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ITCZ Splitting and the Influence of Large-Scale Eddy Fields on the Tropical Mean State

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Abstract

A spectral aqua-planet atmospheric general circulation model (AGCM) is forced with a series of zonally constant sea surface temperature (SST) distributions which are symmetric about the equator. For every oceanic forcing, the AGCM is run twice; a first time keeping all spectral modes and a second time with only the zonally symmetric ones. Parameterizations and boundary conditions remain the same in all cases thus allowing a consistent comparison of 3-D and 2-D flows. The comparative study shows that the structure of the tropical mean state of the full model is basically captured by the zonally symmetric model and that eddy fields merely modify this structure. This shows that the structure of the tropical mean state is mainly determined by the shape of the effective SST forcing. We confirm previous studies where the shape and strength of the Hadley circulation is comparable in the 3-D and 2-D experiments for cases with a well pronounced single ITCZ. So the underestimation of the Hadley circulation often found in idealized zonally symmetric models is not only due to the neglect of large-scale eddy fields. A new result is that both the full as well as the zonally symmetric model show the phenomenon of ITCZ splitting if the SST distribution gets *flat* enough at the equator. So ITCZ splitting can be explained by purely zonally symmetric mechanisms and is not necessarily induced by eddy fields. Eddies seem to stabilize single ITCZ circulation regimes. For SST distributions where ITCZ splitting occurs, multiple states exist in the zonally symmetric model. The atmosphere switches, for the same SST, between a single and double ITCZ state introducing a long-term variability in the tropics without the influence of mid-latitudes and without atmosphere-ocean coupling.

1. Introduction

The question about the importance of large-scale eddies for the tropical mean state has a long tradition. Already in the work of Schneider and Lindzen (1977), the question is raised if eddies are absolutely crucial in producing the observed time and zonally averaged mean circulation or if they merely produce qualitative modifications. In a series of follow up investigations, as for example in Held and Hou (1980), Satoh (1994), and Fang and Tung (1996), it was shown that the basic characteristics of the tropical mean state, such as the Hadley cell and subtropical jets, can be nicely reproduced by purely zonally symmetric models. An important drawback of the above models is underestimation by an order of magnitude of the transport of the Hadley circulation.

Several improvements to the zonally symmetric approach have been achieved by poleward shifting (Lindzen and Hou 1988) or by concentrating (Hou and Lindzen 1992) the convective heat source. The investigations of Held and Phillips (1990) show that the feed-

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back between a single Rossby wave and the Hadley circulation in a shallow water model exhibits highly nontrivial feedback behavior.

Starting from the first satellite observations, it was obvious that the tropical circulation was highly variable in space and time (see e.g., Hubert et al. 1969). Since then, the question about position and structure of the ITCZ has become an important issue. Numerical atmospheric general circulation models are very sensitive in the deep tropics and often have problems in reproducing the correct structure of the ITCZ, also on climatological time scales (see e.g., Zhang and Wang 2006 and references therein.) For conceptual models, there is the fundamental question about the processes which determine the position of the ITCZ and the connected phenomenon of ITCZ splitting.

Two different paradigms have been established. One paradigm which goes back to at least the pioneering work of Charney (1971) is based on purely zonally symmetric mechanisms. The other paradigm put forward by Holton et al. (1971) is based on equatorial waves which are by definition not zonally symmetric. Which of the two paradigms is the more appropriate one is up to now under discussion. On the one hand, the dynamics of the ITCZ are dominated by waves (see e.g., Wheeler and Kiladis 1999). On the other hand, the climatological circulation in the tropics is captured, to a large extent, by the stationary mean, as already described in Lorenz (1967).

In our investigation we quantify the influence of eddy fields by comparing two runs of the same model, one time with all spectral modes and another time only with the zonally symmetric ones. We use an AGCM with parameterized radiation, moisture processes and turbulent processes. In our investigations only the boundary conditions are prescribed, so that the circulation, eddy-fields and diabatic heating are free to adjust to a statistically equilibrated state. This means that the structure of the ITCZ and baroclinic zones change from case to case.

Satoh et al. (1995) did similar experiments showing that the Hadley cell had comparable width and strength in the 3-D and 2-D cases for a large range of rotation rates. We confirm this result in our investigations, supporting the view that the result is of a more general nature since their model and our model have two different sets of parameterizations and two different temperature differences between equator and pole. Our analysis is extended to the hydrological cycle and focuses more on the phenomenon of ITCZ splitting.

Becker et al. (1997) have also investigated the feedback between eddy fields and the Hadley circulation using the same method. In contrast to us, they used a dry primitive equation model in which the strength and location of the tropical heat source (ITCZ) is prescribed a priori. A similar method was used in Kim and Lee (2001a, b), but their model is a dry primitive model driven by Newtonian cooling without an explicit hydrological cycle. So the mean circulation, eddy fields, and hydrological cycle are not free to adjust.

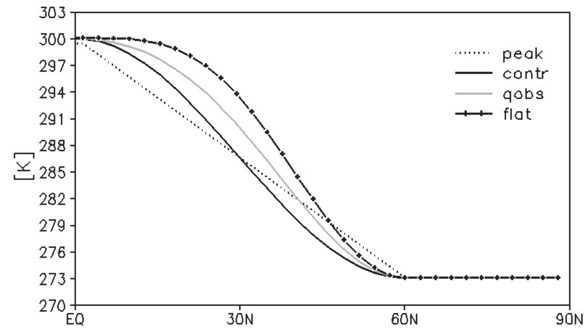

Fig. 1. Idealized zonally symmetric SST distributions: peak, control, qobs, and flat (northern hemisphere only).

In a more recent study, Walker and Schneider (2006) investigate the influence of eddies on the Hadley cell using an idealized aqua-planet AGCM forced by Newtonian cooling. Changing the rotation rate and the planetary radius, they derive scaling laws for the strength and the extent of the Hadley cell. Modifying the reference temperature and relaxation times produces different eddy regimes. In their study, eddy fields are not suppressed in a controllable way and no hydrological cycle is included in the model.

Moist Hadley cell dynamics have been analyzed in previous studies. Numaguti (1993, 1995) focuses in his studies on the role of surface evaporation and the influence of the position of the maximum SST on the Hadley circulation and the ITCZ in a series of numerical experiments. Frierson (2007) compares different idealized convection schemes and their role for the zonal mean circulation of the tropics.

Our article is organized as follows: In Section 2 the model and experimental set-up are described, in Section 3 the zonally symmetric model is compared to the climatological mean fields of the full model. In addition the structural variability is discussed. A summary of the results and a conclusion are presented in Section 4.

2. Model and experimental design

The numerical model applied for this study is the Planet Simulator (Fraedrich et al. 2005), a model of intermediate complexity (MIC). It is freely available under http://www.mi.uni-hamburg.de/plasim. The dynamical core is based on the Portable University Model of the Atmosphere (PUMA; Fraedrich et al. 1998). The primi tive equations are solved by the spectral transform method (Eliasen et al. 1970, Orszag 1970). Unresolved processes are parameterized. The parameterization packet includes long- (Sasamori 1968) and short- (Lacis and Hansen 1974) wave radiation with interactive clouds (Stephens 1978; Stephens et al. 1984; Slingo and Slingo 1991). A horizontal diffusion according to Laursen and Eliasen (1989) is applied. Formulations for boundary layer fluxes of latent and sensible heat and for vertical diffusion follow Louis (1979), Louis et al. (1982), and Roeckner et al. (1992). Stratiform precipitation is generated in supersaturated states. The Kuo scheme (Kuo 1965, 1974) is used for deep moist convection while shallow cumulus convection is parameterized by means of vertical diffusion.

For the present study, a T42 spectral resolution (approx. 2.8° on the corresponding Gaussian grid) is used with ten non-equally spaced σ-levels in the vertical. All experiments are carried out in an aqua-planet mode, i.e. a planet completely covered by an ocean with prescribed surface temperature. The model is run under perpetual equinoctial conditions so that seasonal variations are suppressed. To keep the external forcing fully zonally symmetric, we have additionally suppressed the annual cycle of ozone concentration.

Four zonally symmetric sea surface temperature distributions are applied. The SST profiles are based on Neale and Hoskins (Neale 2001b). We used the distributions *peaked*, *control*, *qobs*, and *flat*. All four profiles show their maximum temperature (300.15 K) at the equator. Between the equator and 60° north and south, the SST decreases monotonically. As sea-ice is excluded from the experiments, the SST is fixed at a constant value of 273.15K poleward of 60°. The SST profiles are displayed in Fig. 1. The *peaked* SST profile leads to the strongest surface temperature gradient around the equator, while the *flat* SST profile shows an almost uniform temperature distribution in the tropics. The *control* and the *qobs* profiles contain tropical SST gradients that are weaker than in the *peaked* and stronger than in the *flat* experiments. In the midlatitudes the situation is reversed: there, the *flat* SST profile shows the largest temperature gradient.

A beneficial property of the Planet Simulator is that the simulated circulation remains zonally symmetric if the model is initialized in a zonally symmetric state and is driven by zonally symmetric boundary conditions. Using this feature, two experiments are implemented for each of the four SST profiles: One in the zonally symmetric mode and one in the full mode (i.e., including the full eddy spectrum). The latter is obtained by initializing the model with a small, random, zonally asymmetric perturbation in the surface pressure. The resulting eight experiments are summarized in Table 1.

Table 1. Experiments carried out.

	Experiment	SST	Model
1	*peaked full*	peaked	full
2	*peaked sym*	peaked	zonally symmetric
3	*control full*	control	full
4	*control sym*	control	zonally symmetric
5	*qobs full*	qobs	full
6	*qobs sym*	qobs	zonally symmetric
7	*flat full*	flat	full
8	*flat sym*	flat	zonally symmetric

All simulations are run for two years (730 days). To account for the spin up, only the last year is analyzed. As the set-up of the experiments has symmetric conditions about the equator, the results are shown for the northern hemisphere only.

3. Results

In the following, we analyze how the eddy fields influence the tropical mean state for the different SST forcings.

3.1 Structure of the tropical mean state

Going from the *peaked*, over the *control* and *qobs*, to the *flat* SST forcing, the atmospheric response of the full Planet Simulator model shows typical aqua-planet behavior which is comparable to the results of previous studies (see for example Neale and Hoskins 2001a).

As illustrated in Figs. 2 and 3, we find for the *peaked* and *control* SST distributions, in the full as well as in the symmetric case, single ITCZ circulation regimes with a well pronounced ITCZ, an intense Hadley cell, and strong subtropical jets. In the *peaked* case, the precipitation is nearly the same ($\approx$ 25 mm d^{-1}) as in the full and zonally symmetric case. The main difference is the missing mid-latitude local rain maximum in the zonally symmetric model. At the same time the subsidence zones receive more precipitation and the relative humidity (Fig. 4, only shown for the *control* case as an example) is higher when large-scale eddies are

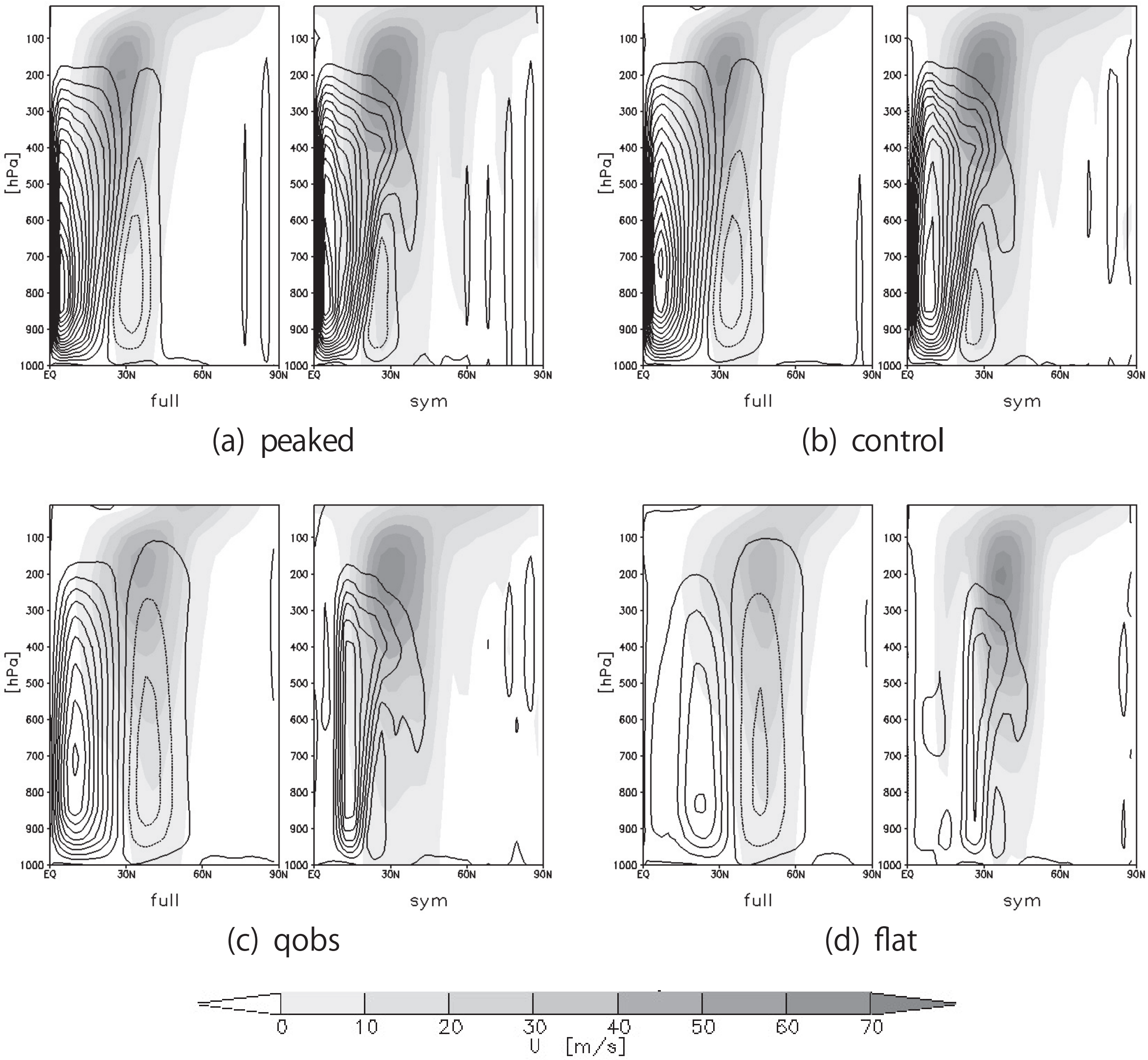

Fig. 2. Eulerian mean mass stream function (isolines, 2×10^{10} kg s^{-1}) and mean zonal wind (dark shading: westerly winds, white: easterly winds) for full and zonally symmetric (a) peak, (b) control, (c) qobs, and (d) flat SST profiles.

present. This feature is even more pronounced for the other SST cases. Even though extra-tropical cyclones can cause dehydration of the subtropics (see for example Galewsky et al. 2005), in our case, eddy-transport of moisture (see Subsection 3.2) leads to a moistening of the subsidence regions.

In the *control* case we observe more pronounced differences. Here the eddy fields concentrate and strengthen the mean tropical precipitation zone. The strength of the Hadley circulation is comparable in both cases. The maximum of the Eulerian mean stream function is located in the lower half of the troposphere and reaches 28×10^{10} kg s^{-1} for the *control* full case and 22×10^{10} kg s^{-1} for the *control* sym case. The structure and location of the subtropical jets are again very similar. The jet maximum is stronger in the *control* sym case (76 m s^{-1}) than in the *control* full case (60 m s^{-1}), which is due to a stronger upper tropospheric meridional temperature gradient in the zonally symmetric model. Stronger subtropical jets in the zonally symmetric cases are also observed for all other SST distributions (for further explanation, see Subsection 3.2).

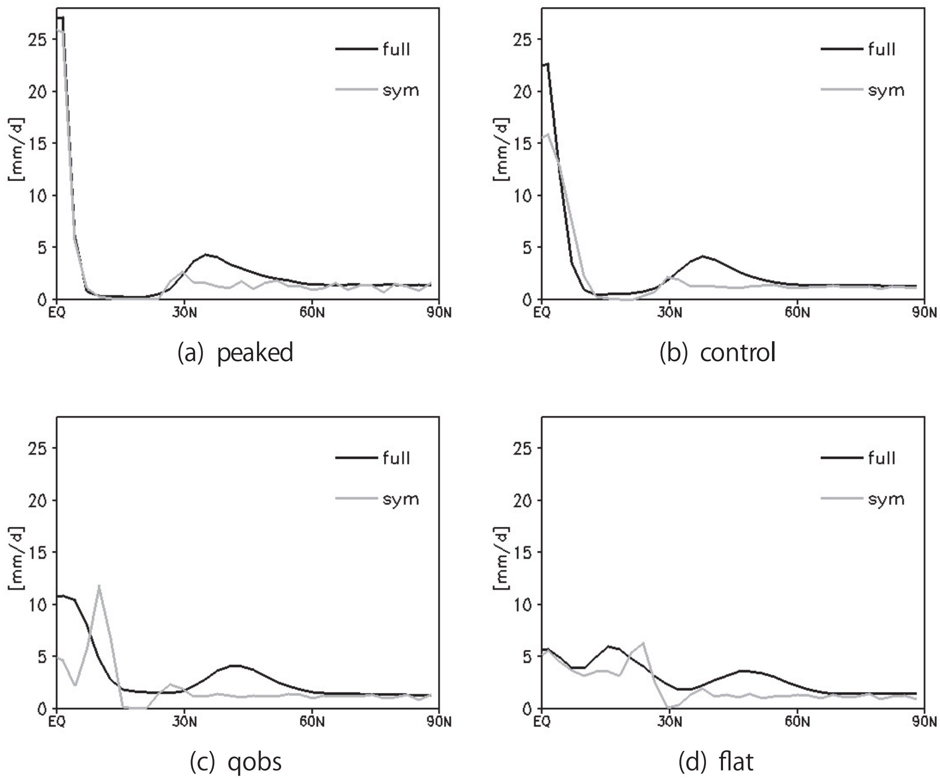

Fig. 3. Zonal mean total (large scale and convective) precipitation (in mm d^{-1}).

Significant structural differences are observed for the *qobs* and *flat* SST distributions which are less steep at the equator. In the *qobs* full case, the eddy fields stabilize the single ITCZ regime leading to a single broad precipitation peak at the equator. In the *qobs* sym case, on the other hand, a double ITCZ is observed. Taking the precipitation maximum at the equator into account, we can even talk of a triple ITCZ regime. In the *flat* case, eddy fields induce an equatorward shift of the tropical rain bands. At the same time subtropical jets are shifted poleward.

Not surprisingly, the greatest differences between full and zonally symmetric model runs occur for the Ferrel cell, which is basically driven by large-scale transient eddy fields. In the zonally symmetric model the Ferrel cell nearly vanishes. Only in the lower levels of the atmosphere, a small and weak indirect cell develops which, as we will see in Subsection 3.2, is driven by vertical subgrid-scale diffusion.

The differences in the local evaporation efficiencies between the full and the zonally symmetric model are rather small (not shown). For example, the stronger precipitation inside the ITCZ in the *control* full case ($\approx$ 23 mm d^{-1}), compared to the *control* sym case ($\approx$ 16 mm d^{-1}), cannot solely be explained by stronger surface evaporation. The precipitation maximum in the full experiment is approximately 7 mm d^{-1} stronger, however, in the tropics the evaporation efficiency is only 1 mm d^{-1} greater than in the zonally symmetric case. The difference can rather be explained by an enhanced moisture transport toward the equator (see Fig. 6a).

The dry and moist static stabilities do not differ significantly between the different cases. The vertical profiles of the potential temperatures (moist and dry, not shown here) at various locations are very similar in all simulations, as the tropics follow the moist adiabatic curve and the maximum SST is the same in all cases.

3.2 Diabatic heating and mean meridional transports

To get a deeper insight into the processes which cause the differences between full and zonally symmetric cases, we analyze the heating rates and the mean meridional transports of specific moist static energy, moisture and momentum. We restrict ourselves to the

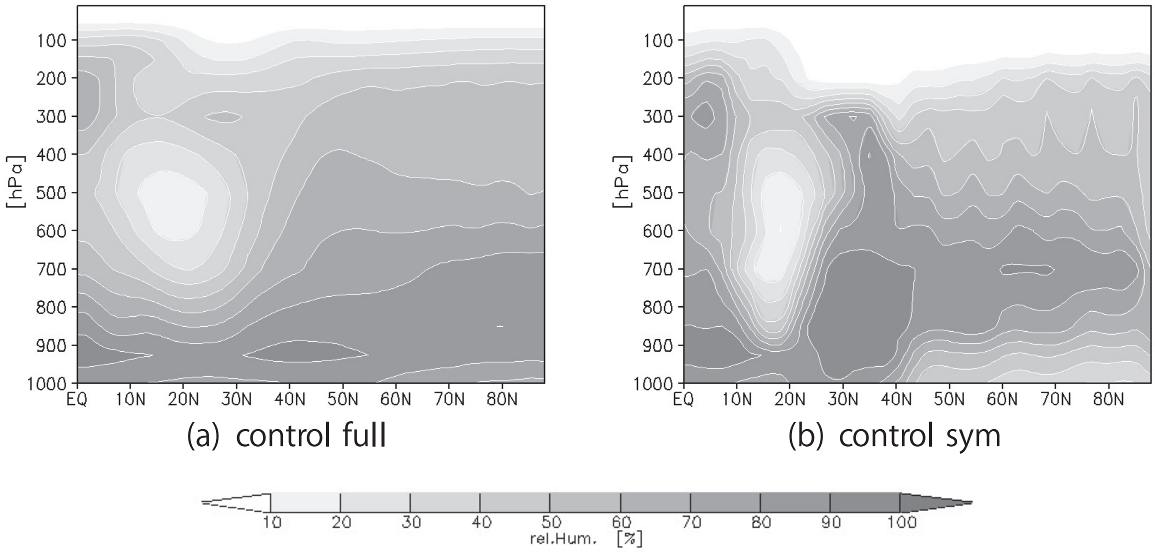

Fig. 4. Zonal mean relative humidity (in %) for the *control* case in the full and the zonally symmetric model.

control case as a representative example.

Figures 5a and 5b represent the total diabatic heating rates and show that the structure of cooling and heating areas are, to a large extent, the same in the full and symmetric case. The main differences are of a quantitative nature and occur within the ITCZ where convective heating dominates and within the subsidence areas where radiative cooling and eddy heat flux divergence dominate. We observe a much stronger convective heating for the full run (10 K d^{-1} compared to 4 K d^{-1}). In the areas of subsidence, we have in the symmetric case a stronger cooling (up to 4 K d^{-1}) in the upper troposphere at the poleward boundary of the Hadley cell. As can be seen from Figs. 5c and 5d, the difference is due to stronger long-wave cooling as well as stronger vertical diffusion. The subgrid-scale vertical diffusion transports heat downward and locally heats the troposphere leading to a small Ferrel cell in the lower troposphere for all symmetric cases. In the full cases, the Ferrel cell is induced by the divergence of the transient meridional eddy heat flux (not shown). The more horizontal orientation of the heat transport induced by large-scale eddies explains the different shapes of the Ferrel cells.

To clarify the dynamical role of the eddy fields for the climatological mean, we now study the vertically integrated meridional transports shown in Figs. 6a–c. Decomposing the total meridional transports of the full model into a stationary mean and transient eddy part (the other parts can be neglected in our case), and then comparing the results to the transports of the zonally symmetric model shows the direct and indirect influence of the eddy fields.

The influence of the eddy fields is the weakest for the hydrological cycle. Here the zonally symmetric model is a good approximation for the full model within the Hadley cell and for the stationary mean part everywhere. The direct influence of the eddy fields is to transport moisture poleward and to feed the precipitation zones in the mid-latitudes.

For the momentum transport the picture gets more complex. We only have good agreement between the full and the zonally symmetric model equatorward of $\pm 10°$. For the other latitudes, the transient eddy transport dominates. The new feature here is that the eddy fields also influence the stationary mean part of the poleward momentum transport, indicating a more interdependent feedback mechanism between eddy fields and the stationary mean circulation.

For the meridional energy transport, we have a similar picture with a good agreement between the full and zonally symmetric model for latitudes between $\pm 15°$. In this case we also observe a feedback mechanism between eddy fields and the stationary mean part which dominates the transport. At higher latitudes, the energy transport differs significantly in the two models.

Figure 6d illustrates this fact from the point of view of the vertically integrated atmospheric energy budget, which is the same as the horizontal divergence of the

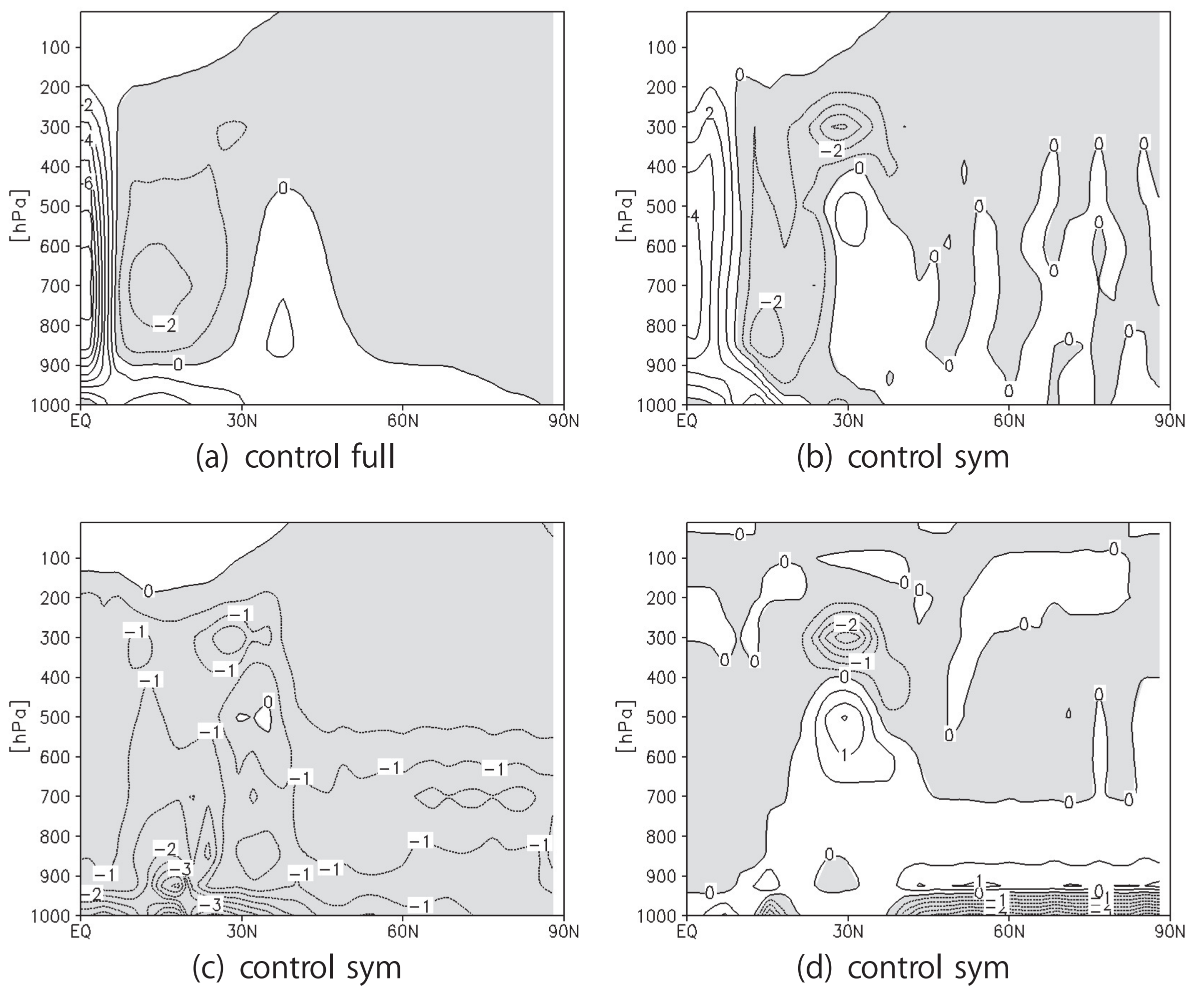

Fig. 5. Zonal mean temperature tendency dT/dt of all diabatic processes for (a) control full (in 1 K d^{-1}) and (b) control sym (in 1 K d^{-1}) and dT/dt (c) due to radiation for control sym (in 0.5 K d^{-1}) and (d) vertical diffusion for *control* sym (in 0.5 K d^{-1}). Cooling areas are shaded.

moist static energy fluxes. We see that the atmosphere starts to lose energy poleward of roughly $\pm 20°$. The large drop in the *control* sym case is largely due to the missing eddy induced latent heat flux within and poleward of the Hadley cell. The smaller poleward transport in the symmetric case leads to a less negative net radiation budget at the surface in polar regions, whereas the surface heat flux remains nearly the same.

3.3 *Time dependence of the zonal mean structure*

To illustrate the variability differences of the circulation in the full and zonally symmetric model, we analyze the structure of the deep convective zones (ITCZs), subsidence zones, and the precipitation maxima of the mid-latitudes. We use Hovmöller diagrams of the zonal mean total precipitation (see Fig. 7).

The Hovmöller diagrams confirm once again the main result of our investigation, that the eddy fields do not modify the structure of the tropical mean state qualitatively except in the *qobs* case. So in the *peaked*, *control*, and *flat* cases, the mean position and width of the subsidence zones are nearly the same in the full and zonally symmetric model. Only in the *qobs* case we observe substantial differences since we compare two different circulation regimes.

The most obvious impact of the eddy fields is the variability of precipitation introduced in the extra-tropical cyclones of the mid-latitudes. In the tropics, the eddy

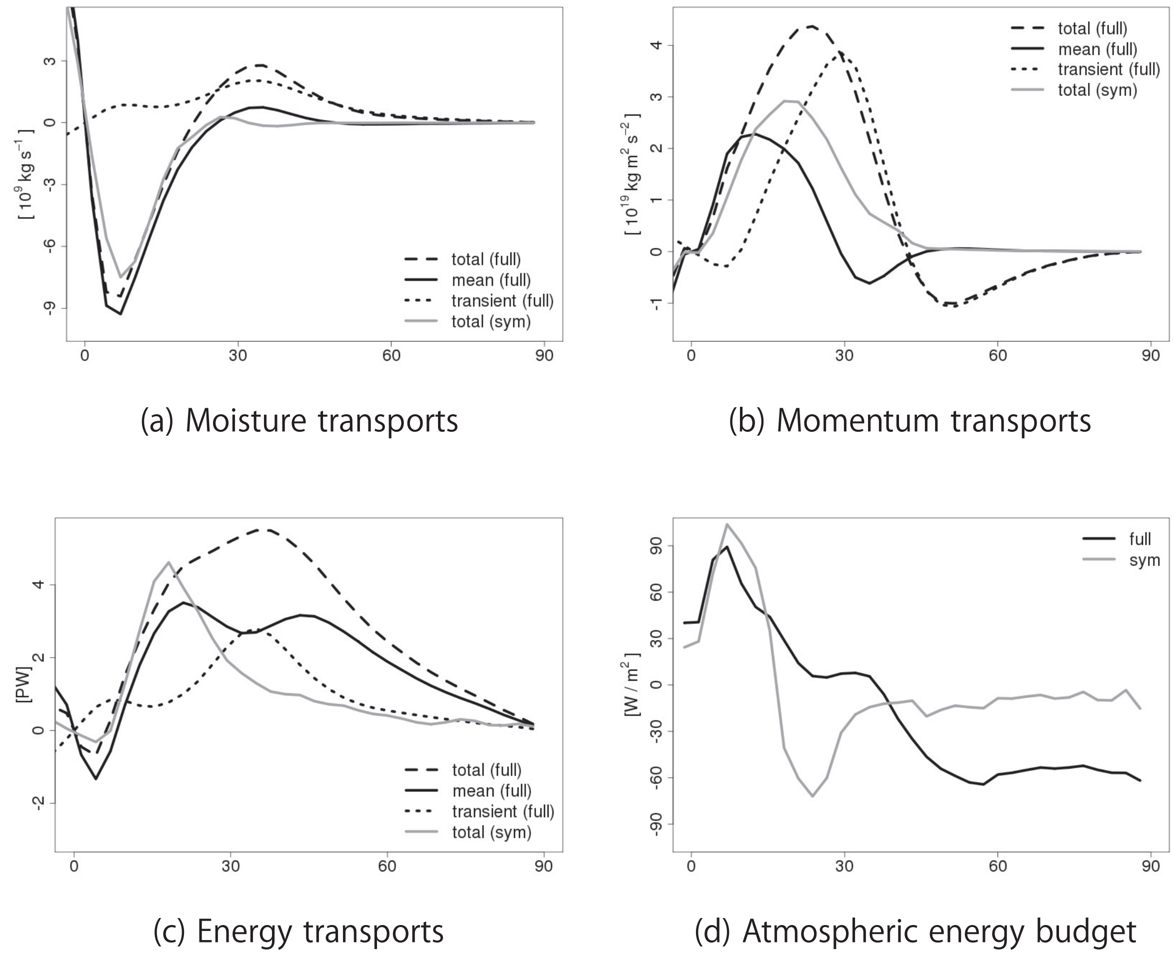

Fig. 6. Vertically integrated zonal mean meridional transports of (a) specific moisture, (b) momentum, and (c) energy. Displayed are the total atmospheric transports and their decomposition into stationary mean and transient part of the full model and the transport of the zonally symmetric model; (d) meridional atmospheric energy budget.

fields have at the same time a stabilizing effect on the zonal mean precipitation structure by preventing the long-term fluctuations observed in symmetric models (the *peaked* case is an exception). In the control sym case, the long-term fluctuations lead, to a switching between a single and double ITCZ state on a time scale of several months. In the *qobs* sym and *flat* sym cases, we observe a slow fluctuation between different multiple ITCZ states.

The eddy fields induce short-term fluctuations of the ITCZ width, in particular for *flat* SST distributions with strong mid-latitude gradients. The fluctuations of ITCZ width seem to be associated to a strong coupling between tropics and extra-tropics. In the zonal mean, precipitation maxima appear to be moving from the deep tropics poleward, which is especially visible in *qobs* and in *flat*. This poleward migration is discussed in more detail in the appendix. A closer look also reveals fluctuations on a longer time-scale, but a spectral analysis of the fluctuations is beyond the scope of this investigation.

4. Summary and Conclusions

In our investigations, we study the influence of large-scale eddy fields on the tropical mean state and the splitting of the ITCZ. A spectral atmospheric general circulation model (AGCM) run in aqua-planet mode is forced

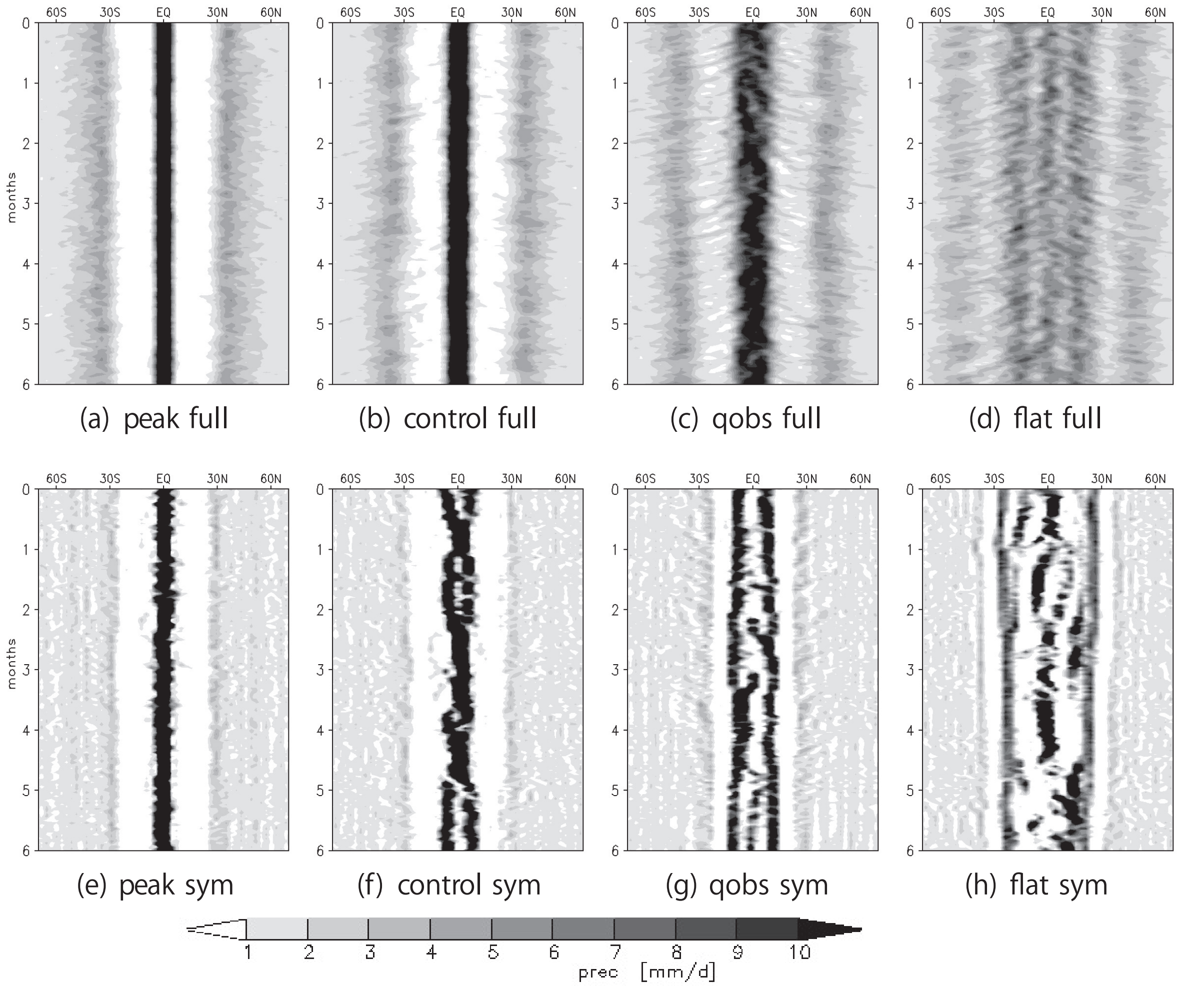

Fig. 7. Hovmöller diagrams (time-latitude) of the zonal mean total precipitation for a time series of six months are shown for all experiments between 75° south and north.

with a series of zonally constant sea surface temperature (SST) distributions which are symmetric about the equator. The AGCM is run twice, a first time with all spectral modes and a second time only with the zonally symmetric ones. The parameterizations and boundary conditions are kept the same in all cases, thus allowing a consistent comparison of 3-D and 2-D flows where eddy fields and the mean circulation are free to adjust.

Our investigations show that a purely zonally symmetric model can capture a substantial part of the climatological mean circulation in the tropics, and that eddy fields merely modify the structure. This suggests that the structure of the tropical mean state is, to a large extent, determined by the shape of the effective SST forcing. The good agreement, especially in the upper subsidence region of the Hadley cell, is due to the fact that the heat transport of large-scale eddies in the full 3-D model is compensated in the 2-D model by vertical subgrid-scale diffusion of heat and an enhanced radiative long-wave cooling. In the *control* case, eddies strengthen the Hadley circulation by approx. 22% if we take the full run as reference. This confirms the results of Satoh et al. (1995), who also find that structure and strength of the Hadley cell are comparable in 3-D and 2-D simulations. The differences in the Ferrel cell between the 3-D and 2-D model can be explained by the large-scale horizontal eddy heat transport which is absent in the 2-D model.

We showed that in the absence of eddies, the relative humidity in the subtropics is weaker, especially close to the surface. Sherwood et al. (2010) discussed that the relative humidity in the subsidence region of the Hadley cells is a significant factor for the global warming problem, and is therefore an important field of research.

The strongest influence of eddy fields is observed for double ITCZ states with weak gradients near the equator. Here the eddy fields are responsible for a poleward shift of the subtropical jets and an equatorward shift of the precipitation maxima in the convergence zone.

In dry experiments with primitive circulation models which are run with Newtonian cooling, differences between 3-D and 2-D have already been analyzed. A poleward shift of the subtropical jets was also found by Becker et al. (1997). In contrast to our results, they find a much stronger increase of the strength of the Hadley cell if eddy fields are allowed. In their investigations the position of the ITCZ and the strength of the latent heating is fixed a priori, so that the mean flow and eddy fields can only partly adjust to each other. A strong influence of eddy fields on the strength of the Hadley circulation is also found by Kim and Lee (2001), who observed intensification by four.

The inclusion of the hydrological cycle is, however, of importance for the Hadley cell dynamics. Satoh (1994) analyzed Hadley circulations in radiative-convective equilibrium, and showed that the distribution of temperature in the Hadley cell is controlled by the moist process. Numaguti (1993, 1995) examines the structure of the Hadley circulation and the ITCZ from the standpoints of the water vapor and the energy budgets. He finds that the distribution of the evaporation rate is an important factor in the formation of the structure of the ITCZ and the possible formation of a double ITCZ, and therefore concludes that the form of the Hadley circulation is highly sensitive to the evaporation rate, which is the principal energy source into the system.

What is strongly affected by eddy fields in our model runs are the energy and momentum cycles, especially for latitudes poleward of $\pm 10^{\circ}$. The eddy fields are also crucial for the moisture transport to the extra-tropics, but within the Hadley cell the eddy-transport of moisture is rather small.

Satoh (1994) shows that the dry static stability in the non-precipitating branch of the Hadley cell is a key factor for determining its strength, and Frierson (2007) demonstrates that the strength of the Hadley cell also depends on the moist static stability, which can be altered by modifying convection scheme parameters. However, in our simulations the static stability (whether moist or dry) does not change considerably between the different cases.

Walker and Schneider (2006) concentrated on the influence of eddy momentum transport on the strength and width of the Hadley circulation. They found a transition between regimes where the influence of eddies on the circulation strength is small, to regimes where it is strong. We also observe such a transition in circulation regimes. The freedom of the mean circulation, eddy fields, and hydrological cycle to adjust to each other in our simulations reveals that the transition in circulation regimes is associated with the phenomenon of ITCZ splitting. We find that the eddy dominated Hadley circulation observed for the *flat* SST distribution is weak. From our simulations with a free hydrological cycle, it seems that for earth-type conditions it is difficult to obtain a strong eddy-dominated Hadley circulation regime. The single ITCZ regime breaks down before the eddy field can dominate. If this is still true for different planetary radii and rotation rates, as the investigations of Walker and Schneider (2006) suggest, has to be shown by future research.

We find that the phenomenon of ITCZ splitting is encountered in both the full and zonally symmetric model if the SST distribution gets flat at the equator. Thus ITCZ splitting occurs even without wave instabilities and can be explained by purely zonally symmetric mechanisms. For SST distributions where the ITCZ splitting is observed, multiple states exist in the zonally symmetric model. Here for the same SST, the atmosphere switches on large time scales between a single and double ITCZ state. This introduces a long-term variability in the tropics without the influence of mid-latitudes and without atmosphere-ocean coupling.

We also observe the interesting fact that the introduction of an additional noise source (due to zonally asymmetric eddies) stabilizes the zonal mean structure of the tropical circulation and destroys the variability on long time scales. So for intermediate SST gradients near the equator, the presence of eddy fields can stabilize a single ITCZ state.

The short-term variability of the zonal mean tropical precipitation in the full cases needs further investigation. In the zonally averaged picture, areas of high precipitation migrate poleward to the mid-latitudes. This kind of poleward transport seems to be linked to eddies, as it does not appear in the zonally symmetric cases, but more analyses is needed to clarify the exact mechanisms. A short comparison to observational data and an explanation of the horizontal structure of this feature is presented in the appendix.

The Planet Simulator in our GCM experiments is run with a Kuo convection parameterization only. It has been shown that the behavior of the ITCZ also depends

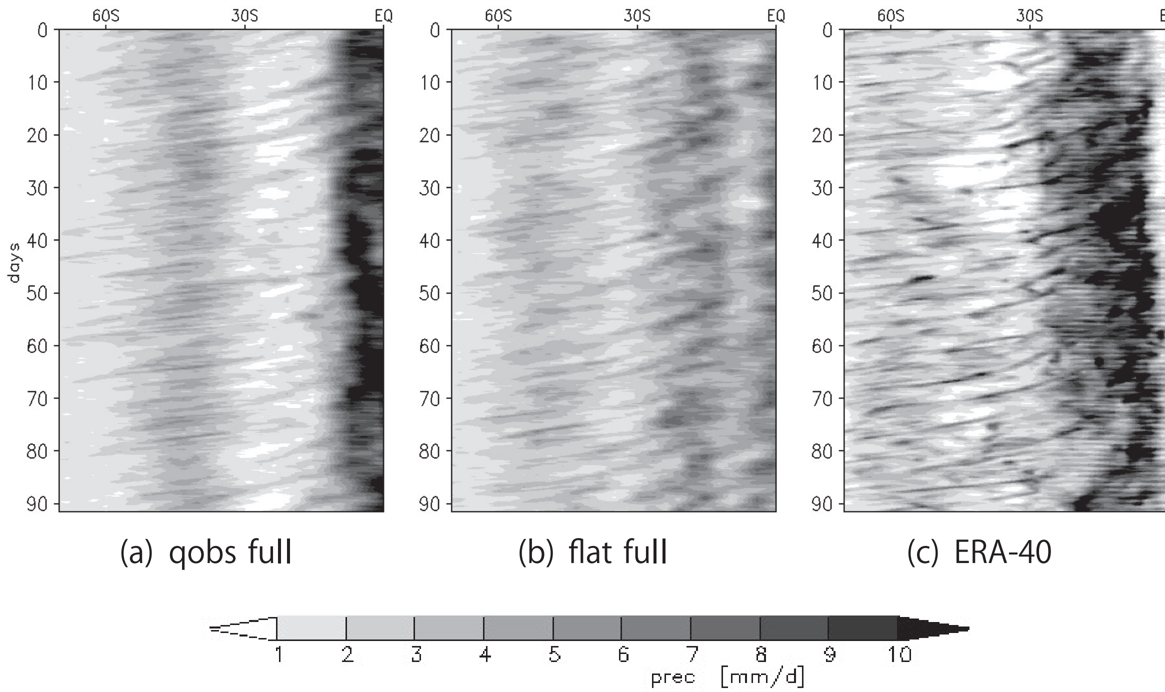

Fig. 8. Hovmöller diagrams of the zonal mean total precipitation in the southern hemisphere for (a) the *qobs* and (b) the *flat* full case, and (c) a zonal average (160°E–80°W) is from the ERA-40 reanalysis data.

on the cumulus parameterization. Numaguti (1993) compared numerical experiments with different cumulus parameterization schemes and found that the difference in the vertical stratification affects the energy budget of the Hadley cell and causes a change in the distribution of precipitation. Hess et al. (1993) also analyzed the influence of cumulus convection parameterization on the location, structure, energetics, and dynamics of the ITCZ and found a significant dependence. Frierson (2007) analyzed the effect of simple convection schemes on the zonal mean tropical circulation and came to the same conclusion. Further analysis has to show if our results are robust under different cumulus parameterization schemes.

Even though we find that the evaporation efficiencies do not differ greatly between the full and the zonally symmetric model runs, a feature of the prescribed SST framework should be considered. When evaporation is increased, the SST does not respond by decreasing as it would if a feedback between the ocean surface and the atmosphere was included in the model. Potential feedbacks between evaporation (via surface winds) and the Hadley circulation may therefore be exaggerated. Other factors, like cloudiness, also affect the SST in the real world.

A spectral analysis of the fluctuations of the ITCZ state together with an investigation of long-term memory is a natural next step to get a deeper insight into the role of eddy fields on atmospheric variability. In order to obtain a better understanding of the long-term atmospheric variability and to include a feedback between atmospheric circulation and the sea surface temperatures, our investigations also have to take into account the influence of a coupled ocean. By this, one can in addition asses the importance of the atmosphere-ocean coupling for the double ITCZ formation, a line of research started by Pike (1971).

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Appendix A

Comparison to observational data

In Figs. 7c and 7d, the Hovmöller diagrams of the total precipitation for the *qobs* and *flat* full simulations show tropical precipitation areas that migrate poleward. The horizontal structure of this feature consists of a number of heavy precipitation clusters, some of which are able to leave the tropics and migrate poleward. When the convective clusters enter higher latitudes, they propagate with the westerlies into the midlatitudes, where they become synoptic disturbances.

Close-ups of the two Hovmöller diagrams are shown in Figs. 8a and 8b. The temporal resolution is higher and only one hemisphere (0°–70°S) is shown for a time period of 3 months. For comparison with observations, Fig. 8c shows a Hovmöller diagram of the total precipitation from ERA-40 data. A zonal average from 160°E to 80°W is taken and displayed from 0° to 70°S, which covers the area of the southern Pacific. The southern Pacific with hardly any land mass resembles our aquaplanet configuration. Furthermore, the months February, March, and April are selected as they are close to equinoctial conditions.

In both cases from our simulation, a double ITCZ structure exists (in *flat* mostly a triple precipitation regime and in *qobs* a splitting of the single ITCZ occurs occasionally). From the ERA-40 dataset, the year 2000 is shown as an example where a double ITCZ has been observed in the tropical Pacific. Comparing our simulation results with a double ITCZ to the observations yields very similar structures. It can therefore be concluded that these poleward migrating precipitation areas also occur in reality when a double ITCZ is present.

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