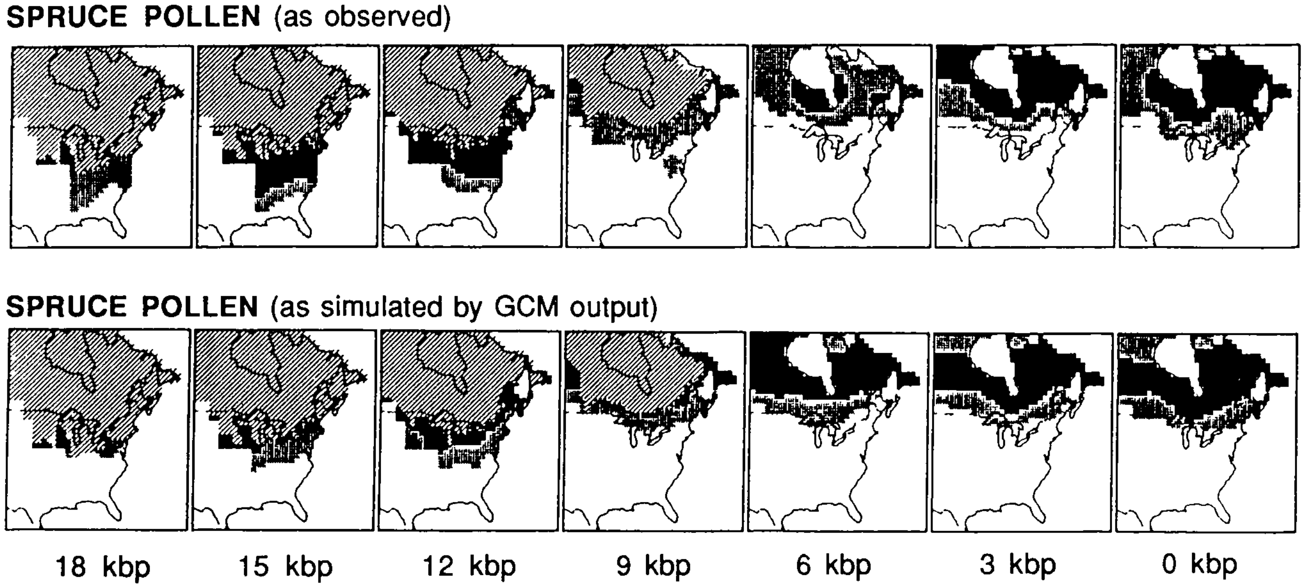


Figure 4.24: Maps showing observed (upper row) and simulated (lower row) percentages of spruce pollen for each 3000-year interval from 18,000 YBP to the present. The region with diagonal lines in the north is a digital representation of the location of the Laurentide ice sheet. Area of spruce abundance as determined by spruce pollen is shown by dark stippling for >20%, intermediate stippling for 5 to 20%, and light stippling for 1 to 5%. Simulation values were produced by applying the observed (present) association between spruce pollen and climatic variables to the temperature and precipitation values simulated by the climate model. (From COHMAP Members, 1988)

experiment also demonstrated the sensitivity of glacial age climate simulations to the lowered level of glacial-age atmospheric CO_2 (Broccoli and Manabe, 1987). The climate's sensitivity to orbital parameter changes has been confirmed through comparisons of model simulations with palaeo-climatic data both using atmospheric GCMs (Kutzbach and Guetter, 1986, Royer et al. 1984) and using atmospheric GCMs coupled to mixed layer ocean models (Kutzbach and Gallimore 1988, Mitchell et al., 1988). Manabe and Stouffer (1988), moreover, report evidence of two stable equilibria of a coupled atmosphere-ocean GCM that may be of importance for explaining abrupt short-term climate changes such as the cooling which occurred about 10,500 years ago. Rind et al. (1986), Overpeck et al. (1989) and Oglesby et al. (1989) have sought understanding of this cooling from model experiments in which cooling of the North Atlantic or the Gulf of Mexico was specified.

In general, palaeo-climate modelling studies have found encouraging agreement between simulations and observations on continental scales. For example, the COHMAP comparisons using the NCAR model show temperature and precipitation changes, 18kbp to present, that are generally consistent with observations in North America, at least as interpreted by the movement of spruce populations (Figure 4.24), while the simulated enhancement of northern tropical monsoons around 9kbp is also supported by palaeo-climatic data (COHMAP Members, 1988). On the other hand, palaeo-climate modelling studies, like their modern counterparts, also reveal regions and times where model and data disagree. For example, Figure 4.24 shows errors over southeastern North America from 18 to 12kbp associated with simulated summer temperatures that are too high, while Manabe and Broccoli (1985) obtain larger cooling of the tropical oceans at 18kbp than palaeo-climatic data suggest.

Because the mid-Holocene may have been warmer than now at least during northern summer, the question arises whether or not this period might be in some sense analogous to the climate with doubled CO_2. Gallimore and Kutzbach (1989) and Mitchell (1990) have discussed the differences in forcing (orbital parameters versus CO_2) and differences in the climatic response as simulated by GCMs. Even though the two types of forcing are very different, we can learn a great deal about our models by determining how well model experiments with orbitally-caused changes in solar radiation simulate the observed extent of increase in northern mid continent summer warmth and dryness, the decrease in Arctic sea-ice, and the increase in northern tropical precipitation.

4.10.3 Other Validation Opportunities

Studies of the previous interglacial around 125kbp by CLIMAP Project Members (1984) and Prell and Kutzbach (1987) among others show evidence for warmer conditions, especially in high latitudes, reduced sea-ice extent, and enhanced northern tropical monsoons. At this time CO_2 levels were above pre-industrial levels, sea-level was somewhat higher than now, the Greenland ice sheet was perhaps smaller, and orbital parameters favoured greatly enhanced Northern Hemisphere seasonality Because of the indications of warmth and relatively high CO_2 levels (relative to before and after 125 kbp) this period is also of interest for modelling and model validation studies Modelling experiments by Royer et al (1984) have emphasised the strong cooling from the equilibrium climate with orbital parameters for 125kbp to that for 115kbp However, data sets are not nearly as extensive or as well-dated as for the mid-Holocene

There is strong evidence that the first growth of ice sheets and the development of glacial/interglacial cycles began in North America and northern Eurasia around 2 4 million years ago, prior to this time the climate was presumably significantly warmer than at present This period may well be our only geologically-recent example of a climate that was significantly warmer than now over large areas However, the period poses many problems, including the marked differences from the present day in major global topographic features and the uncertainties in forcing conditions, these factors make it unsuitable for detailed model validation at the present time, although such simulations would be of considerable scientific interest

In summary, palaeo-climatic data have provided encouraging evidence of the ability of climate models to simulate climates different from the present, especially during the Holocene This indicates that further such data would be useful for climate model validation

4.11 Conclusions and Recommendations

This somewhat selective review of the performance of current global climate models has shown that there is considerable skill in the simulation of the present day climate by atmospheric general circulation models in the portrayal of the large-scale distribution of the pressure, temperature, wind and precipitation in both summer and winter As discussed in Section 4 1 2 the responses to perturbations can be given credence, provided simulated and observed patterns are sufficiently similar for corresponding features and mechanisms to be identified Recent models appear to satisfy this condition over most of the globe Although quantification of this conclusion is difficult it is supported by the skill demonstrated by atmospheric models in simulating, firstly, the circulation and rainfall changes associated with the El Niño ocean temperature anomalies and, secondly, the rainfall anomalies characteristic of wet and dry periods in the Sahel region of Africa when the observed sea surface temperature anomalies are used

On regional scales there are significant errors in these variables in all models Validation for selected regions shows mean surface air temperature errors of 2 to 3°C, compared with an average seasonal variation of 15°C The large-scale distribution of precipitation can be realistically simulated apart from some errors on sub-continental scales (1000 2000 km) whose locations differ between models Validation on these scales for selected regions shows mean errors of from 20% to 50% of the average rainfall depending on the model

The limited data available show that the simulated summer and winter soil moisture distributions in middle latitudes qualitatively reflect most of the large-scale characteristics of observed soil wetness Snow cover can be well simulated in winter except in regions where the temperature is poorly simulated The radiative fluxes at the top of the atmosphere, important for the response of climate to radiative perturbations, are simulated with average errors in the zonal mean as small as 5 Wm^{-2} There are, however, substantial discrepancies in albedo, particularly in middle and high latitudes

There has been a general reduction in the errors in more recent models as a result of increased resolution, changes in the parameterization of convection, cloudiness and surface processes, and the introduction of parameterizations of gravity wave drag In addition to the conclusions drawn from the validation of atmospheric model control simulations, our overall confidence in the models is increased by their relatively high level of accuracy when used for short and medium-range weather prediction, by their portrayal of low-frequency atmospheric variability such as the atmospheric response to realistic sea surface temperature anomalies (also referred to above), and by their ability to simulate aspects of the climate at selected times during the last 18,000 years Further confidence in atmospheric models would be obtained by their successful simulation of the climate changes shown by the observed instrumental record

Other opportunities for validation not considered in detail here include the simulation of variations in stratospheric temperature and circulation Models have been successful in simulating the impact on temperatures of the Antarctic ozone hole (Kiehl et al , 1988, Cariolle et al , 1990), although they have not successfully simulated the quasi-biennial oscillation in stratospheric wind and temperature

The latest atmospheric models, while by no means perfect, are thus sufficiently close to reality to inspire some confidence in their ability to predict the broad features of a doubled CO_2 climate at equilibrium, provided the changes in sea-surface temperature and sea-ice are correct The models used in simulating the equilibrium responses to increased greenhouse gases employ simple mixed-layer ocean models, in which adjustments to the surface fluxes have usually been made to maintain realistic present day sea-surface temperatures and sea-ice in the control experiments Our confidence in the ability of these models to simulate changes in the climate, including ocean temperatures and sea-ice, is enhanced by their successful simulation of aspects of the climates during and since the most recent ice age

Despite the present computational constraints on resolution, the performance of ocean models lends credence to our ability to simulate many of the observed large-scale features of ocean climate, especially in lower latitudes However, coupled ocean-atmosphere models exhibit characteristic errors which as yet can only be removed by empirical adjustments to the ocean surface fluxes This is due in part to the use of atmospheric and oceanic models of relatively low resolution, and in part to inadequate parameterizations of fluxes at the air-sea interface Nevertheless, the latest long runs with such models, discussed in Section 6, exhibit variability on decadal timescales which is similar to that observed (compare Figure 6 2 and Figure 7 10)

There is a clear need for further improvement of the accuracy of climate models through both increased resolution and improved parameterization of small-scale processes, especially the treatment of convection, clouds and surface effects in atmospheric GCMs, and mixing and sea-ice behaviour in oceanic GCMs Much further experience needs to be gained in the design of coupled models in order to avoid the equally unsatisfactory choices of accepting a progressive climatic drift or of empirically correcting the behaviour of the upper ocean These improvements and the associated extended simulations will require substantial amounts of computer time, along with increased coordination and cooperation among the world's climate modelling community Data from satellite programmes, such as EOS, and from field experiments are needed to provide more complete data sets for specifying land surface characteristics, for initialisation and validation of ocean simulations and to improve parameterizations Of particular value should be ERBE ISCCP and FIRE data for radiation and cloud, the ISLSCP and the HAPEX for land surface processes, the GEWEX for energy and water balances, and WOCE and TOGA data for the oceans

The validation of a number of atmospheric model variables has been handicapped by limitations in the available observed and model data In particular, future model assessments would benefit from improved estimates of precipitation and evaporation over the oceans, and of evaporation, soil moisture and snow depth over land, and by more uniform practices in the retention of model data such as snow-cover frequency and depth, and daily near-surface temperature extremes or means The generation of data suitable for validating cloud simulations deserves continuing attention, as does the assembly of palaeo-climatic data sets appropriate for climate model validation over the Earth's recent geological history The lack of appropriate data has also severely hindered the validation of ocean models Adequate data on the seasonal distribution of ocean currents and their variability and on salinity and sea-ice thickness are especially needed

Although the ten year atmospheric data set for 1963-73 compiled by Oort (1983) and the oceanographic set assembled by Levitus (1982) have been of great value in model assessment, the subsequent availability of 4 dimensional assimilation techniques and the expansion of observing platforms provide the opportunity for considerably improved data sets Indeed, many data sets now used by modellers for validation have been produced by global forecasting centres as a by-product of their operational data assimilation, although changes in forecast and assimilation techniques have led to temporal discontinuities in the data The proposal by Bengtsson and Shukla (1988) for a re analysis of observations over a recent decade (e g , 1979-1988) with a frozen up-to-date assimilation system is therefore of great potential value for climate model validation If carried out over additional decades, such a data set could also contribute to our understanding of how to distinguish between natural climate fluctuations and changes caused by increased greenhouse gases

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