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A standard test for AGCMs including their physical parametrizations. II: Results for The Met Office Model

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Abstract: Example results are shown for the proposed aqua-planet experiments using a version of The Met Office Unified Model (UM). The zonal mean circulation exhibits strong sensitivity to the latitudinal distribution of sea-surface temperatures (SST). Longitudinal variation of SST yields information on the linearity and distribution of the convective response.

Keywords: AGCM, sea-surface temperature, aqua-planet.

1. INTRODUCTION

Part I of this paper (Neale and Hoskins, 2000a) outlines a proposal for a suite for aqua-planet experiments using AGCMs. The aim is to provide a model test of AGCMs similar to that of the Atmospheric Model Intercomparison Project (AMIP) (Gates, 1992) but with the simpler forcing, boundary conditions, and with an ease of comparison comparable with model dynamical cores tests (Held and Suarez, 1994). In this way the model's physical interactions are retained whilst the complexity associated with many surface inhomogeneities are discarded.

The proposed suite of experiments summarized in Part I is designed to test how AGCMs respond to different characteristics of SST forcing. Each experiment was run for 18 months and initialized from a previous statistically steady state of the Control experiment. Averages shown are from the final 12 months of each experiment. The results shown here are from the current standard climate version of the UM, HadAM3 (Pope *et al*., 2000), a grid-point model with a horizontal resolution of 3.75° longitude by 2.5° latitude and 19 hybrid levels in the vertical with a top at 5 mb. For a more extensive suite of experiments and comprehensive analysis of HadAM2b see Neale (1999). A more extensive analysis of the aqua-planet experiments using HadAM3 and an investigation of different aspects of the convective parametrization are currently in progress.

2. RESULTS

The time mean zonal mean model climate in the Control case gives a distribution of winds and temperature (Figure 1). that in many respects resembles those in the observed climate. The zonal wind is predictably too strong and too latitudinally confined since there are no

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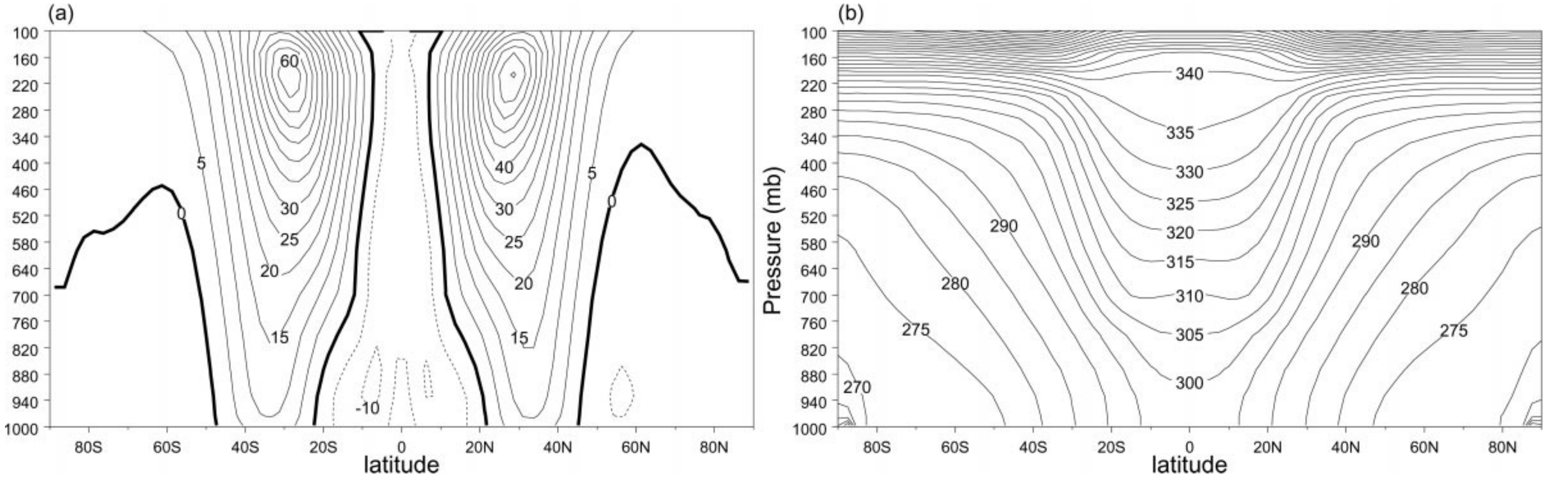

Figure 1. Zonal mean climatology in the Control experiment; (a) zonally averaged zonal wind (in m/s); (b) zonally averaged potential temperature (in K).

asymmetries of land/sea distribution or orography to give large drag or cause the flow to meander. However, the structures are realistic and the distribution and direction of near-surface winds are similar to those observed. Consistent with the zonal wind, the latitudinal gradients in potential temperature are stronger and the largest values are positioned closer to the equator than observed. However, the thermal structure is in general similar to those derived from observations.

Zonally symmetric experiments

Figure 2(a) shows the zonally averaged precipitation for the zonally symmetric suite of experiments (refer to Figure 1(a) of Part I for the SST distributions used to force the model). The first point to note is the variation in the maximum precipitation totals, even though the maximum SST of 27°C is the same in all cases. This clearly demonstrates that the response is far from a local thermodynamic one, and that there is interaction between the formation of a convective maximum and the large-scale circulation. The variation in the strength of the mean-meridional circulation (not shown) also reinforces this point since the strongest localized precipitation maximum is accompanied by an intense vertical branch of the mean meridional circulation. The width of the convective maxima appears to depend quite strongly on the near-equator curvature of SST. The three experiments Peaked, Control and Qobs have very similar values for the integrated tropical precipitation. However the confinement in the peaked case leads to the strong maximum on the equator. The suite of zonally symmetric experiments clearly reveals a regime change in the model in response to a decrease in the curvature of SST near the equator. With large near-equator SST gradient, as in the Peaked experiment, the model is firmly in a single ITCZ regime. As the gradient weakens in the Control case the single ITCZ regime is retained but in the Qobs experiment there is an indication that the ITCZ has split slightly to be either side of the equator and in the vertical velocity field there is evidence of two distinct ascent maxima which are each robust throughout the analysis period. In the Flat experiment with weakest near-equator SST gradient it might be thought that the model has changed regime

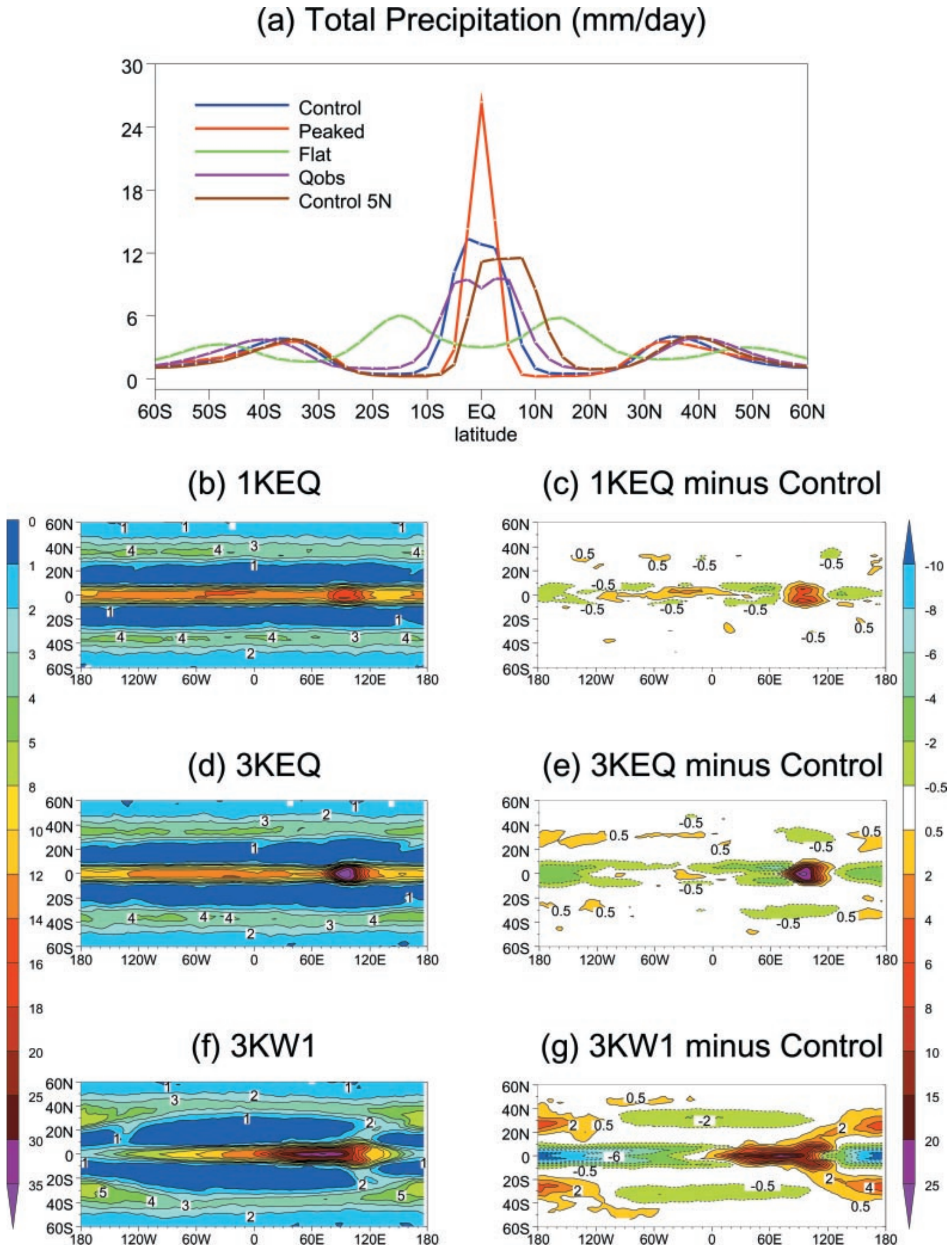

Figure 2. Total precipitation (in mm/day) from the suite of aqua-planet experiments; (a) zonal average from each of the axisymmetric experiments; (b) experiment 1KEQ; (c) experiment 1KEQ with the Control zonally averaged total precipitation removed; (d) and (e) as (b) and (c) but for experiment 3KEQ; (f) and (g) as (b) and (c) but for experiment 3KW1.

to one with separated ITCZs. However, the two convective maxima are some 15° poleward of the equator which would be a considerable excursion of the ITCZ. On closer analysis it is clear that in this experiment the interaction with mid-latitude systems is the main reason for the two convective maxima. Destabilizing troughs are more intense in this experiment, due to the greater baroclinicity, and trigger convection over warmer waters which extend much further poleward than in the other zonally symmetric experiments. In the deep tropics there is essentially a local radiative-convective equilibrium.

Held and Hou (1980) used a simple theoretical model to explore the transition from a local radiative-convective equilibrium to twin ITCZs as a function of the latitudinal curvature of SST in the tropics. The critical point comes when thermal wind balance associated with the SST gradient implies an upper-tropospheric wind that is greater than that achievable under the constraint of angular momentum conservation assuming that the air is displaced from the equator where its zonal wind was zero. The flat experiment has this critical SST profile and in the full AGCM the transition occurs near this point, despite the greater complexity of the aqua-planet. It is anticipated that the proposed aqua-planet experiments will enable the further development of such theories.

With an off-equatorial SST maximum in the Control 5N experiment the convective maxima moves off the equator and has a broader maximum than in the Control experiment. This broader maximum appears to be a consequence of two distinct convective maxima, one with a lower tropospheric ascent maximum close to the equator and the other with an upper-tropospheric ascent maximum over the region of maximum SST. The asymmetry generated in the mean-meridional circulation sees the southern hemisphere Hadley cell dominating. However, this asymmetry is less than suggested by Lindzen and Hou (1988), perhaps because of the larger SST gradients in the northern hemisphere mid-latitudes.

Zonally asymmetric experiments

Figure 2(b)–(g) shows the distribution of precipitation in the zonally asymmetric experiments, along with the changes in precipitation compared with the Control experiment. For the two confined SST anomaly experiments (1KEQ and 3KEQ) there is a local increase of precipitation in the immediate vicinity of the SST anomaly. Although the SST anomaly is symmetric about its maximum in the east/west direction, the pattern of precipitation is confined much closer to the equator on the western side. When the Control precipitation distribution is removed it is apparent that there are regions of reduced precipitation to the east and west of the precipitation maximum. These regions are consistent with a large-scale stationary wave response comprising a Kelvin wave propagating to the cast with its maximum on the equator and a Rossby wave propagating to the west with its maxima off the equator, as in the idealized model of Gill (1980). This combined wave response is also responsible for the asymmetry observed in the local increase in precipitation over the SST anomaly region. The response to the SST anomalies is not linear, the maximum anomaly in precipitation being over 5 times greater in experiment 3KEQ than in 1KEQ.

In experiment 3KW1 the maximum in tropical precipitation lies some 30° to the west of the maximum in SST. Again the convective intensity is not a simple response to the magnitude of the SST, but is also dependent on the gradient of SST and the feedback from the dynamical response to the enhanced diabatic heating. Away from the maximum convection there is a reduction in precipitation due both to the lower SSTs and the remote influence through the equatorial wave response to the enhanced convection. This leads to a complex rainfall distribution and a minimum located some 90° to the west of the equatorial minimum in SST, in a region of near zero SST anomaly.

The response to the tropical SST distribution in this experiment generates a considerable response in the extra-tropics. Downstream from the convective maximum the sub-tropical jet is strengthened and the mid-latitude systems are able to obtain greater intensity, leading to increased rainfall totals particularly on their equatorward flank. Upstream of the convective maximum the jet is considerably weaker with mid-latitude system strength and rainfall reduced compared with the Control. Such extra-tropical changes were evident to a lesser extent in experiments 1KEQ and 3KEQ.

Another aspect of interest in experiment 3KW1 is the occurrence of very strong upper-tropospheric equatorial westerlies downstream from the region of enhanced convection. In the zonal average, there is equatorial superrotation (not shown) in the mid- and upper-troposphere, the maximum equatorial westerlies being 22.5 m/s. As will be discussed in a subsequent paper these westerly winds are forced by equatorward momentum fluxes associated with poleward propagating planetary Rossby waves. This experiment in particular highlights the remote effects of SST anomalies.

Wavenumber–frequency characteristics

Tropical transient motions are important in forming the climatology of the model and its response to different SSTs. They are evidence of the active coupling between the physics and dynamics in the model. Indeed the first aqua-planet experiments of Hayashi and Sumi (1986) focused on them.

Figure 3(a) shows the longitudinal variation in convective precipitation from the Control experiment revealing enhanced and suppressed organized convective activity propagating both eastwards and westwards and covering a wide range of spatial and temporal scales. The tropical wave activity in the analysis period can be summarized by a wavenumber–frequency decomposition. Following Wheeler and Kiladis (1999) the wave behaviour can be highlighted by splitting into components that are symmetric and antisymmetric about the equator and normalising each by a background spectrum. These two summary diagrams for the Control are shown in Figure 4(b) and (c) In the real atmosphere the dominant symmetric wave activity has a spectral peak with periods of greater than 30 days at eastward wavenumbers 1 and 2, which is the signature of the MJO. The lack of such a spectral peak clearly demonstrates the absence of a realistic MJO in this aqua-planet experiment. However, observed wave disturbances are reproduced in the aqua-planet and are consistent with theoretical waves described by the shallow water equations. In particular Kelvin waves account for a significant amount of variability covering the same spectral space as in observations. The antisymmetric waves are much weaker, but given the symmetric nature of many aspects of the model set-up this is not surprising. Power in the antisymmetric spectrum is provided predominantly by incursion of extra-tropical systems into the tropics.

3. CONCLUSIONS

The results summarized here illustrate the potential usefulness of simplified AGCM experimentation for elucidating many aspects of the tropical circulation. It is hoped that such results are the first of many for the model intercomparison proposal outline in Part I and that these experiments will become a basic part of investigating the dynamics and physical parametrizations in AGCMs. The simplified forcing allows a much easier comparison with theory and demonstrates its usefulness, or otherwise, when diagnosing complex AGCMs containing numerous complex interaction not accounted for in the theory. For example, comparison with the theoretical ideas of Held and Hou

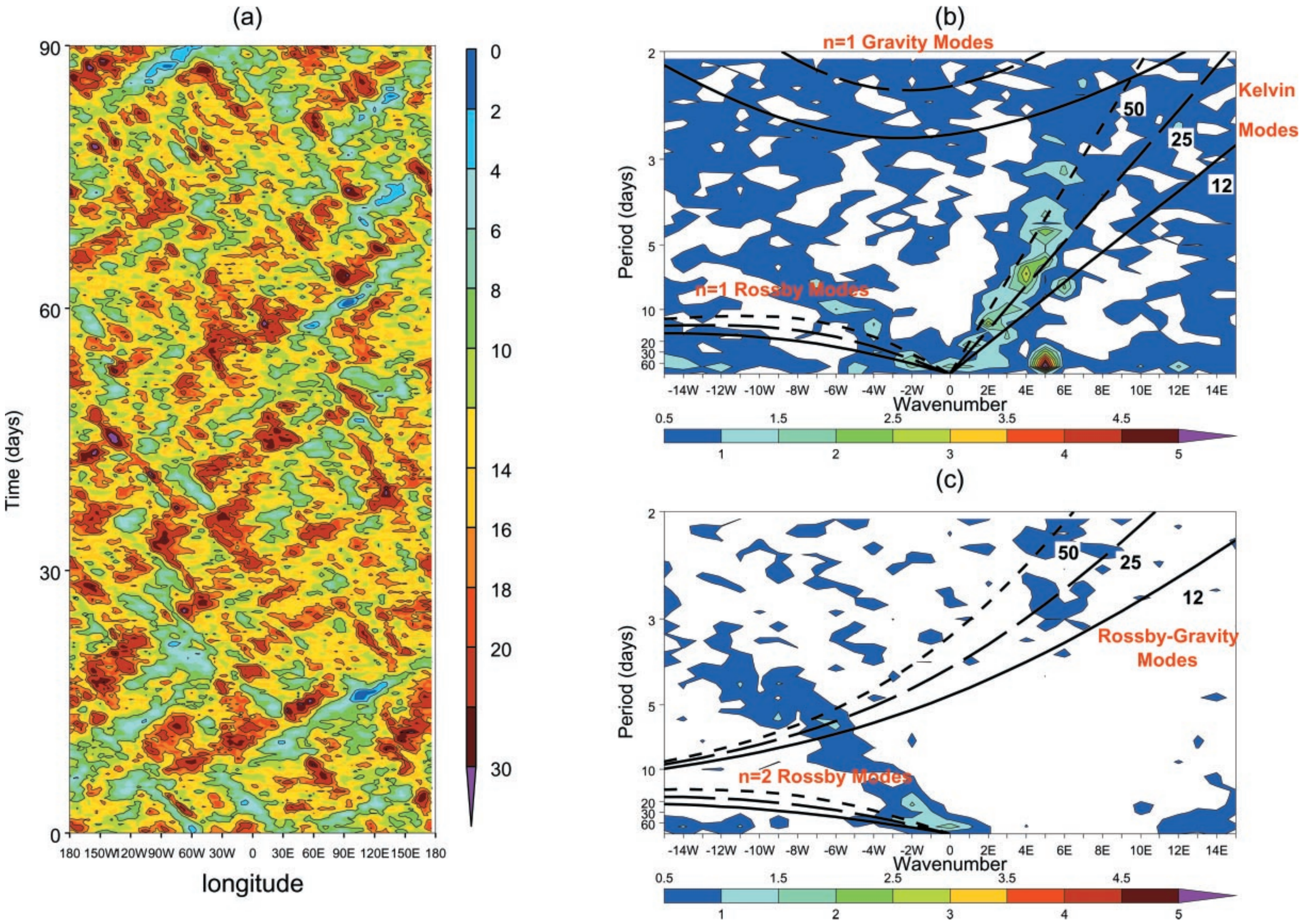

Figure 3. Tropical variability in the Control experiment; (a) Hovmoller plot of convective precipitation averaged between 5° N and 5° S for the first three months of the analysis period (in mm/day); (b) symmetric component of a wavenumber-frequency decomposition in convective precipitation between 5°N and 5°S. The spectrum is divided by a computed background spectrum and has overlain the theoretical dispersion relations for equatorial Kelvin waves, $n = 1$ Rossby waves and $n = 1$ gravity waves, obtained from the shallow water equations with a zero wind basic state and equivalent depths of 12 m (solid line), 25 m (dashed line) and 50 m (dotted line; (c) as (b) but for the antisymmetric component and overlain with the theoretical dispersion relations for Rossby-gravity waves and $n = 2$ Rossby waves for the same equivalent depths.

(1980) has aided our understanding of the zonally averaged response, but the role of the mid-latitudes disturbances, not accounted for in their theory, can also have a significant influence. Furthermore, the response to an SST anomaly in an aqua-planet AGCM provides a bridge between the simple shallow water solutions of Gill (1980) and the situations simulated with full AGCMs response.

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