Sensitivity of general circulation model performance to convective parametrization March 1997

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Table of contents

1 . Introduction

2 . The importance of shallow convection

3 . Sensitivity of climate simulations to the parametrization of deep convection

    3.1 Mean distribution of precipitation

    3.2 Sensitivity of simulated variability

    3.3 Impact of differing precipitation distributions

4 . Summary

REFERENCES

1. INTRODUCTION

The paper attempts to describe the sensitivity of aspects of global circulation model (GCM) performance to convective parametrization. This is a difficult task for a number of reasons. Firstly we have to define what is meant by "performance". From a numerical weather forecasting perspective a model must produces a good estimate of the three-dimensional structure and evolution of synoptic-scale weather systems. On climate time scales the model should capture a realistic mean distribution of thermodynamic variables (including cloud cover), wind and surface precipitation. For coupled ocean–atmosphere modelling the surface fluxes of heat and water vapour need to be correctly simulated. Also the simulated variability of the atmosphere (from diurnal through to the intraseasonal and interannual time scale) needs to be well captured. Convective parametrization has a large influence upon all these areas and it is difficult to make definitive statements covering each area in such a short paper.

Secondly, however, it is difficult to make definitive statements concerning the impact of convection schemes alone as other parametrizations (for example the boundary-layer scheme), together with the methods used to simulated resolved motions, also have a impact upon the ability of atmospheric models to simulated the features of the general circulation referred to above. Even if identical convection schemes were used in two GCMs in which other processes were represented in a substantially different manner, it would not be certain that the distribution of precipitation simulated, together with other features of the mean climate, would be similar. However, as will be illustrated below, some features of GCM simulations appear well correlated with certain convective processes.

This paper will be limited to illustrating areas where simulations of the global circulation are known to be sensitive to the representation of convection, emphasing the mean climate and variability of the tropics. Reference will be mainly made to recent studies using the climate version of the UK Meterological Office (UKMO) Unified Model

(UM) (described briefly by Gregory and Morris (1996) and having a horizontal resolution of 2.5 x 3.75^{o} latitude–longitude and 19 levels) and the T63 31-level configuration of a recent version of the ECMWF model (CY14R3). Other studies will also be referred to but only a summary of relevant results is provided; the reader is referred to the original material for greater details.

2. THE IMPORTANCE OF SHALLOW CONVECTION

When convection on a global scale is discussed it is often deep convection in the tropics that receives the greatest attention. Much recent work on the development of improved representations of convection for use in GCMs has concentrated upon this area. However, shallow convection also plays an important role in global circulation, and global simulations are sensitive to the manner in which it is parametrized. Although several mass-flux parametrizations represent shallow convection (Tiedtke 1989; Gregory and Rowntree 1990), comparatively less attention has been given to considering the effects of such processes.

To illustrate this sensitivity, Fig. 1 shows a latitude–height cross-section of zonal-mean omega for July 1987 from two 40-day integrations carried out using the ECMWF model, one with shallow convection parametrized by a mass-flux scheme, the second with no parametrization of shallow convection, together with the estimate of zonal-mean omega from the ECMWF ReAnalysis (ERA). With shallow convection neglected, the maximum intensity of the ascending branch of the Hadley circulation in the tropics is reduced and its lateral extent broadened. Other consequences of neglecting shallow-convective processes are a moistening of the boundary layer in the tropics and subtropics, drying of the free troposphere, a reduction in surface evaporation and large increases in boundary-layer cloud in the tropics and subtropics. These changes come about as shallow convection plays a crucial role in ventilating the boundary layer in the trade-wind regions, removing moisture from the boundary layer into the free troposphere. With the removal of shallow convection and a drier free troposphere in the descending branches of the Hadley circulation, cooling by infrared radiation is reduced, causing the intensity of the divergent circulation of the equatorial regions to reduce.

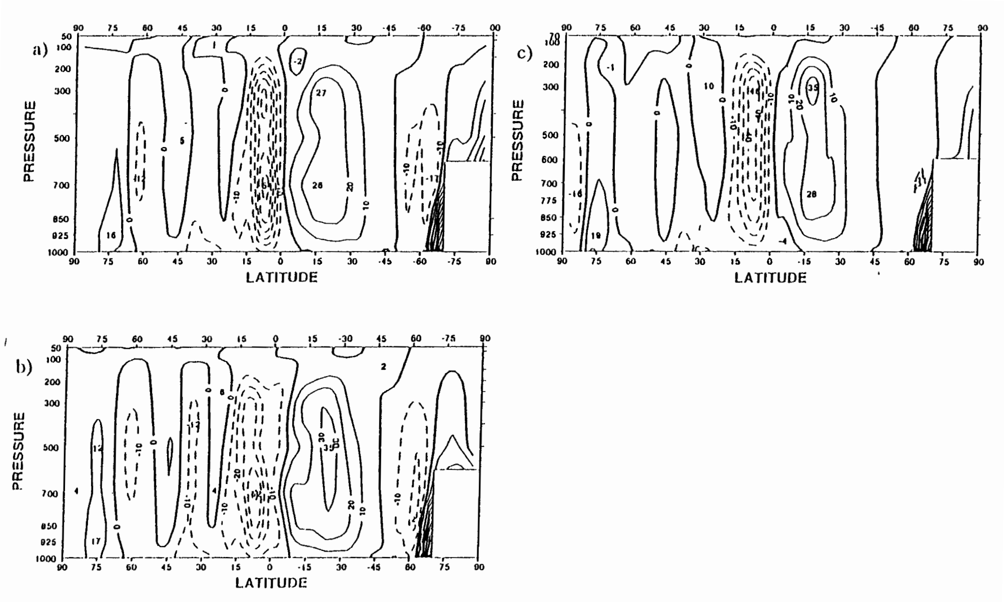


Figure 1. Height–latitude cross-sections of zonal-mean omega (mPa/s) for July 1987 from T63/L31 simulations of the ECMWF model (CY14R3) starting on 20 June 1987 (a) with shallow convection included into the convection scheme, (b) shallow convection switched off in the convection scheme and (c) from the ECMWF ReAnalysis.

A key parameter in a parametrization of shallow convection is the amount of saturated air which is transported through the inversion. Fig. 2 (from Tiedtke 1989) shows single-column simulations based upon ASTEX data in which the amount of mass transported through the inversion by convection (as measured by the parameter β - the fraction of mass within convection in the last buoyant layer that is allowed to ascend into the inversion layer) is varied. Large changes in the intensity of the hydrolapse and temperature inversion are seen as β is varied, with the boundary layer becoming moister and the inversion stronger when less of the updraught is detrained into the inversion layer. This is a consequence of less cloud water being available to cool and moisten the inversion layer by evaporation, balancing the warming and drying effects of large-scale subsidence. Note that removal shallow convection results in a very intense inversion and hydrolapse. Detailed observational studies of this processes are not available and current parametrizations are adjusted to achieve a realistic tropical circulation. However Large Eddy Simulation (LES) models are now able to capture many features of shallow convection and analysis of such detailed models across a variety of situations may be valuable for refining this area.

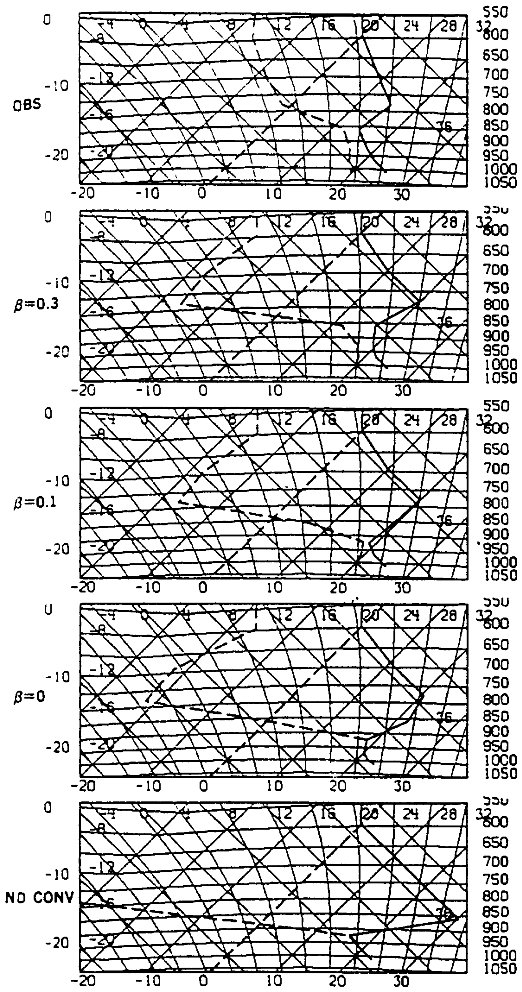


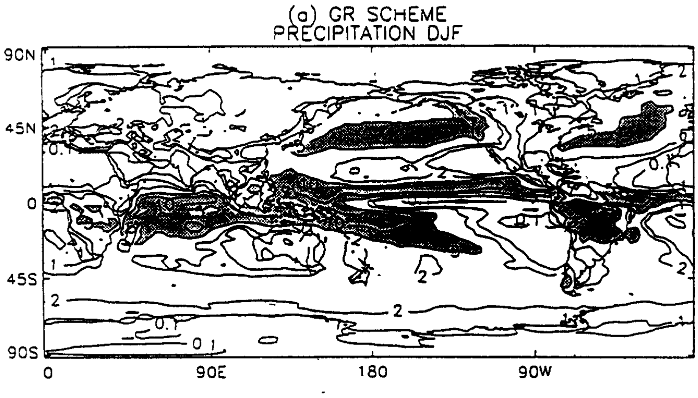
Figure 2. Single-column model simulations for ASTEX illustrating impact of the variation of the fraction of updraught mass flux in the last buoyant layer allowed to penetrate the inversion (β) upon boundary layer and inversion structure.

3. SENSITIVITY OF CLIMATE SIMULATIONS TO THE PARAMETRIZATION OF DEEP CONVECTION

3.1 Mean distribution of precipitation

Several authors have recognised that different convection schemes can have a tendency to produce different spatial patterns of precipitation, especially in the tropics. For example Hess *et al.* (1993) compared aqua-planet simulations using a T42 version of the NCAR Community Climate Model (CCM1) using a moist convective adjustment scheme and Kuo type scheme, which uses moisture convergence to determine the location and intensity of convection. They found that the Kuo scheme produced a double maximum of precipitation straddling the equator, with precipitation maxima at 10^{o}N/S, while using the moist convective adjustment scheme gave a single maximum of precipitation on the equator. Several other studies have indicated a similar sensitivity. Plots of mean December/January/February (DJF) precipitation for 1979–1988 from the Atmospheric Model Intercomparison Project (AMIP

- Gates (1992)) presented by Slingo *et al.* (1996) show that, in the majority of GCMs using some form of moisture convergence to estimate the location and intensity of deep convection, a double ITCZ structure develops over the west Pacific.



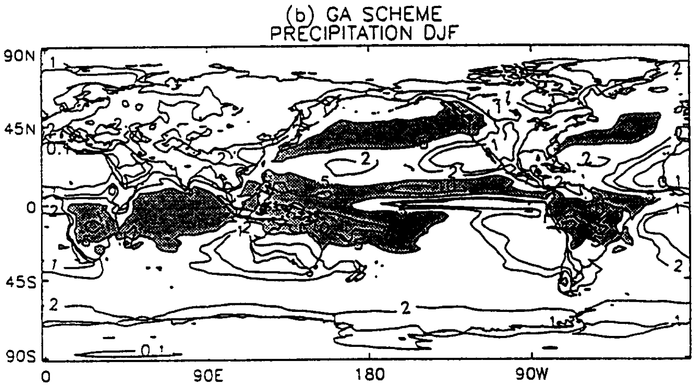


Figure 3. December/January/February precipitation from three-year simulations of the UKMO Unified Model (using climatological SSTs) with a mass-flux convection scheme (a) without and (b) with downdraughts.

Recent studies with the climate version of the UKMO Unified Model have also suggested that, apart from references to moisture convergence made by a convection scheme, several other factors also influence the distribution of precipitation. Fig. 3 shows the impact of including the effects of convective-scale downdraught processes into the convection scheme of Gregory and Rowntree (1990) upon the distribution of simulated precipitation during DJF (3-year mean). In the Pacific a strong ITCZ north of the equator is weakened with the introduction of downdraughts, with a shift of precipitation into the south Pacific Convergence Zone (SPCZ) and a reduced double maximum in precipitation straddling the equator in the Indian Ocean and west Pacific, in better agreement with observations. Monsoon circulations over the tropical continents are also intensified with the introduction of convective downdraughts, leading to improved rainfall amounts over tropical land masses. It should be noted that the convection scheme used (Gregory and Rowntree 1990) only uses instability to determine the location of convection and its intensity, i.e. no reference is made to the presence of moisture convergence as in the Kuo scheme.

Downgradient momentum transports can also affect the mean climatology of precipitation simulated by a GCM. Fig. 4 shows DJF precipitation from two annual cycle simulations performed with the UKMO Unified Model (Inness and Gregory 1996), one in which the vertical transport of horizontal momentum is neglected (10-year mean), the second in which it is included (3-year mean) using the scheme described by Gregory *et al.* (1996). Inclusion of momentum transports leads to a reduction in precipitation rates in the SPCZ and increased rainfall in the ITCZ north of the equator in the Pacific. A greater tendency to form a split ITCZ is noted in both the Indian Ocean and west Pacific. It is should be noted that the convection scheme used in these simulations contains the downdraught parametrization discussed above, indicating the large sensitivity to details of the convection scheme that the processes determining the distribution of precipitation have.

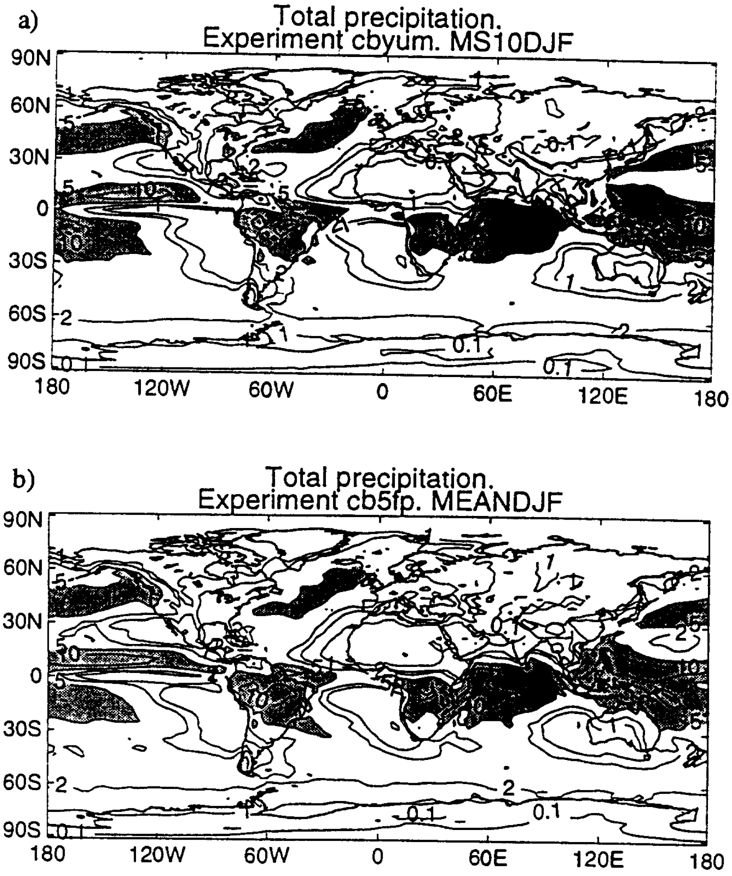


Figure 4. December/January/February precipitation for simulations of the UKMO Unified Model (using climatological SSTs) (a) without convective momentum transports (10-year mean) and (b) with convective momentum transports (3-year mean).

The reasons for this large model sensitivity is not well established. Hess *et al.* (1993) suggested that the ability of a model to represent transient synoptic waves played a role in organising the precipitation maximum off the equator. They found that in simulations using a Kuo type convection scheme, convergence due to transient eddies was a maximum off the equator. When a moist convective adjustment scheme was used, synoptic eddies were not well simulated. However, Inness and Gregory (1996) show that inclusion of convective momentum transports leads to a reduction of transient activity in the central Pacific, together with a greater tendency to splitting the ITCZ, perhaps suggesting that variability has less of a role in organising such precipitation patterns. However, there may be a strong link between the ability of a model to simulate the distribution of tropical precipitation accurately and its ability to simulate observed variability on a variety of time scales.

As commented upon above, there is a similarity in the tropical precipitation pattern in the UKMO Unified Model when either downdraught processes are neglected or downgradient convective momentum transports included. In both cases the band of precipitation located near the Philippines is excessive compared with observations and is associated with a depression track due to the model's attempt to simulated tropical depressions that tend to move in a manner similar to tropical cyclones, although being of much weaker intensity due to the coarse resolution of the model. Downdraughts have a tendency to cool and dry the convective subcloud layer, which may inhibit the formation of tropical depressions within the model by delaying the growth of intense convection. Hence, neglect of such processes may enhance the synoptic variability within the model and, where this occurs, enhance precipitation amounts.

Analysis of the simulations with and without convective momentum transports (Gregory *et al*. 1996) indicates that the inclusion of momentum transports decreases the vertical shear in the west Pacific north of the equator, a situation which may favour the formation of tropical depressions. Indeed, as commented upon later (figure 6a), synoptic variability increases in vicinity of the Philippines when convective momentum transports are included together with mean precipitation. These "observations" of model sensitivity may suggest that the pattern of mean precipitation simulated by a GCM may be closely tied to a models ability to simulate accurately tropical variability. Further comments will be made regarding this subject in the next section.

3.2 Sensitivity of simulated variability

Recent studies of GCM simulations have demonstrated that simulated variability in the tropics on a wide range of time scales is sensitive to the convection scheme employed. Slingo *et al.* (1994) presents results from perpetual January simulations of the UGAMP GCM (based upon a version of the ECMWF model) using both a Kuo and Betts–Miller scheme. They found that the Betts–Miller scheme gave a more realistic distribution of precipitation, with a maximum on the equator over the west Pacific anda narrow ITCZ, while the Kuo scheme gave a very much weaker ITCZ, with precipitation being broadly distributed over the tropical oceans. Associated with this, it was found that higher levels of variability were found in the tropics using the Betts–Miller scheme from time scales ranging from those associated with synoptic-scale systems (2–6 days) to intraseasonal periods (30–70 days).

This contrasting behaviour was attributed by Slingo *et al.* (1994) to the different ways the two schemes operated. For the Kuo scheme used in their study, the only criterion for convection to occur if the profile is conditionally unstable is that moisture convergence is present. In the tropics and subtropics this condition is almost always satisfied due to surface evaporation, and so the Kuo scheme continually acts, giving low instantaneous precipitation rates. With the Betts–Miller scheme, for deep convection to occur the integrated moisture within a column of the atmosphere has to be sufficient to support precipitation. This leads to a delay in the onset of precipitation events and a more intermittent response of the convection. Slingo *et al.* (1994) commented that, if the Kuo scheme was prevented from operating until the water in the column exceeds a critical value (as in the BMRC GCM—McAvaney *et al.* (1991)), then as the fraction of the moisture convergence precipitated by convection increases with relative humidity, spurious rainfall in the subtropics would be eliminated and more intense rainfall events generated in the deep tropics. This may lead to a better mean climate and simulation of variability.

However the link between closure and simulation of variability is complicated. Fig. 5 compares the variance of 850 mb relative vorticity for DJF 1987/88 from a simulation using a recent version of the ECMWF model (at T63 resolution) with that estimated from the ECMWF ReAnalysis data (ERA - at T106 resolution). The ECMWF model uses a mass-flux convection scheme (Tiedtke 1989) in which the mass flux at cloud base is linked to moisture convergence below cloud base. Also, the growth of the mass flux in the vertical in the lower half of the troposphere is linked to the moisture convergence into the column of the atmosphere. Hence, the location of convective activity and its intensity are strongly linked to the presence of moisture convergence. However, unlike the Kuo scheme used by Slingo *et al.* (1996), the location of deep convection is determined by moisture convergence due to atmospheric motion being greater than surface evaporation rather than that the sum of convergence and surface evaporation implying a moistening of a column of the model. Although errors can be seen in the spatial patterns of variability within the tropics in the model simulation (for example in the west Pacific, associated with errors in the mean distribution of precipitation - a strong ITCZ north of the equator in the Pacific and weak SPCZ) the level of variability within the ITCZ is comparable to that from the reanalysis (for example, in the southern Indian Ocean). This contrasts from results presented by Nordeng (1994) which suggested that an earlier version of the ECMWF model (T63/19 levels) with the same convection scheme underestimated tropical variability, especially in the west Pacific. However, many other parts of the mode'ls dynamics and physical parametrizations have changed since this study, indicating that the level of variability simulated is not a function of the convection scheme alone.

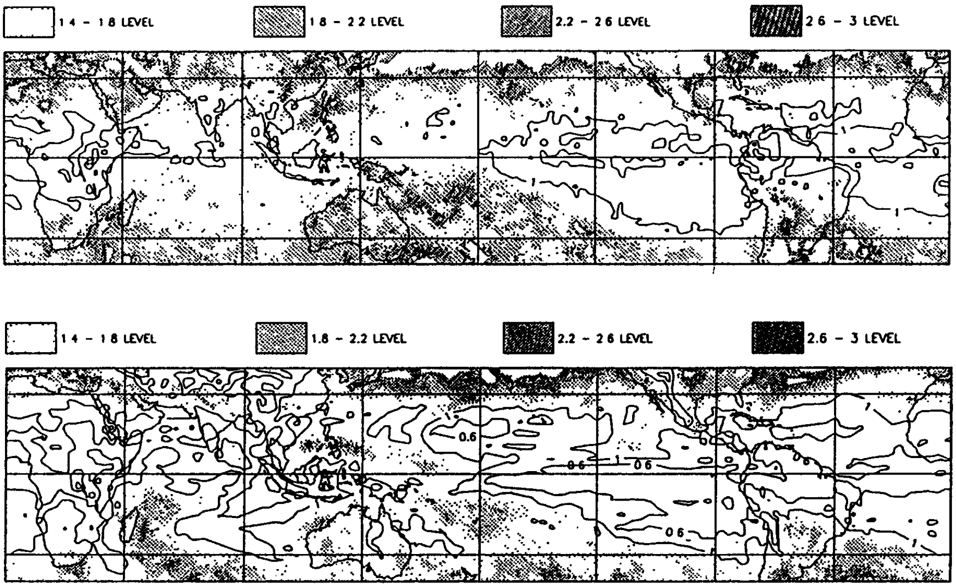


Figure 5. Mean variance of 850 mb relative vorticity for December/January/February 1987/88 for the tropics from (a) ECMWF ReAnalysis and(b) a 120-day T63/L31 simulation (from 1 Nov 1987) using version CY14R4 of the ECMWF model.

Simulated variability is also affected by the parametrization of convective momentum transports. Inness and Gregoy (1996) show that inclusion of such transports into the UKMO Unified Model changes not only the mean precipitation pattern (as shown in Fig. 4 above) but also the simulated variability from synoptic to intraseasonal time scale. Fig. 6 shows the variance of outgoing long-wave radiation on synoptic (2–10 days) and intraseasonal (25–70 days) time scales for the tropics (annual means) from two 3-year simulations, one without convective momentum transports, the other with them included. Synoptic variability is generally reduced along the ITCZ of the central and eastern Pacific and Atlantic oceans although, as noted earlier, it is increased in the west Pacific near the Philippines.

A similar sensitivity to convective momentum transports is seen in the ECMWF model, with simulated variability across the Pacific reducing when convective momentum transports are included into the model. However, near the Philippines, variability is increased in DJF. As noted earlier, this is associated with greater precipitation in both models in this region, indicating a link between variability and mean precipitation. This presence of a strong band of precipitation north of the equator in this region is not supported by observations and may suggest that counter-gradient transports associated with organised convective systems, not accounted for in the current momentum-transport parametrization, may play a role in regulating the formation of tropical depressions in this region. However, the impact of convective-scale downdraught processes discussed previously suggests that interactions between convection and the subcloud layer and ocean surface may also be important.

Fig. 6 also shows a weakening of the intraseasonal oscillation simulated by the Unified Model when convective momentum transports are included. Inness and Gregory (1994) also note that the neglect of downdraught processes weakens the strength of the intraseasonal oscillation. This is correlated with a stronger ITCZ north of the equator, weaker SPCZ and a greater tendency to split the ITCZ in DJF, bringing the model into poorer agreement with observations and an increased easterly bias in the seasonal cycle of the upper level flow of the tropics. Slingo *et al.* (1996), in a study of the ability of 15 different GCMs to simulate intraseasonal variability, note that those with a realistic distribution of precipitation with respect to SST in the Pacific and a unbiased seasonal cycle in tropical upper-level winds (associated with the latitudinal movement of convection) tended to give a strong signal at intra-seasonal time scales in tropical wind fields. The results from the UKMO model referred to here would corroborate this observation, indicating a link between the correct simulation of the mean climate and its seasonal variation with atmospheric variability.

3.3 Impact of differing precipitation distributions

It is important to ask whether such errors in precipitation patterns play a significant role in causing model systematic error in global circulation. A poor distribution of surface precipitation will affect surface fluxes and so impact upon the ability of coupled atmosphere–ocean models to simulated climate. However, the study of Ferranti *et al.* (1994) carried out using an earlier version of the ECMWF model (T42/19 levels) suggests that differences in the structure of convective activity in the Pacific is of more direct importance to the accurate simulation of atmospheric flow in the tropics and mid latitudes. This study considers the response of model systematic error to idealised sea surface temperature anomalies. The mean DJF precipitation distribution simulated by this earlier version of the ECMWF model showed a split ITCZ structure over the west and central Pacific, with a minimum of precipitation on the equator (Fig. 7 (a)), contrasting with observations which suggest a maximum on the equator. Increasing the SSTs in the vicinity of the equator by 2 K between 110^{o}E and 150^{o}E increased precipitation locally on the equator up to 16 mm/day (Fig. 7 (b)). Associated with this response is a strengthening of the upper-level westerly flow in the upper troposphere of the central and west Pacific, reducing an easterly bias in the control simulation (Fig. 8).

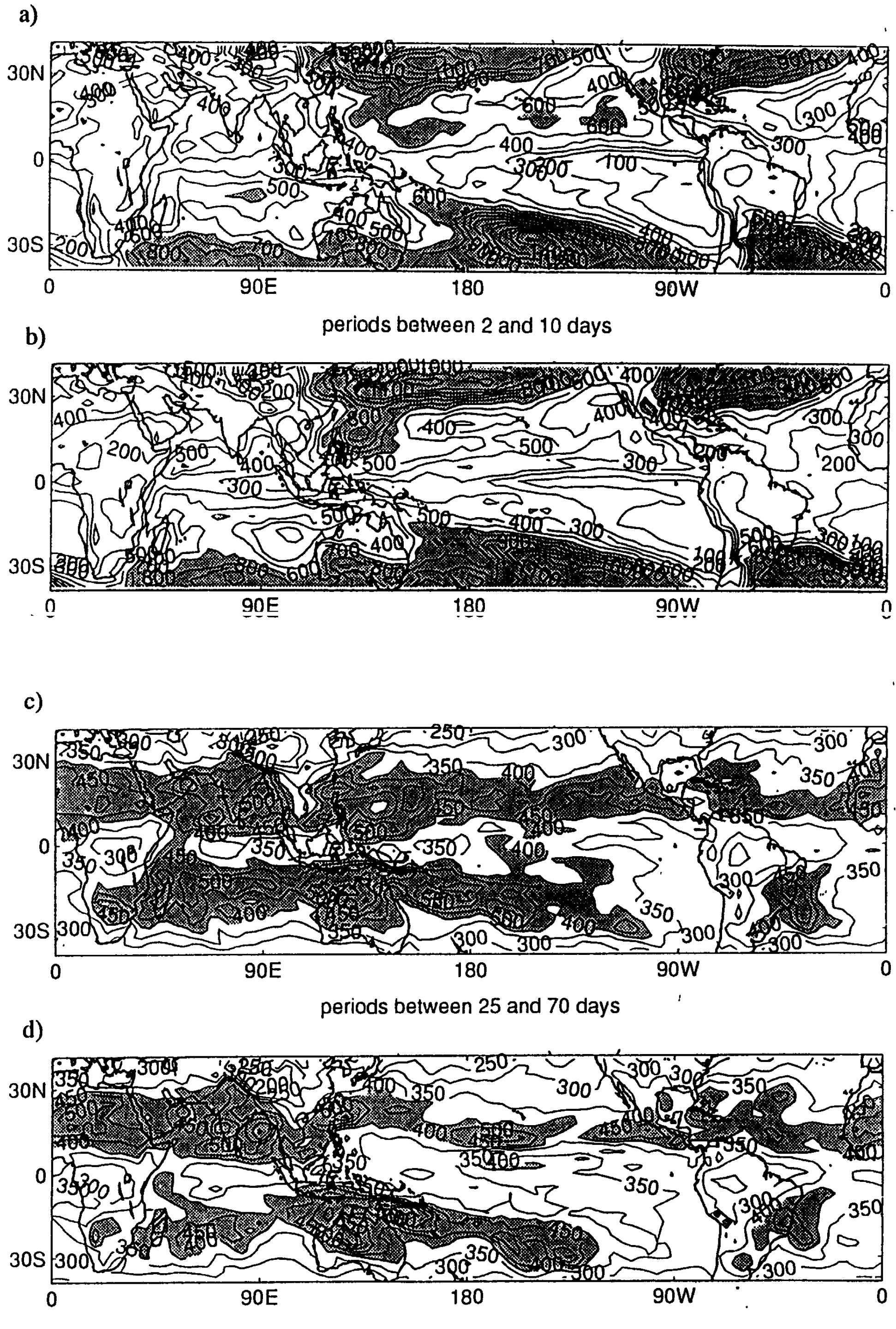


Figure 6. Annual-mean variance of outgoing long-wave radiation (3-year mean) for time periods (a) and (b) between 2 and 10 days, and (c) and (d) 25 and 70 days, for simulations of the UKMO Unified Model (a) and (c) without and (b) and (d) with convective momentum transports.

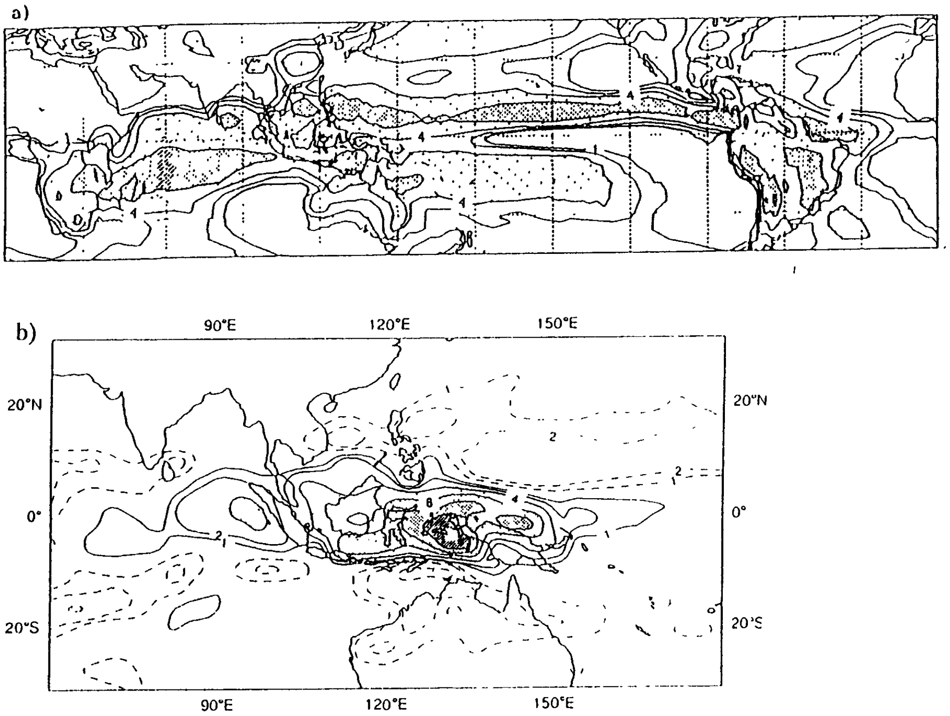


Figure 7. (a) December/January/February average precipitation using climatological SSTs (from an ensemble of 5 simulations) using a T63/L19 version of the ECMWF model, and (b) December/January/February precipitation response to an Indonesian SST anomaly (described in text).

The presence of westerly winds in the east Pacific is important for the interaction of the tropics and mid latitudes, with Rossby waves propagating northwards into the north Atlantic sector leading the to "PNA" pattern associated with blocking activity over Europe. Comparing the Tibaldi blocking index (Tibaldi and Molenti 1990) for the control and Pacific SST anomaly simulations (averaged over an ensemble of 6 simulations started 1 day apart) with that estimated from model analyses shows more realistic blocking occurrence in both Pacific and Atlantic when convection is forced to occur over the equator in the west Pacific. Similar sensitivity has been noted in an experiment of similar design with the climate version of the UKMO Unified Model (R. Stratton, personal communication) and leading one to speculate that a convection schemes that produce a precipitation pattern with a maximum on the equator of the west Pacific might lead to a better simulation by a GCM of the interaction between the tropics and mid latitudes.

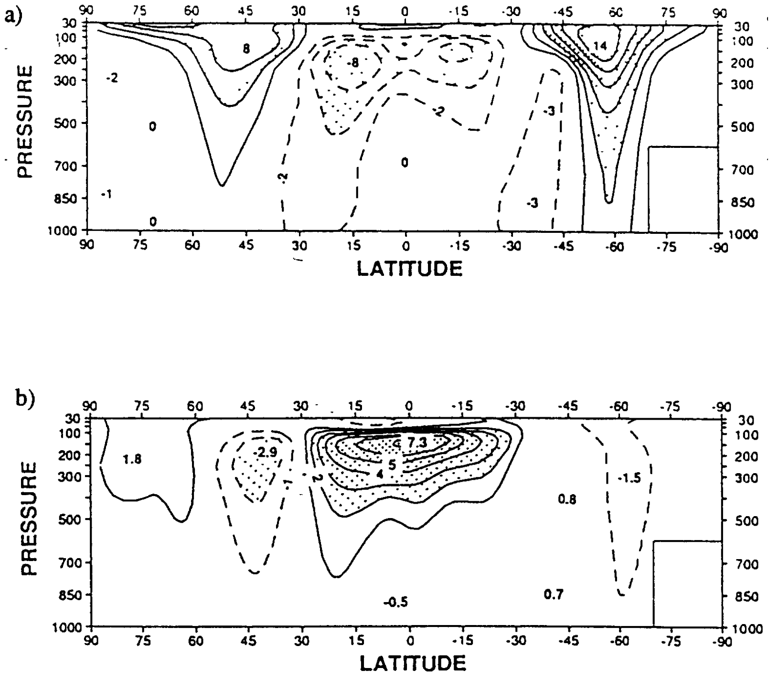


Figure 8. (a) December/January/February zonal-mean cross-section of systematic error in zonal-mean wind from an ensemble of five 120-day simulations using climatological SSTs, and (b) December/January/February zonal-mean cross-section of the response of zonal wind to an Indonesian SST anomaly.

4. SUMMARY

This paper has attempted to review the impact of convection upon the ability of convection to simulate accurately aspects of the general circulation. As stated in the introduction, it has not attempted to be comprehensive but has concentrated upon the circulation and variability of the tropics, although possible consequences of errors there for mid-latitude circulations have been briefly commented upon. It is clear that details of the methods used to parametrize both deep and shallow convection have a large impact upon GCM performance. However, the exact details of such sensitivity are somewhat contradictory at times, with different models showing different sensitivities. Mechanisms to account for these sensitivities are not understood, being difficult to evaluate within the context of a fully interactive global model. However, similarities between the sensitivity of the UKMO Unified Model and a recent version of the ECMWF model to processes such as convective momentum transports has been noted.

Summarising those points with which there is some agreement between various studies;

1) Shallow convective parametrizations plays a key role in the maintenance of the Hadley circulation in GCMs and the global hydrological cycle.

2) Convection schemes that use moisture convergence to determine the location and intensity of deep convection have a detrimental impact upon the mean distribution of tropical precipitation, tending to split the ITCZ in the west Pacific, which may lead to large errors in the simulated circulation of the tropics and mid latitudes. However, other factors, such as the neglect of convective downdraughts and the inclusion of momentum transports in GCMs, may lead to similar errors.

3) Various convection schemes have impact upon the variability of the tropical atmosphere, although it is too simplistic to conclude that moisture-convergence type schemes produce weaker levels of variability. However, it is clear that the ability of a GCM to capture details of atmospheric variability accurately is an important test of a parametrization scheme. Sensitivity studies presented above also tend to suggest that the simulation of a correct distribution of precipitation may be coupled with a model's ability to provide a realistic simulation of atmospheric variability.

4) Down-gradient transport of horizontal momentum in the vertical by convection reduces model wind errors in the tropics and also (generally) tropical variability on a broad range of time scales. However, in certain regions errors in the precipitation distribution are enhanced by such processes, perhaps indicating the need to consider counter-gradient momentum transports associated with organised convection in some regions (for example the west Pacific).

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