GEOPHYSICAL RESEARCH LETTERS, VOL. 29, NO. 8, 1245, 10.1029/2002GL014756, 2002

Forcing of the quasi-biennial oscillation from a broad spectrum of atmospheric waves

Marco A. Giorgetta, Elisa Manzini, and Erich Roeckner
Max Planck Institute for Meteorology, Hamburg, Germany

Received 17 January 2002; revised 23 February 2002; accepted 24 February 2002; published 27 April 2002.

[1] The circulation of the stratosphere, and its influence on the trace constituent distribution, is an important component of the climate system, which must be included in simulations of global climate change. However, the ability to simulate a dominant stratospheric phenomenon, the Quasi-Biennial Oscillation (QBO) in equatorial zonal wind, is an outstanding challenge in climate modeling. Although confined to the tropics, the QBO affects the circulation and the interannual variability of the entire stratosphere, parts of the mesosphere and possibly also of the troposphere. Here we show that the QBO is successfully simulated in a general circulation model (GCM) of the newest generation. Key factors are a sufficient spatial resolution, a realistic simulation of tropical convection, and the consideration of the effects of gravity waves. From this simulation it is inferred that a broad spectrum of atmospheric waves is necessary to generate the QBO in the model. *INDEX TERMS:* 3334 Meteorology and Atmospheric Dynamics: Middle atmosphere dynamics (0341, 0342); 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology; 3384 Meteorology and Atmospheric Dynamics: Waves and tides

1. Introduction

[2] The QBO has been discovered in the late 1950s after radio sondes started to probe regularly the winds in the lower equatorial stratosphere. The phenomenon is best described as a quasi-periodic succession of zonally uniform, downward propagating, eastward and westward jets (Figure 1a) with average cycle duration of slightly more than 28 months. The jets are formed near 40 km altitude and disappear once they have arrived at about 18 km. A review of the QBO and its relevance to the general circulation and the composition of the atmosphere is given in *Baldwin et al.* [2001].

[3] The QBO in zonal wind dominates the interannual variability in the tropical stratosphere and causes a secondary circulation in the meridional plane with an associated response in the temperature distribution and nearly global effects on trace gas distributions [*Randel and Wu*, 1996; *Randel et al.*, 1998]. Evidence for a feedback of the QBO to the tropospheric circulation has been found for Atlantic hurricane activity [*Gray*, 1984], Asian monsoon and deep convection in the tropics [*Giorgetta et al.*, 1999]. The QBO also affects the variability of the equatorial upper atmosphere by modulating the types of waves that can reach levels in the mesosphere or higher [*Garcia et al.*, 1997].

[4] The theory of the QBO was developed a decade after its discovery [*Lindzen and Holton*, 1968; *Holton and Lindzen*, 1972], based on the idea that upward propagating waves excited in the upper troposphere by convective systems carry horizontal momentum vertically from the level of excitation to the level of dissipation. Dissipation of upward propagating waves occurs where the phase speed of the wave is similar to the background wind speed. For this reason, waves with eastward and westward propagation accelerate the background flow at different levels, specifically in regions with strong vertical shears in the background wind, where the relative phase speed of the wave becomes small. As a result the equatorial jets of the QBO are reinforced in the shear zone below the jet maximum and tend to propagate downwards.

[5] Though the general mechanism seems to be comparatively well understood, the knowledge about the wave spectrum that is involved is limited [*Dunkerton*, 1997]. Observations of tropical waves are insufficient to assess the precise contributions of different wave types and scales to the QBO forcing. The forcing by observed planetary scale Kelvin and Rossby-gravity waves is too weak to explain the QBO [*Gray and Pyle*, 1989]. However, the total wave activity in the tropics, which is approximately 2.5 times larger than the activity provided by the planetary scale waves [*Bergman and Salby*, 1994], is potentially sufficient to explain the downward propagation of the QBO phases against the mean upwelling in the tropical stratosphere. Obviously inertia-gravity waves and gravity waves must be considered for the QBO forcing, though observations are too sparse to determine precisely their respective roles.

[6] The difficulties in reproducing a realistic QBO in GCMs arise from a number of reasons: (a) Vertical resolution must be sufficient to adequately resolve vertically propagating tropical waves which cause the momentum flux necessary for the QBO generation; (b) Parameterizations of deep convection need not only to generate a realistic spatial distribution of precipitation in seasonal averages, but must also provide a realistic temporal variability of precipitation within seasons. This aspect is important because the generation of a realistic spectrum of atmospheric waves in the tropical troposphere requires a realistic spatial and temporal variation of convective heating. Wave types known to be important for the QBO have time scales from 1 day to 2 weeks. While various parameterizations for deep convection agree reasonably well in the seasonal distribution of the tropical precipitation, there is a wide spread in the temporal variability of precipitation on shorter time scales generated by different schemes. Simulated precipitation in the intertropical convergence zone may range from almost continuous drizzle, as generated by some flux-based schemes, to intermittent heavy precipitation, typically generated by moist convective adjustment schemes. More active schemes favor the excitation of high frequency atmospheric waves [*Manzini and Hamilton*, 1993; *Ricciardulli and Garcia*, 2000] and hence are more likely to generate a QBO; (c) The tropical upwelling in the lower stratosphere advects momentum in the QBO domain and determines the QBO period provided that the QBO forcing by dissipating waves is well captured. Hence the tropical upwelling must be reproduced realistically by the GCM. Too slow/fast upwelling in the tropical stratosphere favors too fast/slow downward propagation of the QBO jets.

[7] Previous attempts to simulate the QBO in GCMs have resulted in QBO-like oscillation (some having rather quasi-annual than quasi-biennial periods) provided that the convection was parameterized by moist convective adjustment schemes [*Takahashi*, 1996; *Horinouchi and Yoden*, 1998; *Hamilton et al.*, 1999; *Takahashi*, 1999] and/or that the standard horizontal diffusion was

0094-8276/02/2002GL014756

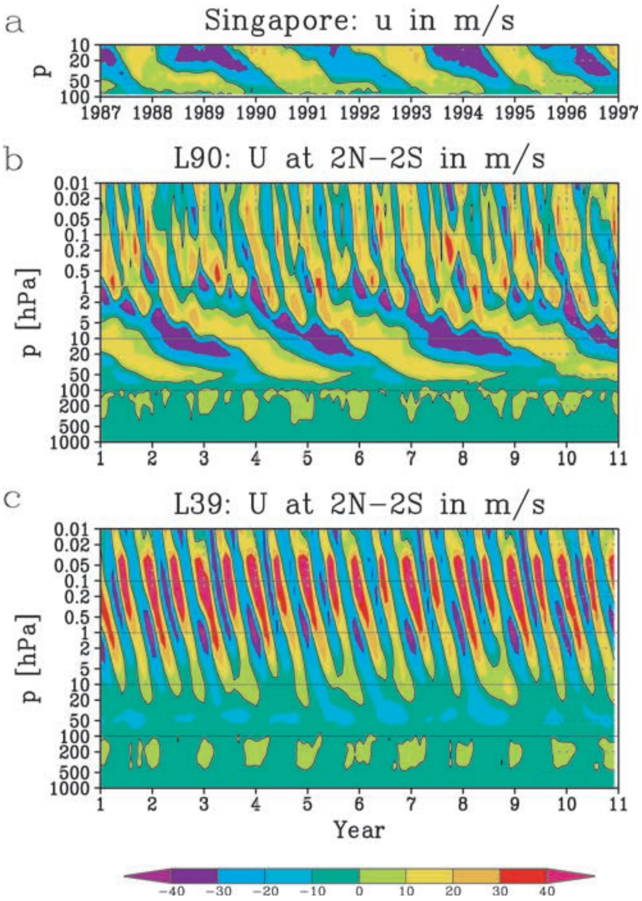


Figure 1. Singapore monthly mean zonal wind (m/s) in the lower stratosphere from 1987 to 1996 (a). Monthly and zonal mean zonal wind (m/s) at the equator in experiment L90 (b) and experiment L39 (c). The zero contour is shown in bold.

reduced substantially [*Takahashi*, 1996, 1999; *Nagashima et al.*, 1998]. The moist convective adjustment scheme is known to be overly active on very short time scales, generating highly intermittent precipitation, while lower than normal horizontal diffusion strengthens the energy spectrum at the truncation limit of the GCM. Recently, a QBO was simulated in a GCM including a specifically adjusted gravity wave drag parameterization [*Scaife et al.*, 2000].

[8] The purpose of this work is to evaluate the performance of a newly developed GCM in the equatorial lower stratosphere in its standard configuration and in a configuration where the vertical resolution has been increased by a factor of 2 or more. The focus is to assess the ability of the new model to develop a QBO by improving the representation of the vertical structure of the tropical waves, without specializing in other ways the high-resolution model.

2. Experiments

[9] The GCM employed for these experiments is MAE-CHAM5, the Middle Atmosphere configuration of ECHAM5. With respect to its predecessor [*Roeckner et al.*, 1996; *Manzini et al.*, 1997] this new middle atmosphere GCM differs mainly in the treatment of radiation processes [*Morcrette et al.*, 1998], surface fluxes [*Schulz et al.*, 2001], and cloud physics [*Lohmann and Roeckner*, 1996]. The GCM includes parameterizations for deep convection [*Tiedtke*, 1989; *Nordeng*, 1996] and for momentum flux deposition from a spectrum of gravity waves [*Manzini et al.*, 1997].

[10] Two experiments have been carried out, which differ by the vertical resolution only. Experiment L39 represents the control experiment using the standard vertical grid of the model, which resolves the atmosphere by 39 layers from surface up to 0.01 hPa or approximately 80 km altitude. The vertical resolution in the stratosphere decreases continuously from typically 1.5 km at the tropical tropopause to 3 km at the stratopause. Experiment L39 is integrated for 10 years starting from an initial state that does not contain a QBO structure.

[11] Experiment L90 resolves the atmosphere by 90 layers from surface to 0.01 hPa. The lowermost 5 layers are identical to those of L39 in order to avoid differences in turbulent vertical fluxes of momentum and energy near the surface. The uppermost layer is also identical to that of L39. The vertical resolution in the stratosphere is approximately 700 m between the tropopause and the level situated at 42 km altitude, and better than 1 km up to the stratopause. This resolution is sufficient to resolve waves with vertical wavelengths of 2.8 km or longer. Experiment L90 is integrated for 17 years starting from initial conditions without any representation of the QBO, as in experiment L39. The first 7 years of the L90 integration show a transition from the initial no-QBO state to a realistic QBO structure. Only the last 10 years of this integration are shown and discussed below.

[12] Both experiments use the same horizontal resolution. Dynamics, the motion of air, is computed for a spectrum of atmospheric waves up to wave number 42 or wavelengths of approximately 1000 km. The physical processes, as for example convection, are calculated at a resolution of approximately 2.8° in longitude and latitude. Sea surface temperature and sea ice distribution are prescribed equally in both experiments and follow the climatological annual cycle, averaged for the period 1979 to 1995.

3. Results

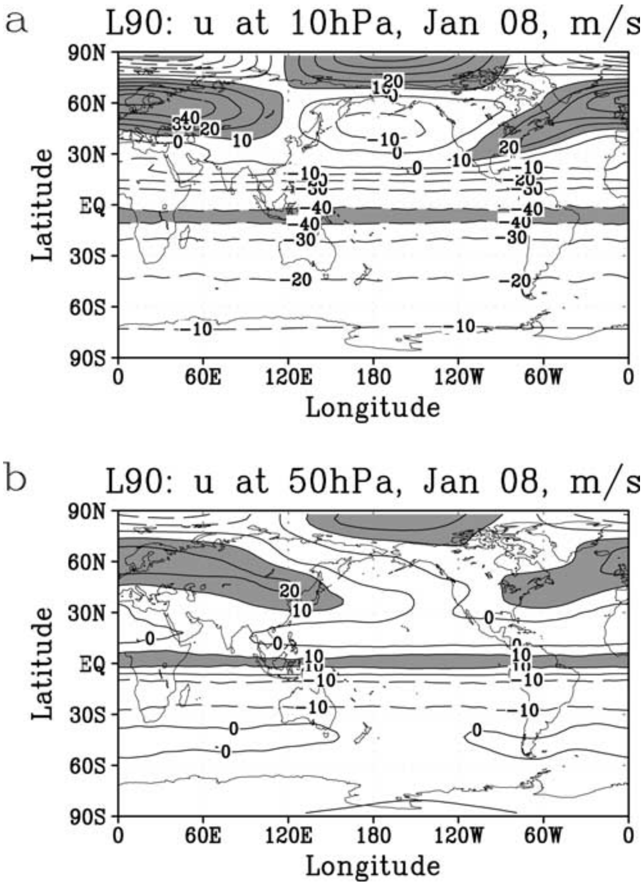
[13] Experiments L39 and L90 result in very different zonal wind structures in the equatorial middle atmosphere, as shown for the last 10 years of each experiment in Figures 1b and 1c. In L90, eastward winds appear in the lower equatorial stratosphere soon after the initialization, although somewhat irregularly. After 7 years of integration a regular oscillation in zonal wind is established in the lower tropical stratosphere which shows the main features of the observed QBO. The QBO cycle produced by the model has an average period of 32 months, 4 months longer than in observations, but within the observed range. Simulated eastward winds of the QBO reach 15 m/s and seldom exceed 20 m/s near 5 hPa, while westward winds exceed 30 m/s above 20 hPa. This asymmetry in wind strengths is a typical feature of the observed QBO, though the westward winds produced by the model tend to be slightly too weak at 30 hPa and below. The simulated downward propagation of eastward winds occurs in a regular manner, without loss in amplitude, while that of the westward winds is less continuous, as in observations. The simulation has a consistent QBO signal in temperature in the equatorial stratosphere with anomalies of 4 K and −3 K in eastward and westward wind shears, respectively (not shown). The annual and zonal mean tropical upwelling at 80 hPa between 15°N and 15°S is typically 0.3 mm/s and follows qualitatively the profile shown in *Rosenlof et al.* [1997].

[14] The control experiment L39 does not develop the QBO. The equatorial zonal mean zonal wind shows a pronounced semi-annual oscillation (SAO) in the mesosphere and upper stratosphere which is forced in part by the meridional advection of westward winds, and in part by dissipation of gravity waves. Equatorial eastward winds occasionally propagate downwards to 20 hPa. In year 8 in Figure 1c, the eastward jet propagates slowly downwards to 24 hPa and connects to the next descending eastward jet of the SAO, reminiscent of an onset of an eastward equatorial jet of the

QBO. Otherwise, weak easterlies of approximately 10 m/s dominate in the lower equatorial stratosphere. The annual and zonal mean tropical upwelling at 80 hPa between 15°S and 15°N is 0.3 mm/s as in L90. Note that the SAO in L90 is considerably less regular than in L39 due to the QBO related wave filtering [*Garcia et al.*, 1997].

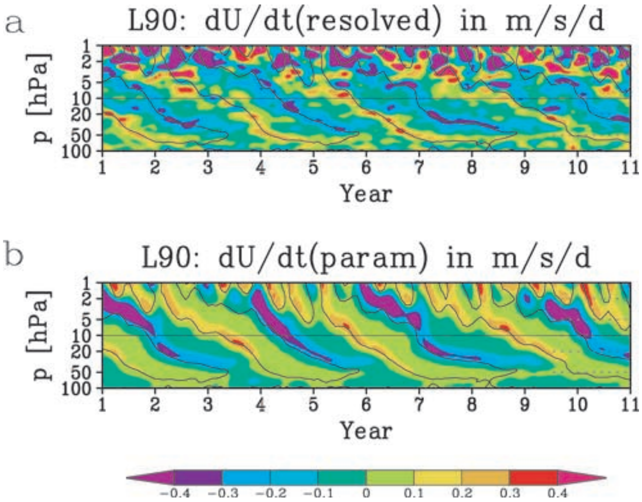
[15] The simulated QBO consists of equatorial jets encircling the whole globe with a high degree of zonal symmetry as shown in Figure 2 for January of year 8, when the eastward and westward jets are positioned at 10 and 50 hPa, respectively. The eastward jet is characterized by a small latitudinal offset from the equator towards the winter hemisphere, while the westwards winds show a latitudinal offset of a few degrees to the summer hemisphere. The zonal symmetry is more pronounced for the westward jet than for the eastward jet, which is susceptible to planetary waves in the winter hemisphere. During equinox both QBO phases are centered on the equator (not shown).

[16] An important issue is to assess the relative role played by the long and medium scale waves (resolved) and the small-scale gravity waves (parameterized), respectively, in the forcing of the QBO. Both contributions are shown in Figure 3. In the present simulation the zonal wind tendencies due to resolved waves are generally more intermittent than those produced by parameterized gravity wave forcing. A comparison of zonal wind tendencies in the eastward shear zone shows that both contributions are of similar strength at levels higher than 20 hPa (0.2 to 0.4 m/s/d). Below 20 hPa, however, the contribution of the resolved waves is stronger (0.2 to 0.4 m/s/d) than the contribution of the parameterized gravity waves (0 to 0.2 m/s/d). The downward propagation of the QBO eastward winds in the lower stratosphere is mainly the result of resolved wave mean-flow interaction. In the westward shear zone, the gravity wave contribution (−0.2 to −0.4 m/s/d) exceeds that of the resolved waves down to 30 hPa, while the resolved waves are more important at 40 hPa and at lower levels. The relative role of the resolved waves in the simulated QBO is therefore more important for the forcing of the eastward jet than for the forcing of the westward jet of the QBO.


a L90: u at 10hPa, Jan 08, m/s

b L90: u at 50hPa, Jan 08, m/s

Figure 2. Monthly mean zonal wind (m/s) in experiment L90 at 10 hPa (a) and 50 hPa (b). Westward winds stronger than 40 m/s and eastward winds stronger than 10 m/s are shaded. The contour interval is 10 m/s.


a L90: dU/dt(resolved) in m/s/d

b L90: dU/dt(param) in m/s/d

Figure 3. Monthly and zonal mean tendency of zonal wind (m/s/d) at the equator by resolved waves diagnosed as divergence of EP-flux (a) and by parameterized gravity wave dissipation (b). The zero contour of the zonal mean wind is shown in bold.

4. Conclusions

[17] The simulated QBO exhibits the typical properties of the observed QBO. Amplitudes of eastward and westward jets, the period of the QBO, the propagation characteristics of both phases as well as the differences in the latitudinal extent of both phases are realistically captured in the simulation. Both phases show a high degree of zonal symmetry, with visible deviations in the eastward jet, as observed. The QBO is obtained in an experiment that differs only by the substantially increased vertical resolution of the model (700 m in the lower and middle stratosphere) compared to the control experiment. This vertical resolution has been selected in order to allow for a better representation of the vertical structure of tropical atmospheric waves that are resolved at the given horizontal resolution [*Boville and Randel*, 1992]. Thus, the QBO wave mean-flow interaction can be resolved in the model, provided that the simulated convective heating excites a realistic spectrum of tropical waves in the troposphere.

[18] In ECHAM5, convective activity is parameterized using a mass-flux scheme that is known to produce realistic precipitation patterns [*Roeckner et al.*, 1996]. On going work has shown that this scheme is neither biased towards intensive intermittent precipitation, as typical for moist convective adjustment schemes, nor to predominant drizzle as found in other flux based schemes.

[19] The analysis of the wave-induced zonal mean forcing due to the resolved and parameterized portions of the wave spectrum shows that both parts are relevant for the QBO forcing, in agreement with current estimates of tropical wave activity and wave mean-flow interaction in the tropical stratosphere. Resolved waves provide, however, the largest tendencies for the downward propagation of the QBO in the lower stratosphere. Analyses of the resolved wave spectrum and detailed characterization of the variability in convection will be presented in future work.

[20] **Acknowledgments.** We would like to thank L. Bengtsson who has initiated and supported this work, and the ECHAM working group for contributing to the model development. Constructive comments by G. Brasseur, L. Bengtsson, and J. Fyfe on the manuscript are gratefully acknowledged. B. Naujokat kindly provided data for Figure 1a. The extensive computations were carried out in cooperation of NEC and MPI, and as part of special projects at ECMWF. Part of this work was funded by BMBF project 07ATF43 (KODYACS).

References

Baldwin, M. P., L. J. Gray, T. J. Dunkerton, K. Hamilton, P. H. Haynes, W. J. Randel, J. R. Holton, M. J. Alexander, I. Hirota, T. Horinouchi, D. B. A. Jones, J. S. Kinnersley, C. Marquardt, K. Sato, and M. Takahashi, The quasi-biennial oscillation, *Rev. Geophys.*, *39*, 179–229, 2001.

Bergman, J. W., and M. L. Salby, Equatorial wave activity derived from fluctuations in observed convection, *J. Atmos. Sci.*, *51*, 3791–3806, 1994.

Dunkerton, T. J., The role of gravity waves in the quasi-biennial oscillation, *J. Geophys. Res.*, *102*, 26,053–26,076, 1997.

Garcia, R. R., T. J. Dunkerton, R. S. Lieberman, and R. A. Vincent, Climatology of the semiannual oscillation of the tropical middle atmosphere, *J. Geophys. Res.*, *102*, 26,019–26,032, 1997.

Giorgetta, M. A., L. Bengtsson, and K. Arpe, An investigation of QBO signals in the east Asian and Indian monsoon in GCM experiments, *Clim. Dyn.*, *15*, 435–450, 1999.

Gray, L. J., and J. A. Pyle, A two-dimensional model of the quasi-biennial oscillation in ozone, *J. Atmos. Sci.*, *46*, 203–220, 1989.

Gray, W. M., Atlantic seasonal hurricane frequency, part I, El Niño and 30 mb quasi-biennial oscillation influences, *Mon. Weather Rev.*, *112*, 1649–1668, 1984.

Hamilton, K., R. J. Wilson, and R. S. Hemler, Middle Atmosphere simulations with high vertical and horizontal resolution versions of a GCM: Improvements in the cold pole bias and generation of a QBO-like oscillation in the tropics, *J. Atmos. Sci.*, *56*, 3829–3846, 1999.

Horinouchi, T., and S. Yoden, Wave-mean flow interaction associated with a QBO-like oscillation in a simplified GCM, *J. Atmos. Sci.*, *55*, 502–526, 1998.

Holton, J. R., and R. S. Lindzen, An updated theory for the quasi-biennial cycle of the tropical stratosphere, *J. Atmos. Sci.*, *29*, 1076–1080, 1972.

Lindzen, R. S., and J. R. Holton, A theory of the quasi-biennial oscillation, *J. Atmos. Sci.*, *25*, 1095–1107, 1968.

Lohmann, U., and E. Roeckner, Design and performance of a new cloud microphysics scheme developed for the ECHAM general circulation model, *Climate Dyn.*, *12*, 557–572, 1996.

Manzini, E., and K. Hamilton, Middle atmospheric travelling waves forced by latent and convective heating, *J. Atmos. Sci.*, *50*, 2180–2200, 1993.

Manzini, E., N. A. McFarlane, and C. McLandress, Impact of the Doppler spread parameterization on the simulation of the middle atmosphere circulation using the MA/ECHAM4 general circulation model, *J. Geophys. Res.*, *102*, 25,751–25,762, 1997.

Morcrette, J.-J., S. A. Clough, E. J. Mlawer, and M. J. Iacono, Impact of a validated radiative transfer scheme, RRTM, on the ECMWF model climate and 10 day forecasts, ECMWF Research Department Tech. Memo. No. 252, ECMWF, Reading, 1998.

Nagashima, T., M. Takahashi, and F. Hasebe, The first simulation of an ozone QBO in a general circulation model, *Geophys. Res. Lett.*, *25*, 3131–3134, 1998.

Nordeng, T. E., Extended versions of the convective parametrization scheme at ECMWF and their impact on the mean and transient activity of the model in the tropics, ECMWF Research Department Techn. Memo 206, ECMWF, Reading, 1996.

Randel, W. J., and F. Wu, Isolation of the ozone QBO in SAGE II data by singular decomposition, *J. Atmos. Sci.*, *53*, 2546–2559, 1996.

Randel, W. J., F. Wu, J. M. Russel III, A. Roche, and J. Waters, Seasonal cycles and QBO variations in stratospheric CH4 and H2O observed in UARS HALOE data, *J. Atmos. Sci.*, *55*, 163–185, 1998.

Roeckner, E., K. Arpe, L. Bengtsson, M. Christoph, M. Claussen, L. Dümenil, M. Esch, M. Giorgetta, U. Schlese, and U. Schulzweida, The atmospheric general circulation model ECHAM-4: Model description and simulation of present day climate, MPI-Report 218, Max Planck Institute for Meteorology, Hamburg, 1996.

Scaife, A., N. Butchart, C. D. Warner, D. Stainforth, and W. Norton, Realistic quasi-biennial oscillations in a simulation of the global climate, *Geophys. Res. Lett.*, *27*, 3481–3484, 2000.

Schulz, J.-P., L. Dümenil, and J. Polcher, On the land surface atmosphere coupling and its impact in a single-column atmospheric model, *J. Appl. Meteor.*, *40*, 642–663, 2001.

Takahashi, M., Simulation of the stratospheric quasi-biennial oscillation using a general circulation model, *Geophys. Res. Lett.*, *23*, 661–664, 1996.

Takahashi, M., Simulation of the stratospheric quasi-biennial oscillation in a general circulation model, *Geophys. Res. Lett.*, *26*, 1307–1310, 1999.

Tiedtke, M., A comprehensive mass flux scheme for cumulus parameterization in large-scale models, *Mon. Weather Rev.*, *117*, 1779–1800, 1989.

M. A. Giorgetta, E. Manzini, and E. Roeckner, Max Planck Institute for Meteorology, Bundesstrasse 55, 20146, Hamburg, Germany. (giorgetta@dkrz.de; manzini@dkrz.de; roeckner@dkrz.de)