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Numerical general circulation experiments of sensitivity to Earth rotation rate

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Abstract The ECHAM4 general circulation model was tested for its skill in reproducing the sensitivity of the general circulation to the rotation rate of the Earth. The experiments have been designed to investigate the behavior of the model under conditions that are not typical of the parametric regime under which the model has been developed. The model was set at spectral T30 resolution, has 19 vertical levels and it includes a rather complete set of physical parametrizations, seasonal and diurnal cycles, and a mixed layer ocean. The other parameters have been prescribed at present climate values to offer a good comparison with the simulation of the present climate (24 h rotation rates). In particular, the present land–sea mass distribution and mountain ranges have been used. The dynamical response to rotation rate changes was investigated by performing sensitivity experiments at fixed rotation rates, from 18 to 360 h, each integrated for 20 years. The latitudinal extent and the strength of the Hadley Cell increased as the rotation rate was decreased, as expected from idealized models and theory. The tropospheric jets underwent a similar evolution, moving poleward and modifying their intensity, as the rotation rate was decreased. The winter stationary waves have been found to be very sensitive to the rotation rate, turning into longer and longer wavelength quickly as the rotation slowed. The model has been also used to investigate the stability of the general circulation to the variations of the rotation rate. The model was run with a rotation period of 240 h and a direct Hadley Circulation equator to pole was observed. The rotation rate was subsequently increased until baroclinic instabilities at midlatitudes appeared. The experiment demonstrated how ECHAM4 handles the unstable character of the eddy-free circulation typical of slow rotations and the transition to turbulent, eddy rich, regimes. The overall results indicate that rotation rate changes need to be taken into account when designing paleoclimatic simulations. The good agreement between the results of the simulations and the bounds provided by the dynamical theories of the general circulation enhances our confidence in the capability of the model to represent the general circulation in different situations from the present climate.

1 Introduction

Atmospheric general circulation models (GCMs) have been widely employed to perform assessments of climate change, usually performing perturbation simulations with respect to the actual climate. The question of assessing the reliability of the model simulations outside the parametric range within which they can be compared with observations is a very important step in the construction of a reliable assessment of climate change. The model formulations, especially the parametrizations of physical processes, have been developed using as a constraint physical laws and the guide of the observed climate. A certain number of empirical relations are unavoidable and therefore the question can be raised whether the model is capable of working properly under conditions that are different from those under which it was developed.

It is certainly a requirement that a model used for climate change must produce a realistic simulation of the present mean climate and variability, but it is also necessary that the same model expand into uncharted territory in a physically consistent manner. Paleoclimatic simulations offer one opportunity to assess the model performance under different conditions, but they are hindered by the scarcity of reliable data. Another

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approach, that is taken here in this study, is to alter parametrically the model and evaluate how much the model behaviour is still consistent with the predictions of dynamical theories. Ideally, such a program could be carried out for all parameters in the model, but we have selected the rotation rate for its importance and because there is a good understanding of the dynamical effects of rotation. Another motivation lies in the fact that indeed the Earth rotation rate has been varying during the geological history of the Earth, and so this information may be of relevance for paleoclimatic simulations. (Walker and Zahnle 1986; Zahnle and Walker 1987).

We will discuss two issues related to how dynamical balances change under a modification of the rotation rate. The first issue concerns the dynamical features of the circulation at fixed rotation rates and the different adjustments of the components of the circulation, as the position of the Inter Tropical Convergence Zone (ITCZ), the precipitation patterns, the stationary waves, the heat and momentum transports. These issues are relevant to planetary atmospheres studies (within the solar system rotation rate varies greatly amongst the planets endowed with an atmosphere) and paleoclimatology (the rotation rate of the Earth is continuously decreasing due to the increasing orbital radius of the Moon as it revolves around the Earth, so that in the past the rotation rate was higher, about 1 hour longer 60–70 million years before present).

The second issue concerns the stability of the symmetric Hadley circulation itself without eddies. The role of the symmetric circulation and even its existence has been a classic problem in meteorology (Lorenz 1967; Lindzen 1990), with the main result by Bjerknes (1937) that a purely symmetric circulation is indeed dynamically admissible, but it is in practice unrealizable because it is unstable to small perturbations. We will discuss the activation of eddy processes by considering a numerical experiment in which the Earth is accelerated. The transition is observed by monitoring the appearance of intense transient eddy activity when the threshold in rotation rate is crossed. The results show that indeed a smooth eddyless circulation is not possible at the present rotation rate because of baroclinic instabilities, but it would be possible at slower rotation rates.

The sensitivity to rotation rate has been the object of several numerical studies. The numerical equivalent of the annulus experiment (Hide 1977), has been investigated by Geisler et al. (1983) using the Community Climate Model version Zero, with no continents, radiation or hydrological cycle, forced by a prescribed zonally symmetric temperature profile. In that experiment the model was not allowed to adjust the meridional temperature profile and therefore the eddies could not change the baroclinicity. Del Genio and Suozzo (1987) used the Model I version of the GISS GCM, with no hydrological cycle, zero heat capacity of the ocean, and forced with perpetual annual mean solar forcing. They showed that the transition also occurs in their model: at slow rotation rates (period $>$ 8 days) the circulation was very much dominated by the axially symmetric Hadley circulation and the dominant processes were quasi-barotropic; for higher rotation rates the system was dominated by baroclinic processes and moved away from axisymmetry.

A common result of all previous studies was the increasing extent and strength of the Hadley circulation with decreasing rotation rate. Del Genio and Suozzo (1987) also showed a qualitative agreement of the behaviour of the Hadley circulation with that predicted by the axially symmetric model by Held and Hou (1980). They also argued that the analytical model strongly overestimated the extent of the Hadley cell for different rotation rates when compared to their simulations, and noted that this might be due to an oversimplified treatment of eddy transports. Williams and Holloway (1980) have shown how for very high rotation rates (period $< 1/2$ day) there is a clear distinction between tropical and extratropical jet-streams. The extratropical jets are well defined at fast rotation rates, but they tend to disappear for slow rotations, when the tropical jet, linked to the poleward side of the Hadley Cell is the only one left.

The "efficiency" of the atmosphere in meridional transports and its dependence on rotation was a common concern of almost all previous studies. Hunt (1979) using a hemispheric model devoid of topography and forced with annual mean conditions, Del Genio and Suozzo (1987), Jenkins (1993, 1996) using the version 1 of the NCAR CCM all showed that a decrease of rotation is accompanied by a decrease of the dominant wave number in the instability processes and an increase in transport efficiency of momentum and heat of both transient and stationary eddies. The overall transport efficiency of the atmosphere is generally observed to decrease with increasing rotation rate, resulting in a higher equator to pole temperature gradient and baroclinicity. Jenkins (1996) used an advanced model, but he concentrated on fast rotation rates and he used a prescribed sea surface temperature (SST) distribution. The present study investigates mostly slow rotations and the usage of the mixed layer model allows for the adjustment of the SST.

In this work we follow along the lines of the mentioned investigations to assess the capability of the ECHAM4 model to reproduce this crucial facet of the general circulation. We will also extend the previous results by Del Genio and Suozzo (1987) and Geisler et al. (1983) by providing more details of the transition to instability and of the behaviour of stationary waves. The inclusion of a "slab ocean", a simple mixed layer model, will allow us to adjust the equator-pole surface temperature difference. The overall results will be a further validation of the ECHAM4 GCM, a model that is being currently used for climate change and paleoclimatological studies (Roeckner et al. 1999).We will show in the following that the simulations are generally consistent with the previous simplified models and they are consistent with the analytical theory by Held and Hou (1980).

The study is organized as follows: Sect. 2 provides a description of the GCM ECHAM4 and of the numerical experiments; Sect. 3 is a discussion of the general circulation; Sect. 4 presents the results of the sensitivity of the Hadley cell to changes in rotation rate; Sect. 5 is devoted to analysing the maintenance of the general circulation; Sect. 6 presents the results of the time-mean latitude–longitude response. The conclusion is in Sect. 7.

2 Model and experiment description

The numerical experiments have been performed with the ECHAM4 GCM, the most recent evolution in a series originating from the spectral weather prediction model of the European Centre for Medium Range Weather Forecasts and developed at the Max-Planck-Institute for Meteorology in Hamburg. ECHAM4 is a pseudo-spectral model with triangular truncation at wave number 30 (T30) and uses a hybrid sigma-pressure coordinate system with 19 irregularly spaced levels, starting from about 30 m above the surface. For a full description of the model refer to Roeckner et al. (1992, 1996). A simple mixed layer model with a fixed depth of 65 m was introduced to allow for adjustments of the sea surface temperature using a energy balance condition (Roeckner 2000 personal communication). The model reproduces rather well the observed SST distribution with the help of a monthly varying correction representing the implicit effect of ocean currents.

Two kinds of experiments have been considered. The first consisted of experiments at different rotation rates reach a statistically steady state to allow a confident discussion of the general circulation. Simulations, each 20 years long in total, have been performed for the following rotation rates 18, 24, 36, 48, 72, 144 and 360 h a day). The first year is not included in the analysis, so results will be shown in the following, usually as time means, for the remaining 19 years. The model includes seasonal and diurnal cycles. The second is a single experiment starting for convenience at a rotation of 240 h (that yields a basic state very similar to the 360 h case) from January, continuing for one year and then switching to a rotation of 144 h, continuing for another year and increasing to a rotation rate of 72 h for another three years. This simulation is an attempt to verify the claim by Bjerknes (1937) on the unstable nature of the general circulation with no eddies with respect to the rotation rate. The experiments were performed on the NEC SX-4/16 of the INGV in Rome.

3 The nature of the general circulation

It is generally assumed (Lindzen 1990) that the observed circulation is the result of an axially symmetric state, which, although a solution to the equations governing the atmospheric motions, is unstable to the appearance of large-scale eddies. Several laboratory experiments with rotating dishpans have demonstrated that the rotation rate is crucial in determining the transition from a symmetric state to a turbulent regime (Hide 1977). The laboratory experiments have some limitations, like the inability to consider a spherical gravity field, that can be overcome by the usage of GCMs as "numerical rotating tanks". Geisler et al. (1983) were able to show that a GCM can indeed simulate the rotating annulus experiment, identifying the regime dependence with rotation. However, in their attempt to simulate closely the laboratory setup they forced the model with a prescribed meridional temperature profile, effectively preventing the adjustment process of the meridional temperature gradient with the eddy transport. The setup of the numerical experiments used here allows for such an adjustment.

The development of the theories of the general circulation have been discussed in Lorenz (1967) and Lindzen (1990) and it is briefly summarized here. The early theory of Hadley, consisting of a single cell extending from the equator to the poles, was found to be in disagreement with the observation available in the nineteenth century and Ferrel and Thomson modified the Hadley theory by inserting a mid-latitude cell. Their ideas were, however, qualitative and there was no explanation for the observed asymmetries of the circulation. Jeffreys (1926) proposed an argument designed to show that the eddies were indeed needed to maintain the westerly circulation, but his formulation was somewhat inconclusive. A better point was made by Bjerknes (1937) that pointed out that a purely symmetric circulation like Thomson proposed was going to be unstable for the situation of the Earth. These efforts were hindered by the absence of a quantitative consideration of the budget of angular momentum. The achievement of precise results regarding the extent and organization of the circulation was thus precluded. Bjerknes' remarks were confirmed by Schneider and Lindzen (1977) and Schneider (1977), and the analysis was pushed further by Held and Hou (1980), who considered the angular momentum budget and earlier results by Hide (1969). Held and Hou showed that in the inviscid limit the region where a meridional circulation can exist is regulated by the parameter

$$R = \frac{gH\Delta T}{(\Omega a)^2} \ , \tag{1}$$

where ΔT is the non-dimensional fractional equator-to-pole temperature difference at the surface, Ω the rotation rate, a the radius of the Earth, H the height of the return flow of the Hadley Cell and g the gravitational acceleration. The maximum latitudinal extent of the meridional circulation is then obtained by a relation involving R and the latitude θ, which, for small R, reduces to

$$\theta \leq \mathrm{a}\tan([(1+2R)^{1/2}-1]^{1/2}) \tag{2}$$

Inserting typical values in Eqs. (2) and (1) we obtain a value for the latitude θ of about 30° that is the approximate extent of the Hadley cell in the present climate.

The constraint of the conservation of angular momentum requires that a meridional circulation exists in the low latitudes. If Ω tends to zero, finite values for R can be obtained only if the meridional surface temperature gradient is correspondingly reduced. The results of our first group of GCM experiments are displayed in Fig. 1 showing the annual mean meridional circulation expressed in terms of a meridional stream function superposed on the mean zonal flow.

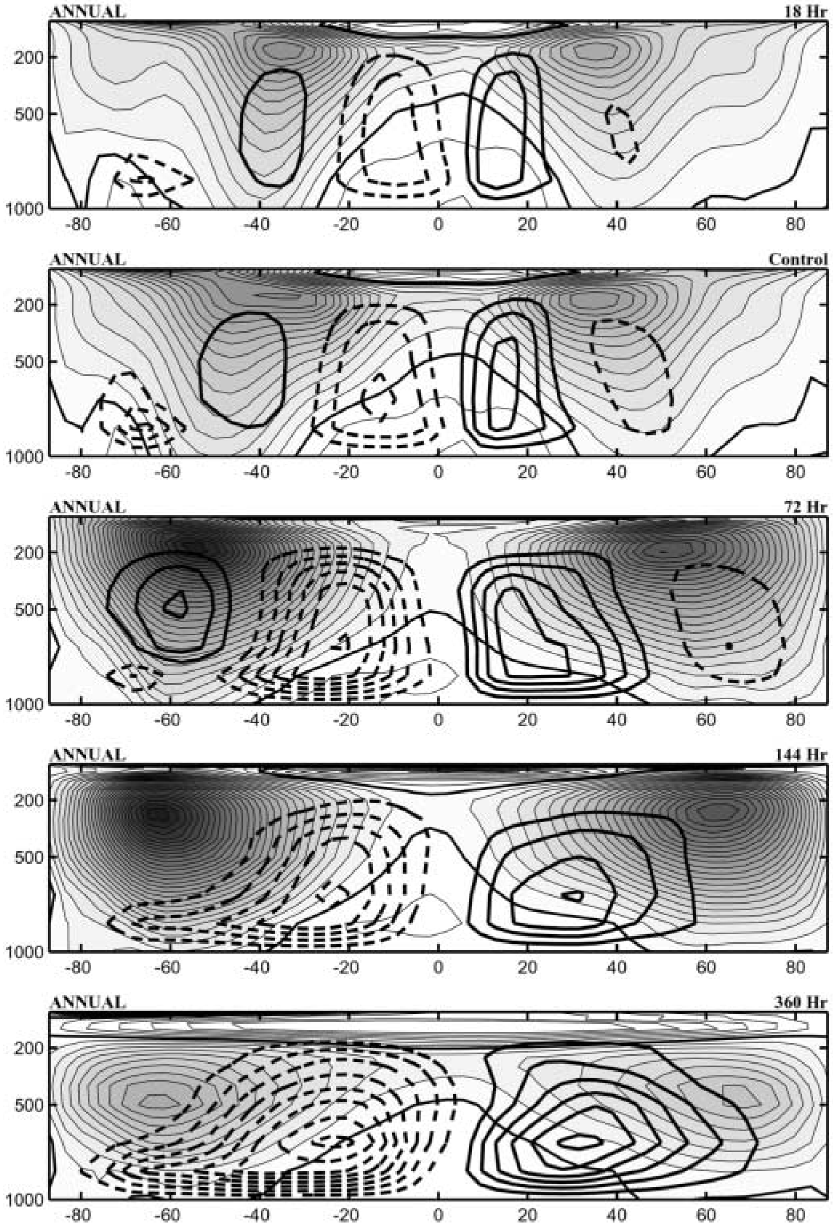


Fig. 1. *Thick line*: latitude-pressure cross section of the meridional stream function (the contour interval is $2 10^{10}$ Kg/s and $4 10^{10}$ Kg/s for the bottom two panels). *Thin line*: zonally averaged zonal velocity (contour interval 2.5 m/s, positive values are *shaded* and the zero line is *enhanced*). From *top* to *bottom*: 18, 24, 72, 144, 360 h a day rotation period

At a rotation period of 360 h the flow is substantially dominated by a single cell extending from the equator to each pole. The mid-latitude Ferrel cell is absent in this regime. The appearance of the Ferrel cell, with the confinement of the Hadley cell to the tropical regions, occurs when the rotation rate is between 144 h and 72 h a day, which is consistent with the results of Del Genio and Suozzo (1987). It is only at 72 h that the mean meridional circulation shows the presence of a Ferrel cell, which is representative of the baroclinic eddy activity.

The faster rotation case at 18 h shows a hint of the separation of the zonal jet between the subtropical jet and the mid-latitude jet discussed by Williams and Holloway (1982) and the shrinking effect on the extension of the Hadley cell is noticeable. Large changes in the rotation rate yields more visible effects. At 72 h the Hadley cell extends well into the 40–50° of latitude and the jet stream is further north, following the border of the cell. The strength of the jet has increased as the latitude of the maximum is shifting poleward as required by the angular momentum balance. The Ferrel cell disappears at 144 h and the jet streams reaches its maximum intensity and the highest latitude location. At an even slower rotation rate (360 h), the Hadley cell reaches 70°N and the jetstreams decrease noticeably, as the amount of angular momentum available is severely curtailed.

The equator to pole temperature difference (Fig. 2) reflects the loss of the Ferrel cell as the rotation rate decreases. The disappearance is rather sharp, corresponding to the transition from the present regime to the

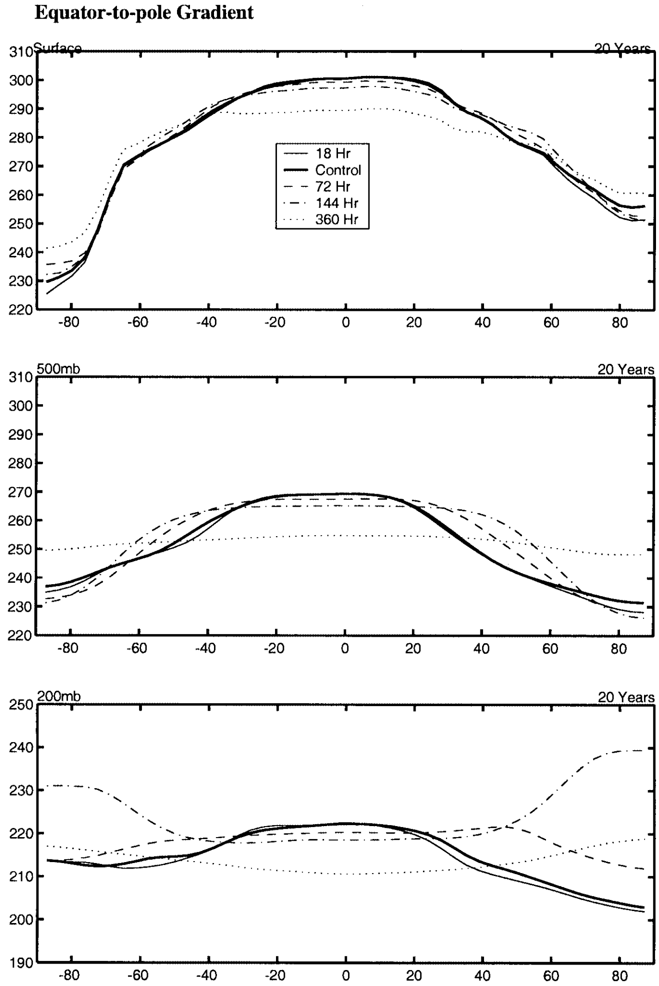


Fig. 2. Annual mean and zonal mean temperature profile from the South Pole to the North Pole for the rotation experiment shown in Fig. 1. From *top* to *bottom*: surface, 500 mb, 200 mb

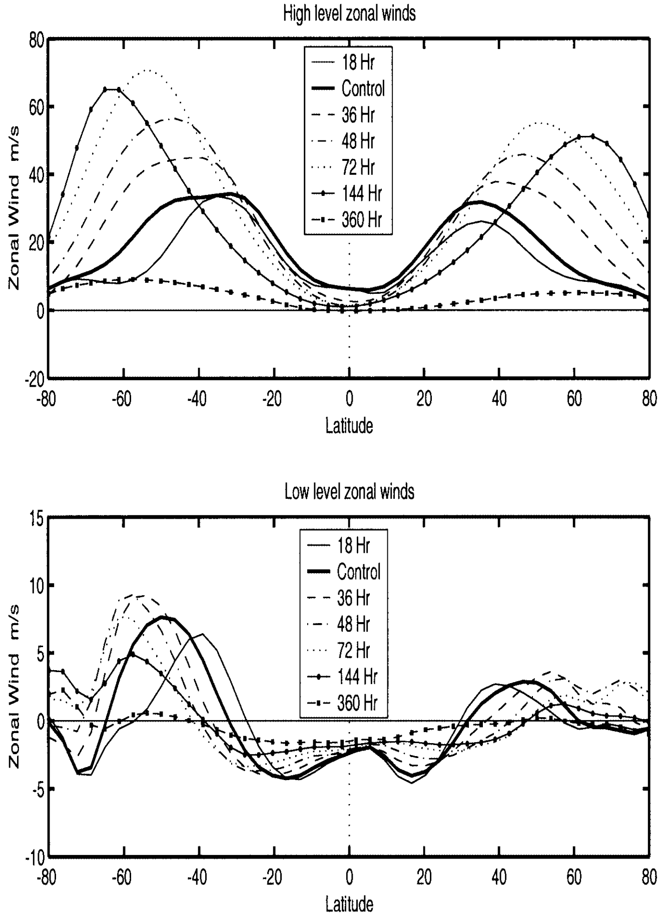


Fig. 3. Annual mean and zonal mean zonal wind profiles for different rotation rates (18, 24, 36, 48, 72, 144, 360 h). *Top panel*: upper level flow (200 mb), *lower panel*: low level flow (1000 mb)

slow rotation regime. The gradient is progressively flattened as the rotation rate slows down and the tropics are cooled down as the higher latitudes are warmed up. Near the surface (top panel) the changes are smaller in amplitude but a reduction of about 10° in the inter tropics is achieved with a corresponding increase in the polar regions. The process occurs through a shift of the area of the intense meridional gradient poleward as the intertropical area (defined as the latitudes between the two strong gradients) becomes nearly isothermal. This is very evident in the mid-troposphere (middle panel) where the intense gradients, located in the control in the Northern Hemisphere around 30°, move to 40°N and 50°N, with an almost symmetrical shift in the other hemisphere. There is almost no meridional temperature gradient at 500 mb for the 360 h rotation case. In the upper atmosphere (bottom panel) the transition from a Ferrel regime to a non-Ferrel regime is marked by an inversion of the meridional gradient, still quite visible in the 144 h case and becoming less evident as the core of the zonal jet moves down and weakens.

The progression of the jet is also visible in Fig. 3 where the pole-to-pole profile of the zonal wind is plotted in the upper atmosphere (top panel) and close to the surface (lower panel). In this diagram we have added also experiments at intermediate rotation rate (36 and 48 h) that were not included in Fig. 1. The profiles show the annual mean results over 20 years of simulation for each rotation case. It is possible to notice the smooth evolution of the jet as the rotation rate is changed. The decrease of the intensity of the jet starts at 144 h and there is a collapse of the westerlies at 360 h. The collapse is actually overemphasized in this diagram, because the core of the jet is moving below the 200 mb level. The maximum of the jet for the 360 h case is located at 500 mb and reaches about 20 m/s, still a substantially smaller value than the other cases. The low-level westerly wind maximum (lower panel) follows the migration to the north of the high-level core and the area of the easterlies is progressively enlarged. When the rotation rate reaches 144 h/day the maximum has increased to 60 m/s, is located at 50°N and at higher altitude (300 mb). The upper level profile of zonal wind related to the Hadley cell appears to be particularly sensitive to a change in rotation rate, consistently with all previous studies. The Northern (Southern) Hemisphere jet at 200 mb shifts its position north (south) with slower rotation, increasing its maximum intensity. This indicates that the jet follows the position of the northern (southern) margin of the Hadley cell as the cell expands and contracts (see also Fig. 1) in response to the changes in rotation. The conservation of angular momentum partly explains the changes in magnitude of the jets as they move poleward. As the Hadley cell expands poleward the high angular momentum equatorial air results in stronger zonal jets as it moves to higher latitudes. The effect is competing with the weakening effect of the jets caused by the slowing rotation rate.

4 Sensitivity of the latitudinal extent of the Hadley cell

We will compare the changes in the extent of the Hadley circulation with the theoretical predictions by Held and Hou (1980). Held and Hou (1980) proposed an analytical model with which they were able to offer a plausible explanation for the localization of the Hadley cell. Their arguments were based on considerations based on conservation of angular momentum and energy. The definition of an objective measure of the extension of the cell, especially if quantities related to the meridional stream function are selected, is complex. It is difficult to judge objectively the location of the border of the Hadley cell in terms of meridional stream function. We have chosen here to compare the GCM results with the Held and Hou (1980) prediction for the location of the upper air westerly maximum and for the maximum extent of the surface easterlies. Since we are about to change the rotation rate substantially we have used the relation valid for all R and not just the simplified derivation for small R that was shown in the previous section. In Fig. 4 we show the theoretical prediction (solid line) and the GCM result (dashed line). The theoretical predictions were obtained using pole-to-equator relative surface temperature difference and actual rotation rate for each experiment in the relation derived by Held and Hou (1980). Annual mean values obtained from each experiment were used for the parameters needed by the Held and Hou (1980) theory.

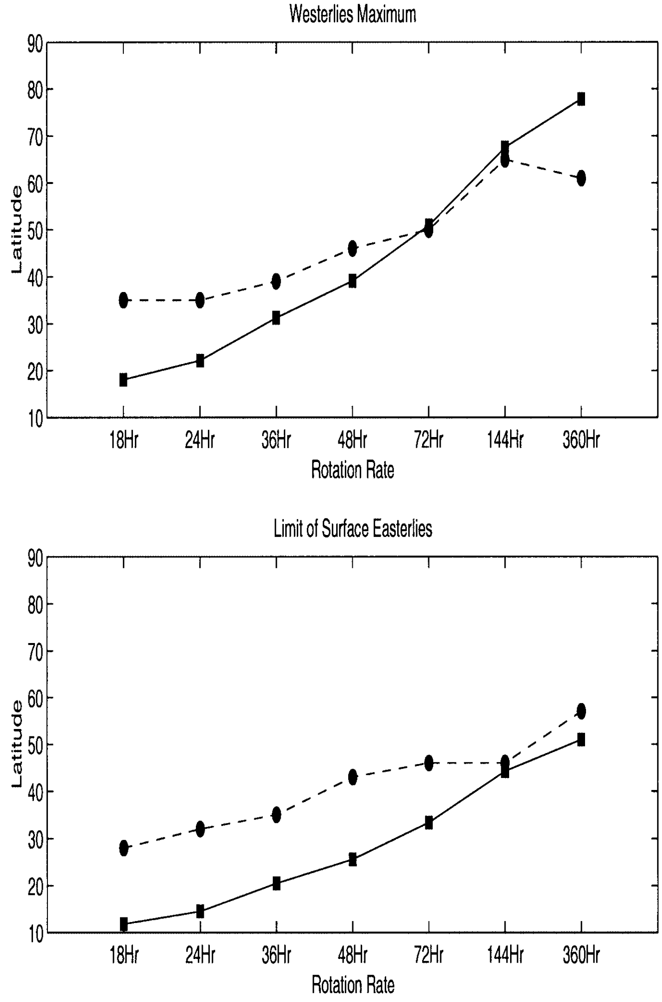


Fig. 4. Latitude of the high level (200 mb) Northern Hemisphere westerly maximum (*top*) as predicted by the Held and Hou (1980) inviscid theory (*solid line*) and in the simulation (*dashed line*). Annual mean values of the meridional temperature gradient and other parameters from the simulations are used in the calculation. Also shown is the extent of the surface easterlies (*bottom*) comparing the prediction of the theory (*solid*) with the simulation (*dashed*)

The theoretical predictions and the GCM results are in qualitative agreement, in fact for the extension of the surface easterlies the agreement is very good. However, a balanced interpretation of this result is that the simple constraints of angular momentum and energy conservation can explain the general behaviour of the sensitivity to rotation of the general circulation. We cannot expect more than a general agreement between theory and GCM because of the severe limitation of the theory. The main differences are that (1) the theory is inviscid and (2) it is applied here to the annual mean. Lindzen and Hou (1988) have extended this theory to the seasonally varying Hadley circulation, but this is probably a secondary error with respect to the usage of an inviscid theory as a comparison with a fully realistic environment as the GCM. By the same token, we cannot attach too much significance to the agreement in the lower panel of Fig. 4. The overall tendency is, however, in good agreement and so we can conclude that the theory does provide the dynamic explanation for the sensitivity of the Hadley cell extension. It can be noted that a departure from the tendency predicted by the theory can be seen for a very low rotation rate (360 h). The deviation from the previous trend is visible also for an intermediate experiment at 240 h rotation (not shown). A very slow rotation rate is an adventurous suggestion for the theory. The Held and Hou (1980) relation is highly non linear (formally mathematically singular for $\Omega = 0$) and the solution in this regime is difficult. It is possible that the theory approaches its limit close to a no-rotation state.

It is intriguing to note that none of the experiments produce the Thomson-Ferrel-like circulation with the mid-latitude cell confined to the lower levels and an extension of the Hadley cell above (Lorenz 1967). Bjerknes' (1937) argument that such a circulation would be present in absence of the eddies does not seem to hold when the eddies disappear at slow rotation. At the 360 h rotation rate the supply of momentum from rotation is becoming limited, but angular momentum is still available at 144 h as can be seen from the presence of significant zonal jets.

5 The maintenance of the general circulation and rotation rates

The general circulation implies poleward transports of momentum and heat that are required by conservation laws to reach a global balance. The poleward transport of heat and momentum can be expressed as,

$$\begin{aligned}[\overline{\mathrm{vT}}] &= [\bar{\mathrm{v}}][\bar{\mathrm{T}}] + [\bar{\mathrm{v}}^*\bar{\mathrm{T}}^*] + [\bar{\mathrm{v}}'\bar{\mathrm{T}}'] \\ [\overline{\mathrm{vu}}] &= [\bar{\mathrm{v}}][\bar{\mathrm{u}}] + [\bar{\mathrm{v}}^*\bar{\mathrm{u}}^*] + [\bar{\mathrm{v}}'\bar{\mathrm{u}}']\end{aligned} \tag{3}$$

where the symbol [·] denotes the zonal mean and the overbar the time mean, deviations from time mean and from the zonal mean are indicated respectively by a single quotation mark (′) and an asterisk (*).

The first term on the right is the contribution of the mean meridional circulation (MMC), the second is the transport due to the standing zonal asymmetries, the stationary waves, and the last term is the contribution due to transient processes (see Peixoto and Oort 1992). Figure 5 shows the vertically integrated terms described in the previous equation for various rotations for the transport of angular momentum. The transport of the mean meridional circulation (top panel, Fig. 5) reflects the growing extension of the Hadley cell as the strong meridional circulation moves to higher and higher latitudes. The barely noticeable change of sign in the midlatitudes connected to the Ferrel cell disappears at slow rotations. The stationary waves component is fairly strong in the control experiment, especially in the Northern Hemisphere, but it progressively disappears as the rotation rate decreases. In the Southern Hemisphere the situation is complicated by the interaction with the orography of Antarctica. As the jets are moving southward, the interaction with the mountains increases, amplifying the magnitude of the southern stationary waves and the corresponding transport terms, before finally disappearing at very slow rotation rates.

The stationary wave contribution is mostly due to the interaction between the mean current and the topography, generating planetary-scale standing Rossby waves. At lower rotations the mean flow-topography interaction is altered as the mean flow is shifted north, decreasing the effect of the main Northern Hemisphere mountain ranges, (see also Sect. 6.). The balance in the control experiment is dominated by the transient and stationary waves terms, whereas at very low rotation (360 h) the main balance is between the transient and the MMC term. In general, as the planet is spinning at a slower rotation, there is less momentum available to be transported.

A strong seasonal cycle appears in the extension of the surface easterlies. The surface easterly wind region expands deep into the summer hemisphere, becoming a source region for westerly momentum. For the present condition (i.e. the control experiment) the transient transport tends to be toward the equator in the region of the Hadley cell (20°S–20°N). It is more evident in JFM (not shown), but it is possible to see the signature of this effect in the annual mean as a small hump, south and north of the equator. As the Hadley cell expands into the hemispheres, the equatorward transport becomes more evident and it is very prominent at 360 h rotation rate.

The splitting here does not indicate which kind of transient processes are responsible for the transport, but some insight can be gained by examining the vertical structure of the transport terms (Figs. 6 and 7). The vertical structure of the transport term is characterized by the familiar dipolar shape in the control experiments. The transients, that in this case can be identified as baroclinic eddies (Peixoto and Oort 1992), are the largest term. They follow the evolution of the jet as it moves poleward at slower rotations, but the signature changes in the transition from 72 h to 144 h rotation. The typical structure caused by the baroclinic eddies disappears to be replaced by a more complicated shape for the experiment with the slowest rotation. The reason is that this kind of transient term includes contributions both from the transient eddies and from the transient mean meridional circulation. Under actual Earth conditions the contribution from the transient mean meridional circulation is small and so the term largely reflects the transient eddies, but in our experiments the situation is more complicated. When the system reaches conditions under which the eddies are not favoured (144 h) the transient term decreases markedly, to recover in the following experiment as the contribution from the transients of the mean meridional circulation increases. The large increase of the term in the last experiment is caused by the further intensification of the mean meridional circulation and its anomaly in this case. It is possible to follow the migration of the transport term poleward as the edge of the Hadley cell shifts. Beyond 144 h there is a breakdown and the regime characterized by strong fluxes aloft changes to a more complex and weaker structure.

Another strong indicator of the activity of the baroclinic eddies is the vertically integrated northward sensible heat flux (Fig. 8). The mean meridional circulation transport (top panel) is straightforward, with the transport corresponding very well to the meridional flow. Under present conditions the flux is made up by the equatorward flux of the Hadley cell in the subtropics and the poleward flux of the Ferrel cell outside. The transients contribute strongly to the poleward transport in the midlatitudes. Slowing the rotation rate has the effect of

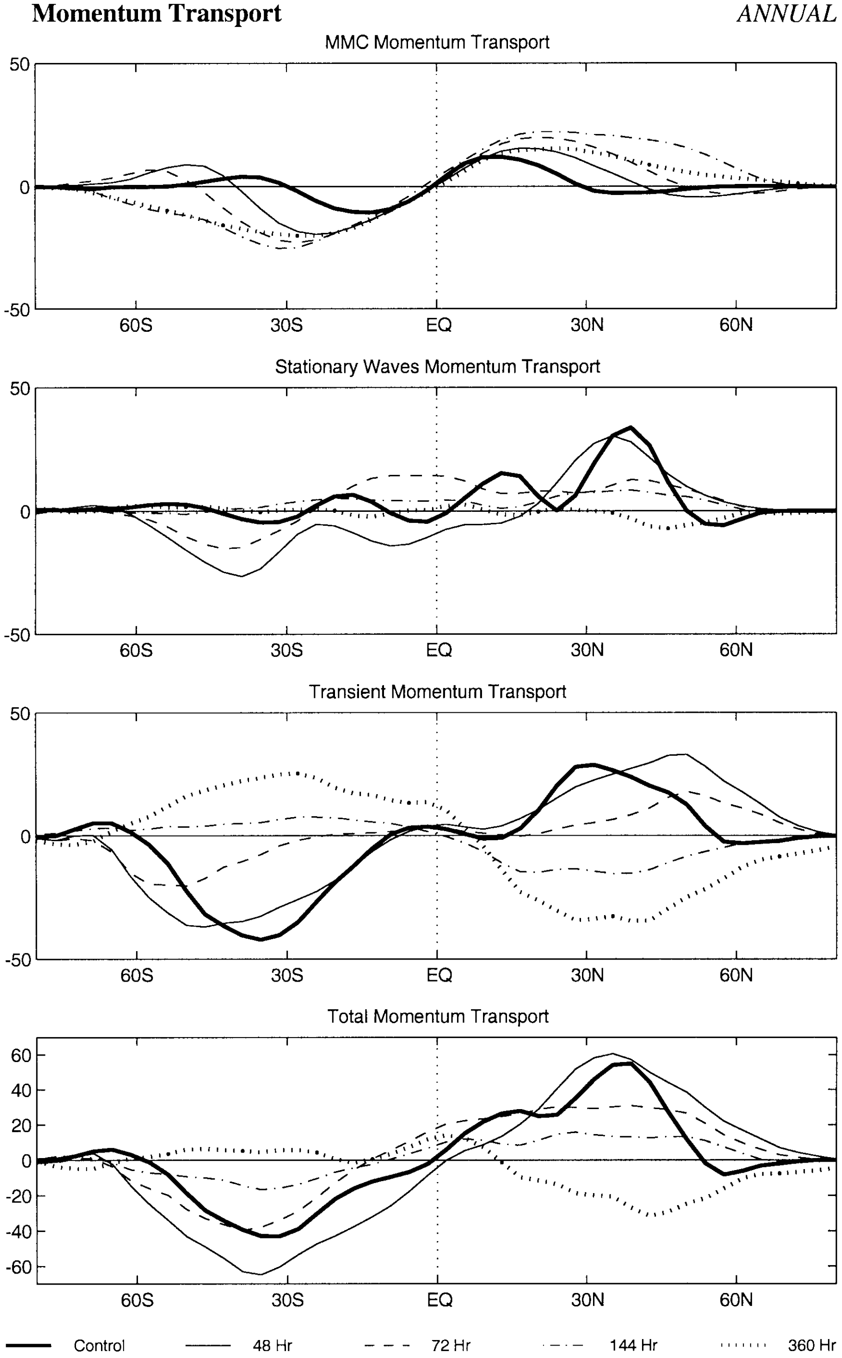


Fig. 5. Vertically integrated northward transport of angular momentum for the cases of 24, 48, 72,144, 360 h rotation. From *top* to *bottom*, transport by the mean meridional circulation, stationary waves, transients and total. Units are 10^{18} Kg m^2/s

expanding the area of the Hadley cell and suppressing the transient sensible heat transport. The total heat transport is then almost entirely taken over by the Hadley cell as baroclinic instability is eliminated. The following diagram (Fig. 9) shows clearly how the mean meridional circulation takes over the transport of heat. Large amounts of sensible heat are carried over to the equatorial region from the tropics and the return flow aloft is not enough to balance it, creating a net divergence of sensible heat from the subtropical region. The transport is so efficient that the meridional temperature gradient is almost entirely wiped out (bottom panel) and the almost flat isotherms reduce the baroclinicity of the flow drastically. The transient transport (Fig. 10) changes character, showing at the slowest rate (bottom panel) the signature of the Hadley cell and indicating that also in this case the transients are now entirely dominated by transients of the Hadley cell itself. An increased efficiency in transporting heat, being the result of an adjustment to a different dynamical state rather than the consequence of a different forcing, necessarily produces a different thermal structure for the atmosphere: the baroclinicity of each hemisphere appears to decrease considerably as the rotation rate decreases (not shown).

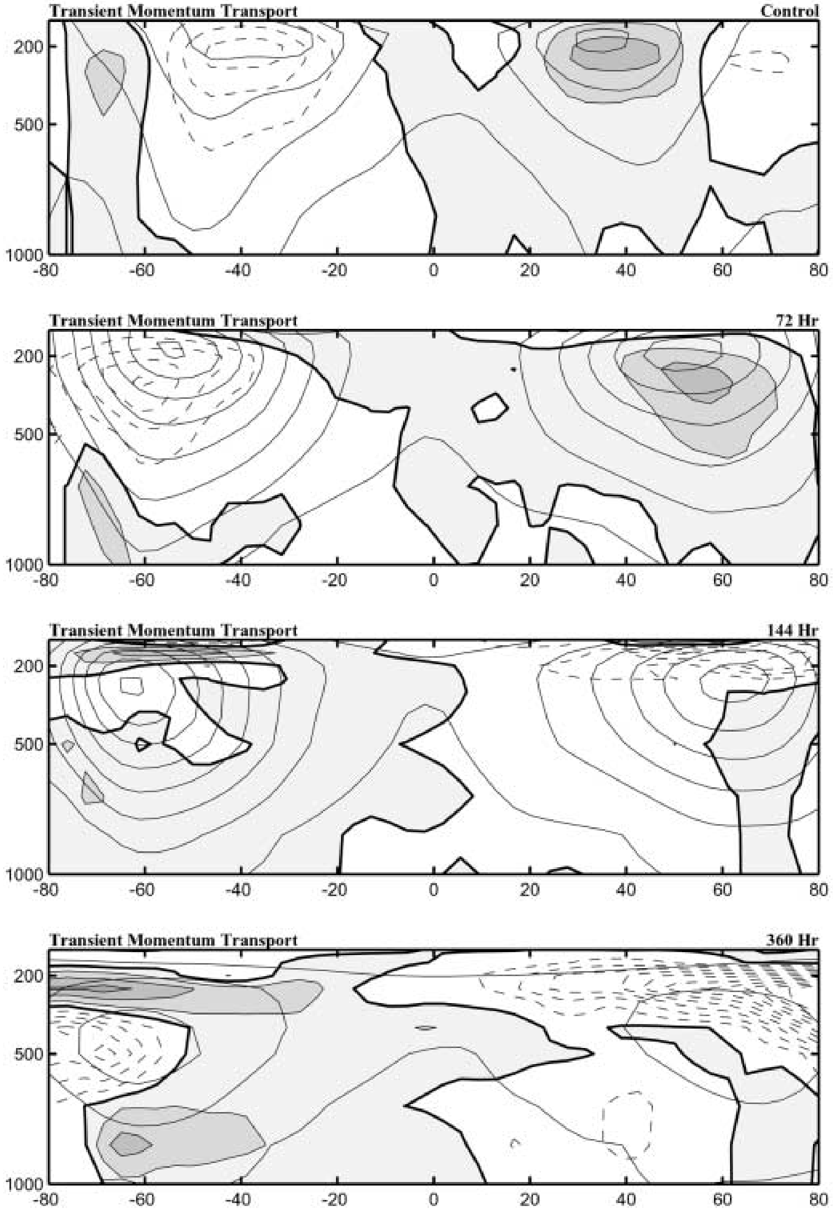


Fig. 6. Zonal mean cross section of the northward momentum transport by transient motions for the selected cases of 24, 72, 144 and 360 h, superposed on the zonal flow for each experiment. Positive values are *shaded*, the contour of the transport is 20 m^2/s^2 The contour of the zonal flow is 10 m/s

The overall conclusion is that the regime that we know from the current planetary conditions breaks down around rotation rates of 144 h. For rotation rates faster than this threshold the general circulation is developed by the same processes we observe from present conditions, albeit modified in extent and intensity by the changes in rotation. The Hadley cell expands according to predictions of the theory and the processes that maintain the circulation are similar to the control. At very slow rotation, however, there is a change in the shape of the circulation. The circulation is characterized by enormous Hadley cells that extend well into the summer hemisphere, whereas flat isotherms preclude instability and the residual variability is due to fluctuations of the Hadley circulation itself.

The eddy-free circulation realized at slow rotation is very reminiscent of the early theory of the general circulation. It is clear from these experiments that this circulation can be easily produced if the rotation rate is sufficiently slow, but what is the mechanism that selects a particular general circulation regime from another? Bjerknes (1937) hypothesized that a circulation like the one obtained for 360 h rotation (eddy free, flat isotherms) would be unstable to a small perturbation for the present condition of our planet. We can verify this hypothesis by performing a time-dependent experiment where we accelerate the Earth from slow rotation to a value similar to what we have today. Figure 11 shows a Hovmoller diagram of the evolution of such an experiment by showing the evolution of momentum transport. A similar picture can be obtained for the sensible heat transport. The top panel shows the mean meridional circulation (MMC) momentum transport. The experiment has been set up starting for convenience at a

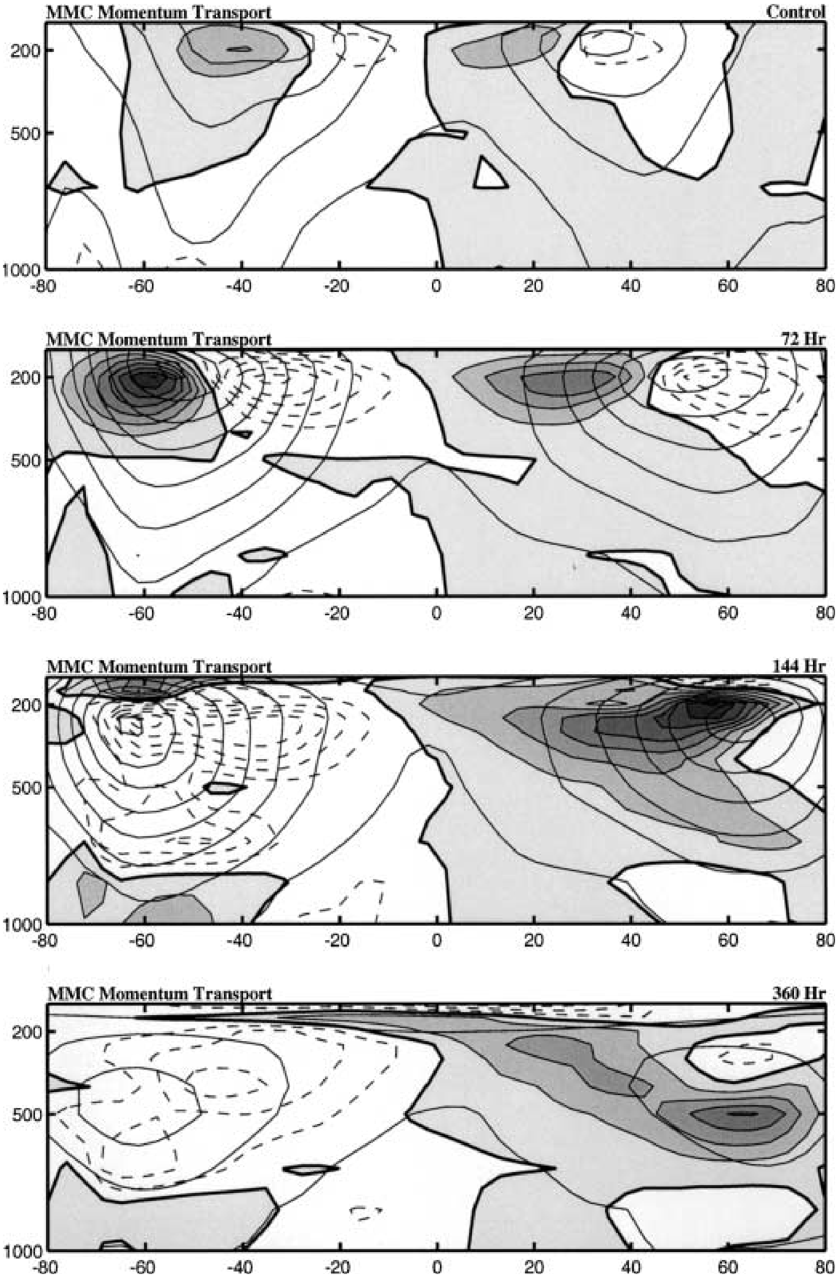


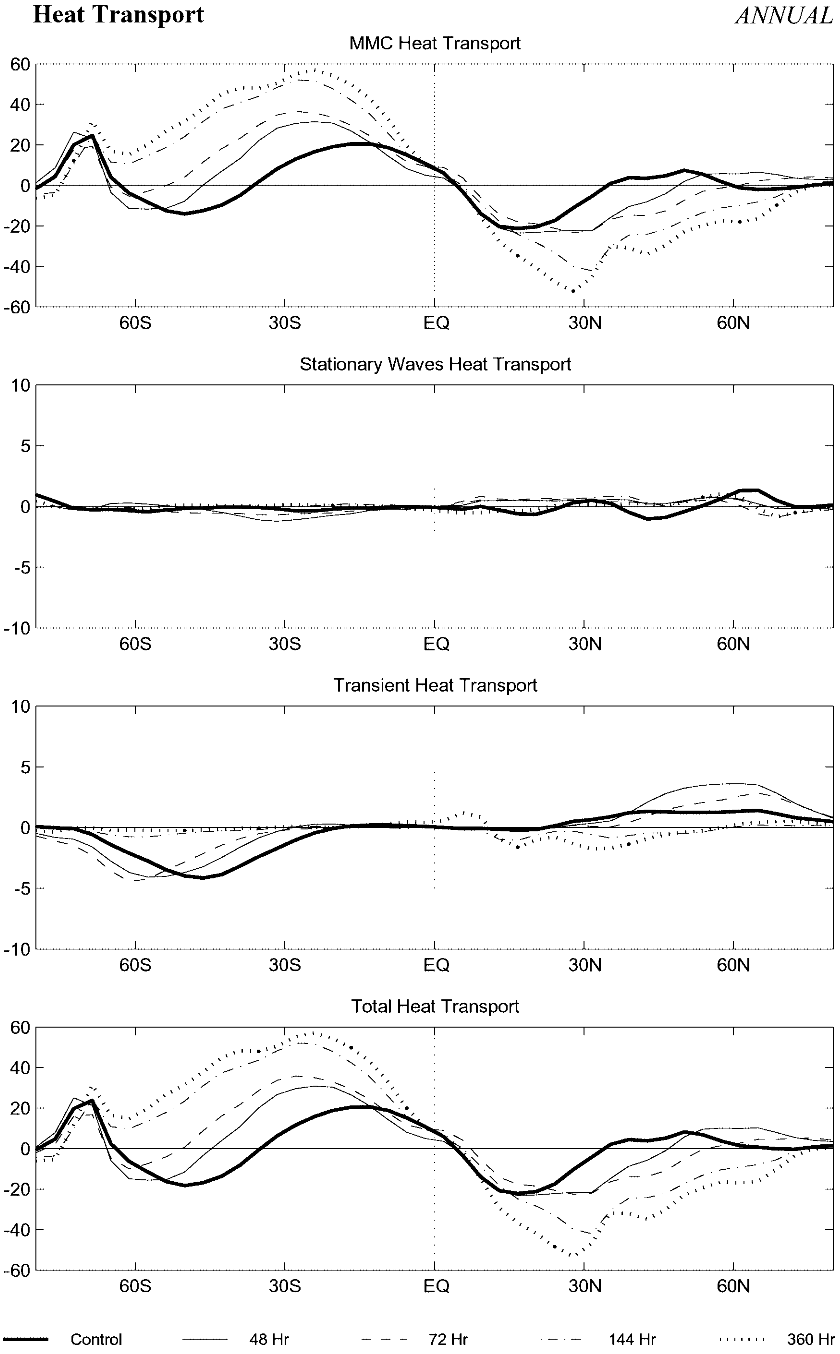
Fig. 7. As in Fig. 6 but for the transport by the mean meridional circulation. The contour interval for the transport is 10 m^2/s^2

rotation of 240 h (that yields a basic state very similar to the 360 h case) from January, continuing for one year and then switching to a rotation of 144 h, continuing for another year and increasing to a rotation rate of 72 h for another three years. The diagram shows the monthly mean transport terms.

The circulation created at 240 h is fairly stable during the transition to 144 h. The cells cover both hemispheres and the seasonal cycle is visible as the cell in the winter hemisphere is stronger than the other. The circulation cannot be maintained once a 72 h rotation is reached. The Hadley cell, visible in the signature of MMC transport, shrinks equatorward and the transient transport becomes more intense. Even more significantly, the stationary waves transport appears to take the familiar form in mid-latitude, although at a more northern latitude than in the control. The transition for this term from the shape indicating asymmetries in the Hadley circulation caused by topography and continents to the shape indicating the presence of long planetary waves is remarkable.

In summary, the eddy-free circulation typical of slow rotation cannot be maintained at faster rotation rates. This regime breaks down under the action of baroclinic eddies and the appearance of eddy-mean flow interactions, creating a mixed regime with a Hadley circulation limited to the neighbourhood of the equator and a wave regime in the mid-latitudes, confirming Bjerknes (1937) idea. Though this is not the first time such a result has been observed (Del Genio and Suozzo 1987); it is however the first time that it was obtained with a fully

Fig. 8. As in Fig. 5 but for the northward transport of sensible heat. Units are 10^{15} W



realistic model with a simple mixed layer to allow for adjustment of the surface temperature.

6 Time mean latitude–longitude response

6.1 Precipitation and SST

A comparison between the precipitation patterns of the 360 hours/day simulation and the simulations of more moderate alterations of rotation rate (Fig. 12) shows some noticeable differences.

The control experiment (top left panel) shows a reasonable simulation of the time mean precipitation distribution, both in winter (January–February–March, JFM) and in summer (July–August–September, JAS). Only JFM is shown for simplicity. The mid-latitude stormtracks in the Northern Hemisphere are well reproduced. The simulation of the tropical rain rates is also generally good, except for the maximum over the Philippines, that is badly underestimated. The South Pacific Convergence Zone (SPCZ) and the oceanic Inter Tropical Convergence Zone (ITCZ) over the Eastern Pacific are well developed. The reduction of the rotation rate produces an immediate

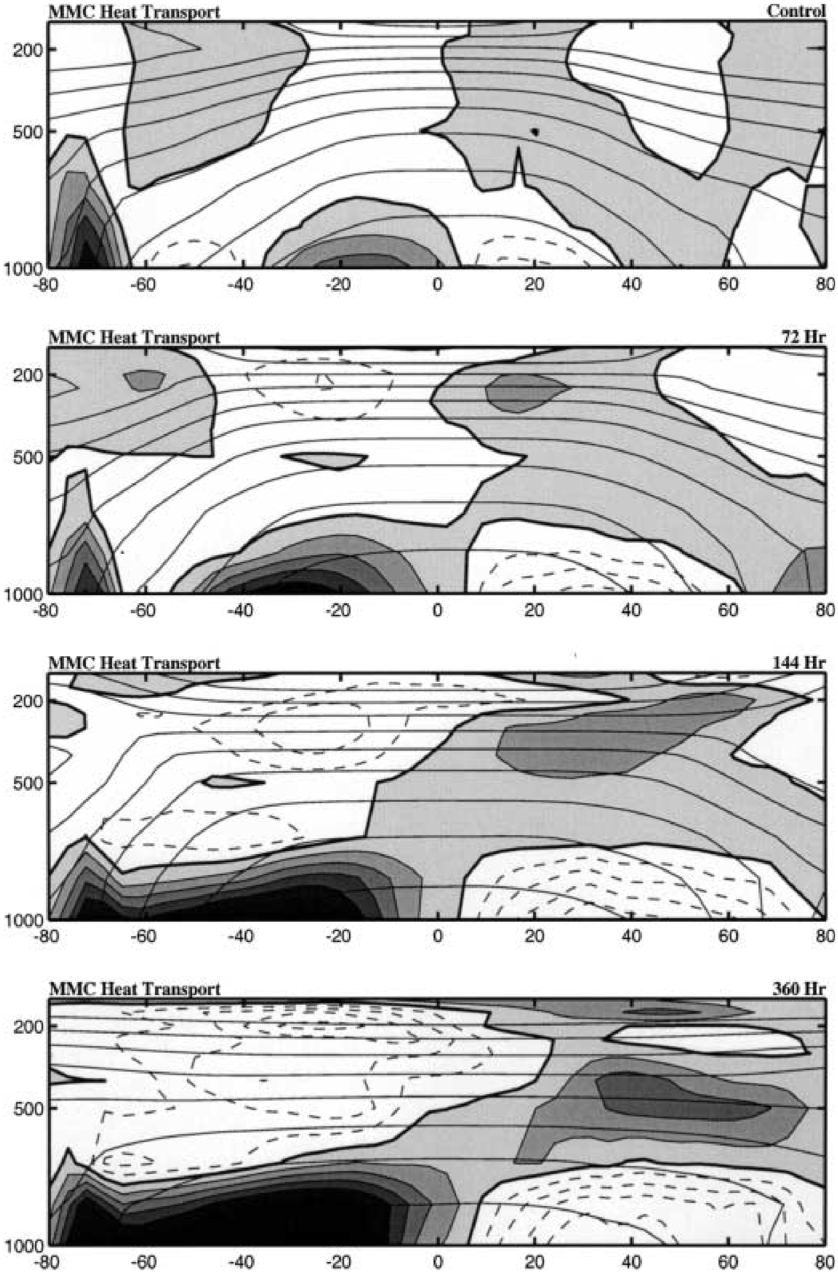
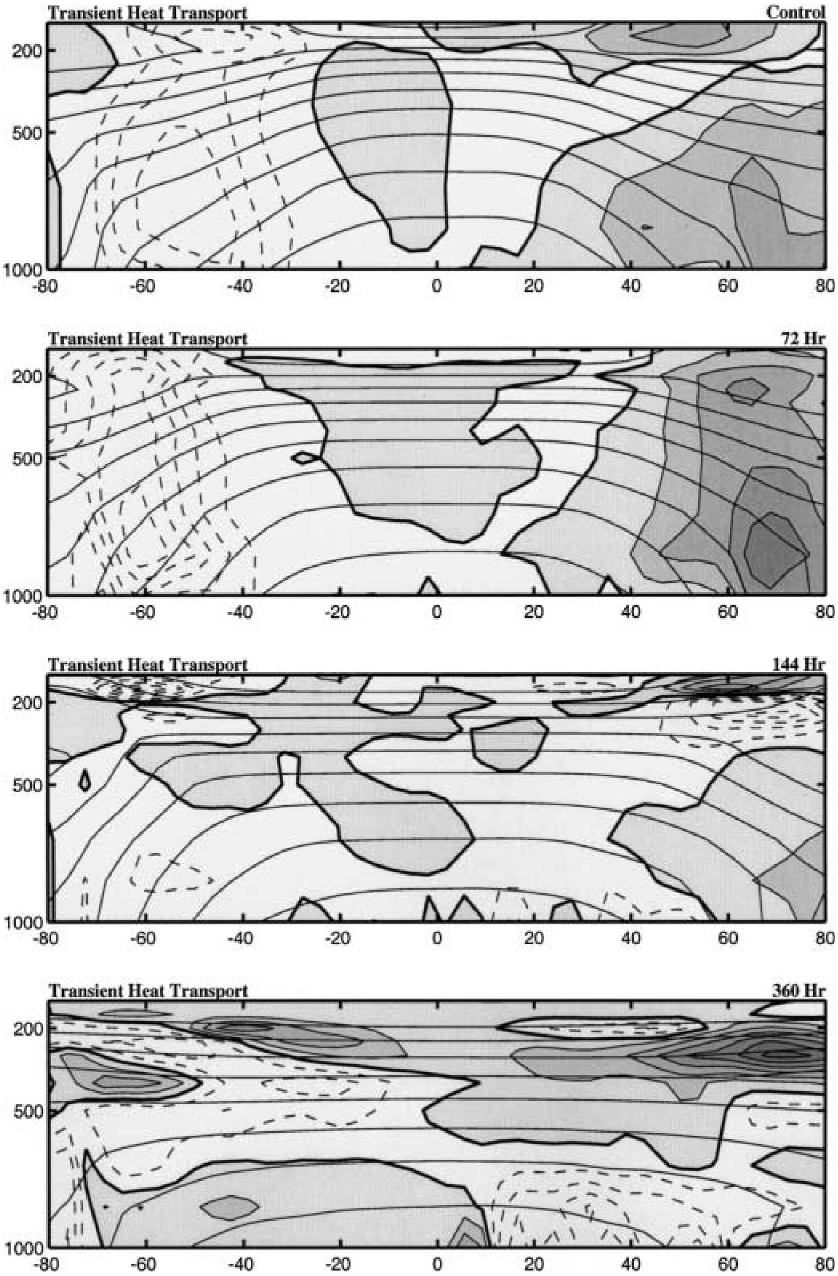


Fig. 9. Zonal mean cross section of the heat transport by mean meridional circulation for the selected cases of 24, 72, 144 and 360 h, superposed on the zonal mean temperature for each experiment. Positive values are *shaded*, the contour of the transport is 200 K m/s and the contour interval for the temperature is 10 K

reduction of the midlatitude storm track precipitation, practically reduced to zero at 144 h rates and slower, and the collapse of the SPCZ that is transformed into an extended equatorial ITCZ already at 72 h, located south and roughly parallel to the equator. The results are consistent with the simplification of the dynamics of the general circulation: a Hadley circulation covers each hemisphere, extending to high latitudes at the expense of typical midlatitude features such as the storm tracks and the precipitation belts poleward of 30° latitude. Intense precipitation are therefore limited to the area where deep convective activity is possible, large-scale precipitation in mid-latitudes is suppressed, another indication of the diminishing role of baroclinic processes. It is interesting to note that the SST distribution is affected in a peculiar way from the changes in rotation. The control experiment (top left panel of Fig. 13) maintains the east–west SST gradient between the west and east Pacific Ocean without difficulty. The weakening of the surface easterly in the Pacific at slow rotation, however, annihilates the east–west SST gradient very rapidly. At 72 h rotation the Walker circulation is eliminated in favour of the newly expanded Hadley cell. It must be remembered that the mixed-layer model includes a term that mimics the present ocean circulation, but it is clearly not sufficient to overcome the changing heating pattern. At 360 h rotation a significant reduction of the north–south gradient also occurs, as the polar regions warm up and the subtropical areas cool off. The relatively cooler SSTs cause a reduction in the intensity of the convective activity.

Fig. 10. As in Fig. 9 but for the heat transport by the transients motions. The contour of the transport is 5 K m/s



The existing theories for the origin and location of the SPCZ involve the low-level forcing of the SST gradients, the land–sea distribution and the tropical-midlatitude influences when the ITCZ interacts with transient midlatitude disturbances (Vincent 1994). Our results show that the SPCZ is significantly weakened when increased rotation rates reduce SST gradients in the western Pacific, especially the east–west gradient, and suppress the role of transient midlatitude disturbances, as it can be seen from the disappearance of the midlatitude storm track. These conclusions are consistent with the findings by Hurrel and Vincent (1992), indicating that land–sea contrast is not the most important factor for the existence of the SPCZ.

6.2 Midlatitude stationary waves

Previous studies (Hunt 1979; Del Genio and Suozzo 1987) have indicated that the horizontal scale of eddies systematically increases as the rotation rate is decreased: smaller longitudinal wave numbers dominate as the rotation period becomes longer.

As an example of the adjustment of spatial scales of wave-like phenomena to a variation in the rotation rate one can consider the response of the stationary eddies of the winter Northern Hemisphere. From Fig. 14 it is clear that as the rotation rate decreases a strong simplification of the pattern occurs. As expected from linear theory (Held 1982) the dispersion relation for Rossby waves,

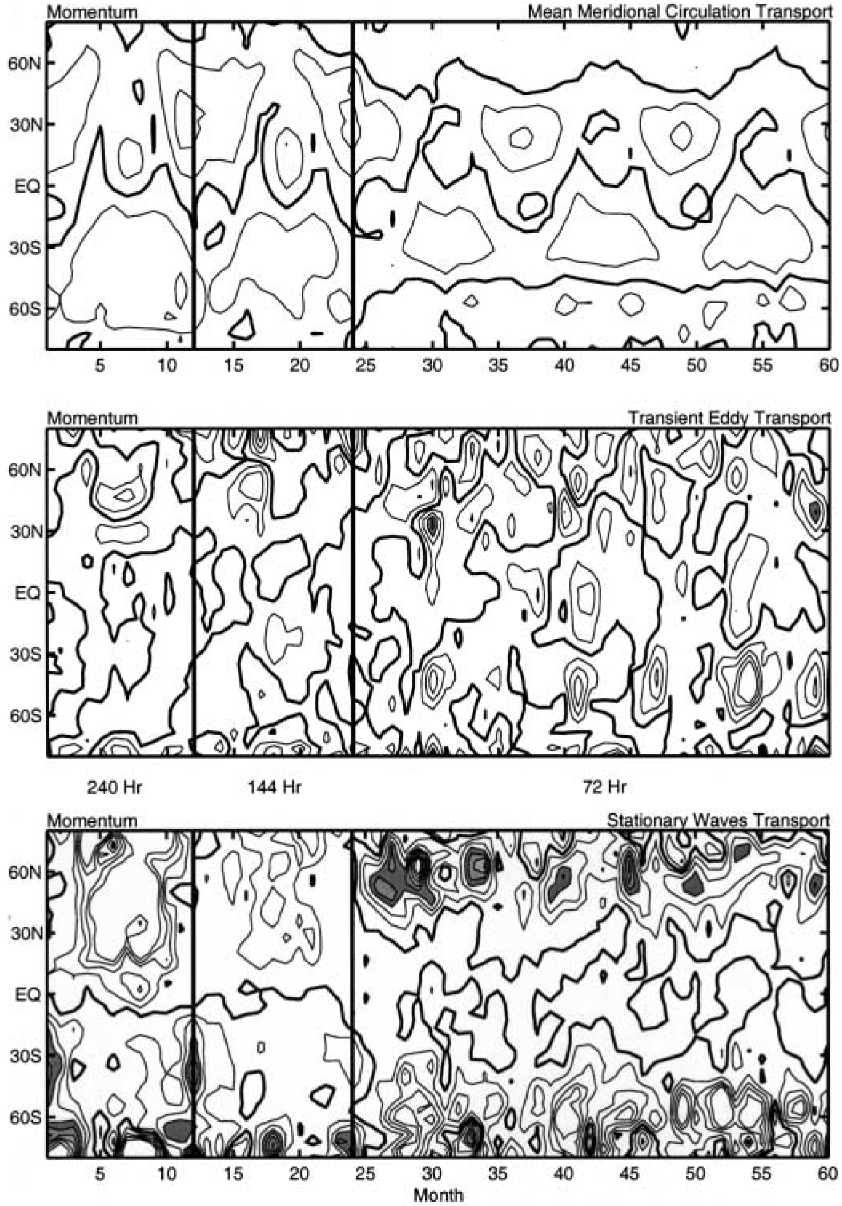


Fig. 11. Hovmoller diagram of the vertically integrated transport of zonal momentum by the mean meridional circulation (*top*), transient motions (*middle*) and stationary waves (*bottom*). The contour interval is 10 m^2/s^2, respectively. Positive values are *shaded*. The diagram has been chosen in order to have the transition from 240 h rotation to 144 h and then to 72 h indicated by the *vertical black lines*. The *horizontal scale* is in months. It is possible to see the sudden increase of transport as the transient develop and the stationary waves start to form

$$\omega = k\frac{[\mathbf{u}](k^2 + l^2) - \beta}{(k^2 + l^2)} \quad , \tag{4}$$

here $[\mathbf{u}]$ is the zonal mean zonal wind, k and l are respectively the zonal and meridional wave numbers, $\beta = 2\Omega\cos\theta$ is the beta parameter and Ω is the Earth rotation rate. The resulting stationary wave number assuming $[\mathbf{u}] > 0$ is given by

$$k^2 + l^2 \equiv K_s^2 = \beta/[u] \tag{5}$$

so that it is expected to decrease with decreasing rotation rate.

The wave number decreases as the trough and crest of the wave become longer. The Himalayan stationary wave train and the Rocky mountain stationary system merge into one wave train centered over the Pacific at 36 h rotation. The effect of the two mountain ranges cannot be distinguished anymore and the resonant wave number is between 2 and 3. The resonant wave number 2 is reached at 48 h and some faint remains can be seen at 72 h, but after this rotation rate the resonant wave number corresponds to a wavelength too long with respect the planetary scale and stationary wave patterns are virtually extinct for slower rotation rates. The sensitivity of the stationary waves is such that it is not necessary to impose very large changes in the rotation to be able to see distinctly their effects. It must be kept in mind that a reduced Walker circulation is still present for these rotations and so the equatorial heating distribution is still somewhat asymmetric in the Pacific, but the main effect is caused by the resonant interaction of the mean flow with the orography. The suppression of

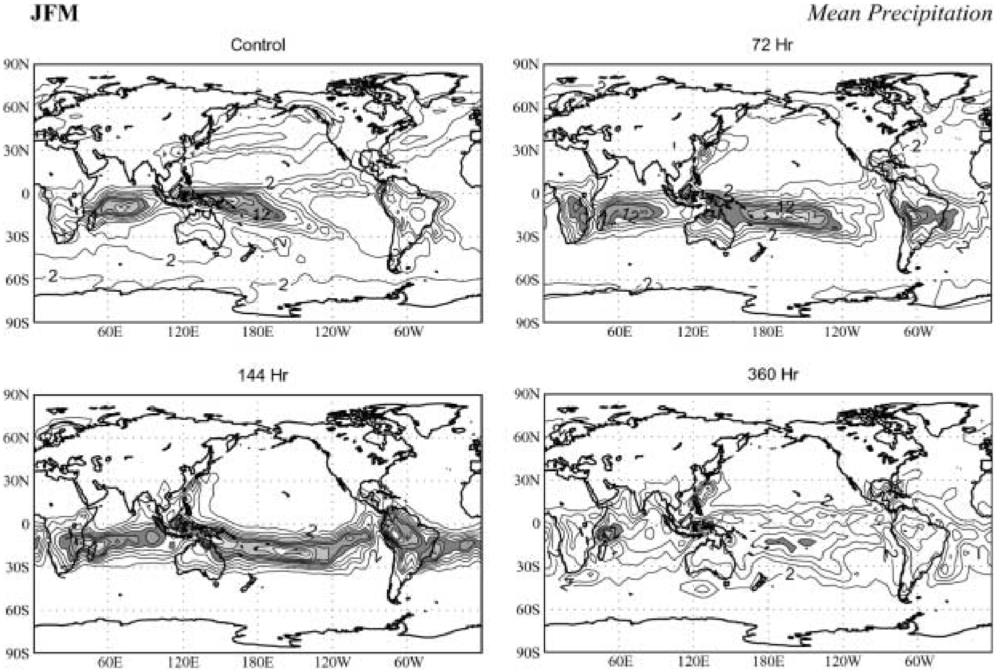


Fig. 12. Winter (*JFM*) total precipitation (in mm/day) for the control experiment (24 h rotation), and other slower rotation cases (72, 144, 360 h). The storm tracks tend to disappear and the ITCZ develop in a simple structure without the development of a SPCZ. The contour interval is 2 mm/day and the values greater than 10 mm/day are *shaded*

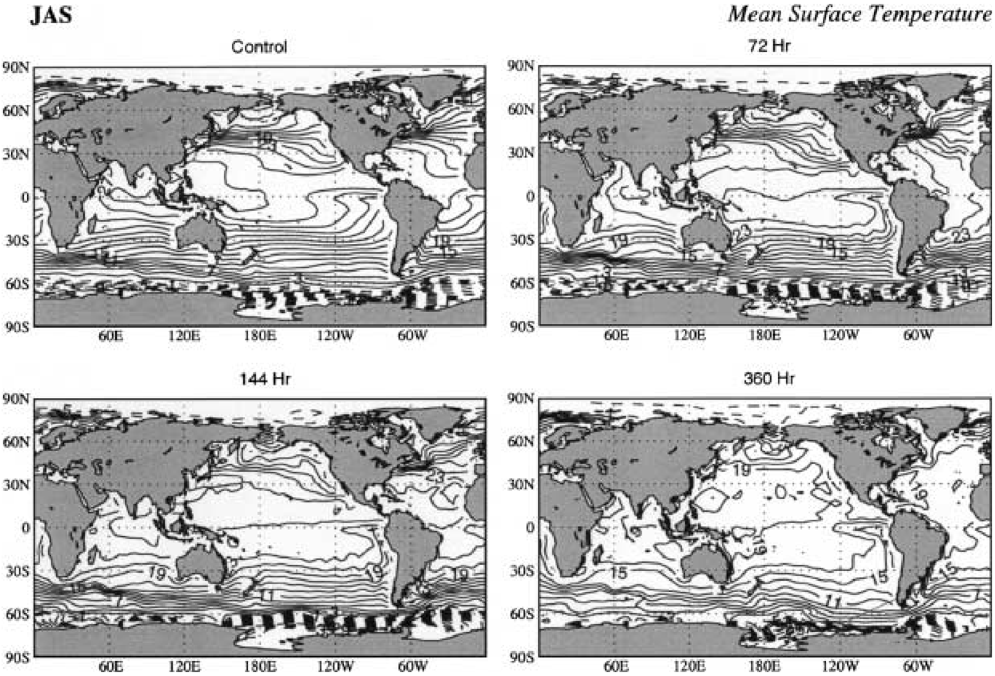


Fig. 13. As in Fig. 12 but for surface temperature. Contour interval is 5 K

the stationary waves is also accelerated by the advance of the surface easterlies north as the planet slows down. The reduction of the westerly flow reduces the areas in which stationary waves are possible, as Eq. (4) requires, in fact, a westerly flow to maintain stationary wave numbers. In the Southern Hemisphere there is a similar general trend for the stationary waves, but the shift towards the pole of the jets causes an amplification of the waves for moderate reductions of the rotation rate before finally subsiding (Fig. 15).

7 Conclusions

The ECHAM4 GCM shows that the present regime of the Earth atmosphere as simulated by the model is the result of the instability, due to the fast rotation rate, of an almost eddy free flow, dominated by the mean meridional circulation. This agrees both with laboratory experiments such as the rotating dishpan experiment and numerical simulations of idealized atmospheres and it is

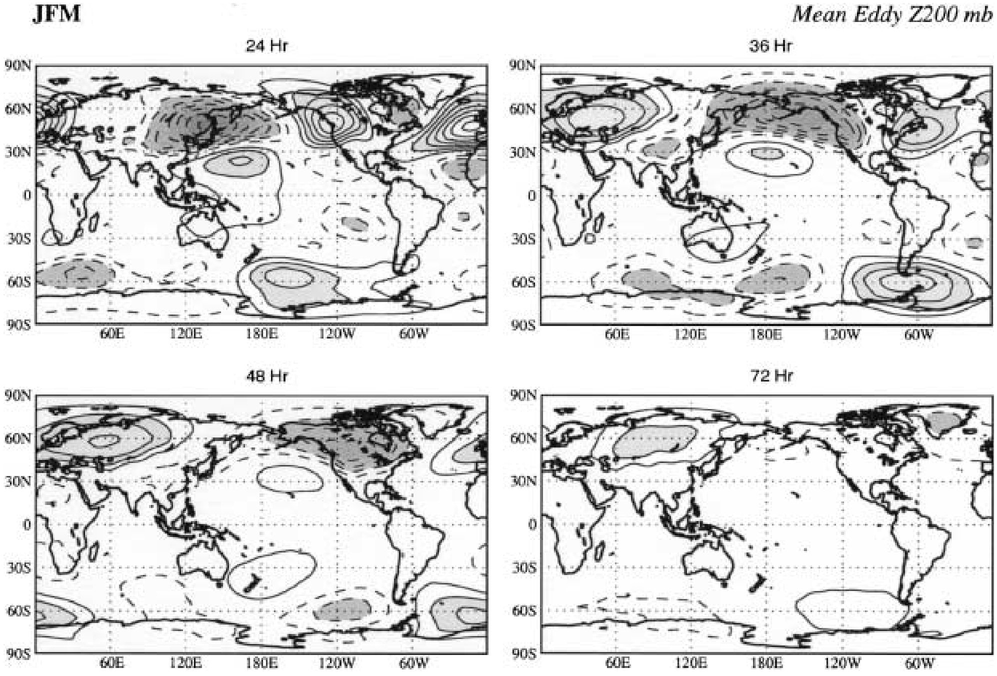


Fig. 14. Winter (January–February–March) northern hemispheric stationary waves (deviation from zonal mean for geopotential heights at 200 mb). The contour interval is 40 m, negative values are *dashed*, values greater than |80| m are *shaded*. The experiments shown are for 24, 36, 48 and 72 h rotation. Cases with even slower rotation rates show no stationary waves

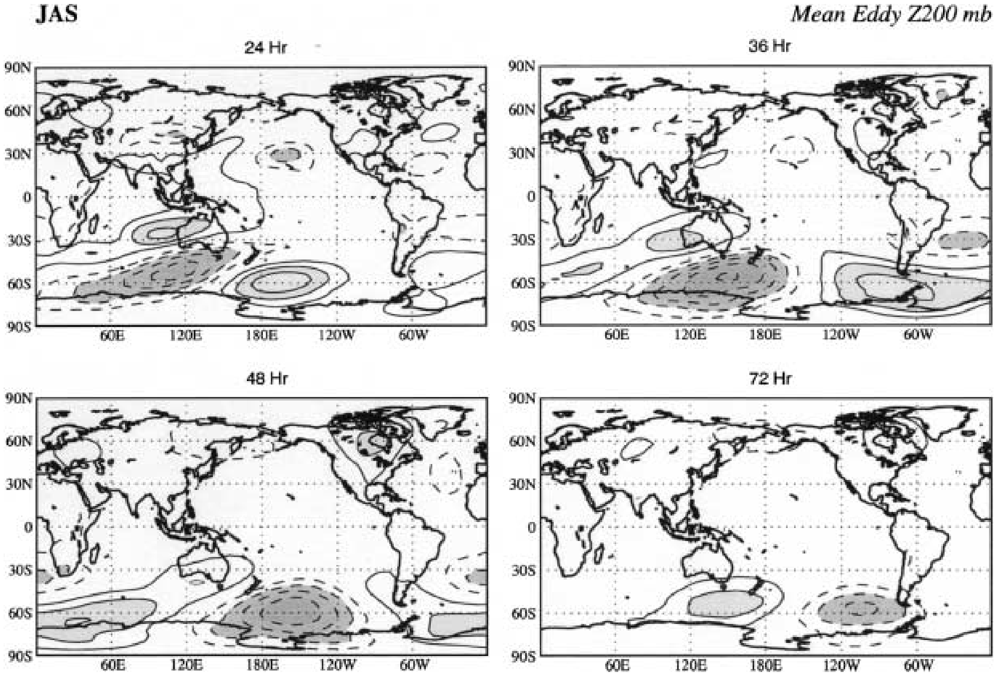


Fig. 15. As in Fig. 14 but for summer months (July–August–September)

an important proof of the "order zero" robustness of the model dynamics and physical parametrizations in a completely different state from the observed one. The model behaves in a dynamically consistent manner under sensitivity to rotation, implying that it is correctly describing the basic climate processes. This result gives some foundations to the application of the model to simulate climates very different from the present climate.

The theory of Held and Hou (1980) appears to fit qualitatively the behaviour of the model, to the extent of the localization of the Hadley cell and its trend with rotation changes. In the case of a very large reduction in the rotation rate the theory appears to break down. The heat transport becomes very efficient at slow rotation and the pole-equator temperature gradient become weak at the surface and virtually disappears aloft.

As expected the eddy mean flow interaction strongly affects the zonal mean state of the atmosphere. The strength of the subtropical jet streams appear to be the most evident proof of this interaction. While the transports of momentum and heat by transients move poleward as the rotation rate decreases, the jet streams increase in strength following the peak of the eddy transport and tends to substantially weaken when the rotation is minimal. The stationary asymmetries of the circulation tend to disappear as the resonant wavelength gets longer and longer and finally become longer than the planet and stationary waves are not possible. The weakening of the westerly also contributes to the suppression of the standing Rossby waves.

Another interesting result is the quick disruption of the SPCZ. The SPCZ disappears at the same time as the SST gradients in the west Pacific are weakened and the transient mid-latitude activity is suppressed, confirming the conclusion that these two processes are the main factors regulating the location and existence of the SPCZ.

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