5.5 MODULATION OF THE GRAVITY WAVE DRIVEN MERIDIONAL CIRCULATION IN THE MESOSPHERE BY PLANETARY WAVE FORCING IN THE TROPOSPHERE

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1. Introduction

The stratospheric residual circulation during boreal winter is primarily driven by orographically and thermally forced planetary waves. In contrast, the break–down of internal gravity waves (hereafter IGWs) forces the summer to winter pole meridional circulation in the mesosphere (Lindzen, 1981). Given this essential difference in the zonal wave drag between the lower and upper part of the middle atmosphere, a possible influence of stationary wave forcing on the mesosphere/lower thermosphere (hereafter MLT) is likely to result from the following mechanism: the modulation of gravity wave break–down via changes of the background winds in the stratosphere and lower mesosphere, which in turn result from variations in planetary wave activity.

A reduction of the IGW zonal drag during periods of strong planetary wave acytivity is well known from sudden stratospheric warmings (e.g. Holton, 1983). In the present study we address the question whether a similar dynamical interaction between the stratosphere and the mesosphere can exist on the climatological scale. Accordingly, we compare long–term model simulations that differ with respect to planetary wave activity.

2. Model

For convenience a simple general circulation model (SGCM) of the troposphere and middle atmosphere is employed (T29 spectral resolution, 60 hybrid layers up to 0.00035 mb). IGWs are parameterized following the Lindzen scheme, which is completed by self–consistent formulations for energy deposition and dissipative heating following Becker and Schmitz (2000). The primary idealizations of the model correspond to representing radiative and latent heating rates by simple parameterizations, namely by temperature relaxation towards a zonally symmetric equilibrium temperature T_E (white contours in Fig. 2a) plus prescribed cumulus heating in the deep tropics and self–induced condensational heating in middle latitudes (Becker and Schmitz, 2001). The heating functions are adjusted to impose permanent January conditions. They can independently be substituted by their zonal averages. Thus, the model idealizations allow to systematically assess the remote effects of orography, land–sea heating contrasts and their combination on the general circulation of the middle atmosphere with particular emphasis on the mesosphere.

In the following we will inspect the climatologies of two long–term integrations (900 day time series). In the first model run we apply full forcing of stationary waves owing to orography, self–induced midlatitude heating and tropical heating. The second model run represents the equivalent aqua–planet simulation where orography and heating functions are substituted by their zonal means.

3. Results

The black contours in Fig. 1 show residual mass streamfunction and Eliassen–Palm flux (EPF) divergence for both model runs. In addition, the residual meridional wind and the averaged zonal wind tendency generated by IGWs via momentum deposition and vertical momentum diffusion are indicated by white contours in the upper and lower panels, respectively. As concerns the stratosphere, Fig. 1 clearly confirms that tropical upwelling and the poleward stratospheric mass flux are substantially amplified as a result of the extratropical planetary wave drag. In contrast, the simulated winter mesospheric residual circulation is strongly reduced as indicated by the additional thick streamfunction contours in Figs. 1a,b. This effect shows up more clearly as a reduction of the northern hemispheric maximum of the residual meridional wind by a factor of 2–3 (white contours in Figs. 1a and b). In the upper mesosphere, momentum forcing owing to IGW saturation dominates over the planetary wave EPF divergence. Consistent with this view, the upper level weakening of the residual circulation is balanced by a corresponding reduction of the zonal wind tendency due to IGW–induced momentum deposition and diffusion (white contours in Figs. 1c,d).

The zonal–mean zonal wind and temperature in the full wave forcing experiment as well as corresponding differences from the equivalent aqua–planet

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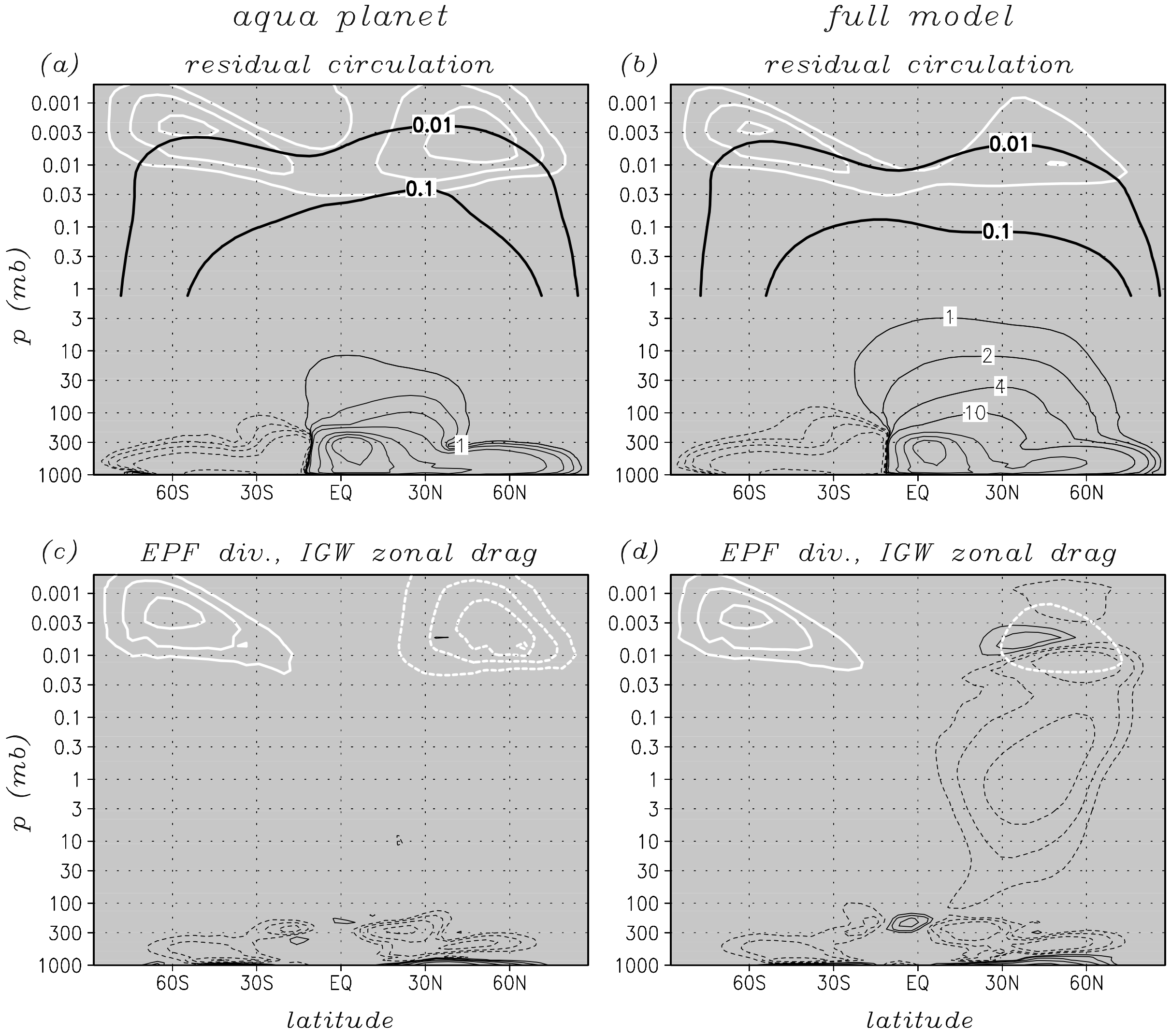

Figure 1: Residual circulation (upper panels) and zonal wave drag (lower panels) in the aqua–planet and full stationary wave forcing experiment. In (a),(b), the residual mass streamfunction is drawn with black contours for 0.01, 0.1, ±1, ±2, ±4, ±10, 50, 100 and 150 $\times 10^9$ kgs^{-1}. The residual meridional wind is indicated by white contours for 5, 10 and 15 ms^{-1}. The Eliassen–Palm flux divergence is calculated in quasi–geostrophic approximation and plotted in (c),(d) for ±1, 2, 4, 8, 16 × 10^{15} m^3 (black contours). In addition, the white contours in (c),(d) give the total zonal force (plotted for ±50, 100 and 150 ms^{-1}d^{-1}) owing to momentum deposition and vertical momentum diffusion generated by gravity wave saturation.

run are displayed in Fig. 2. The climatological model response to stationary wave forcing is quantitatively consistent with the observed asymmetry between boreal and austral winter. Changes in adiabatic heating associated with the residual circulation in the winter hemisphere are reflected by the temperature signal up to about 0.05 mb. Moreover, throughtout this height region there is an approximate compensation between high latitude heating and low latitude cooling and vice versa. The compensation is consistent with results of Yulaeva et al. (1994) obtained for the lower stratosphere. It is due to the fact, that changes in adiabatic heating associated with the residual circulation are balanced by corresponding changes in radiative heating.

The situation is different in the upper mesosphere where the model shows a global increase of temperatures as a remote effect of orography and land–sea heating contrasts. Obviously, in the upper mesosphere, adiabatic and radiative heating (temperature

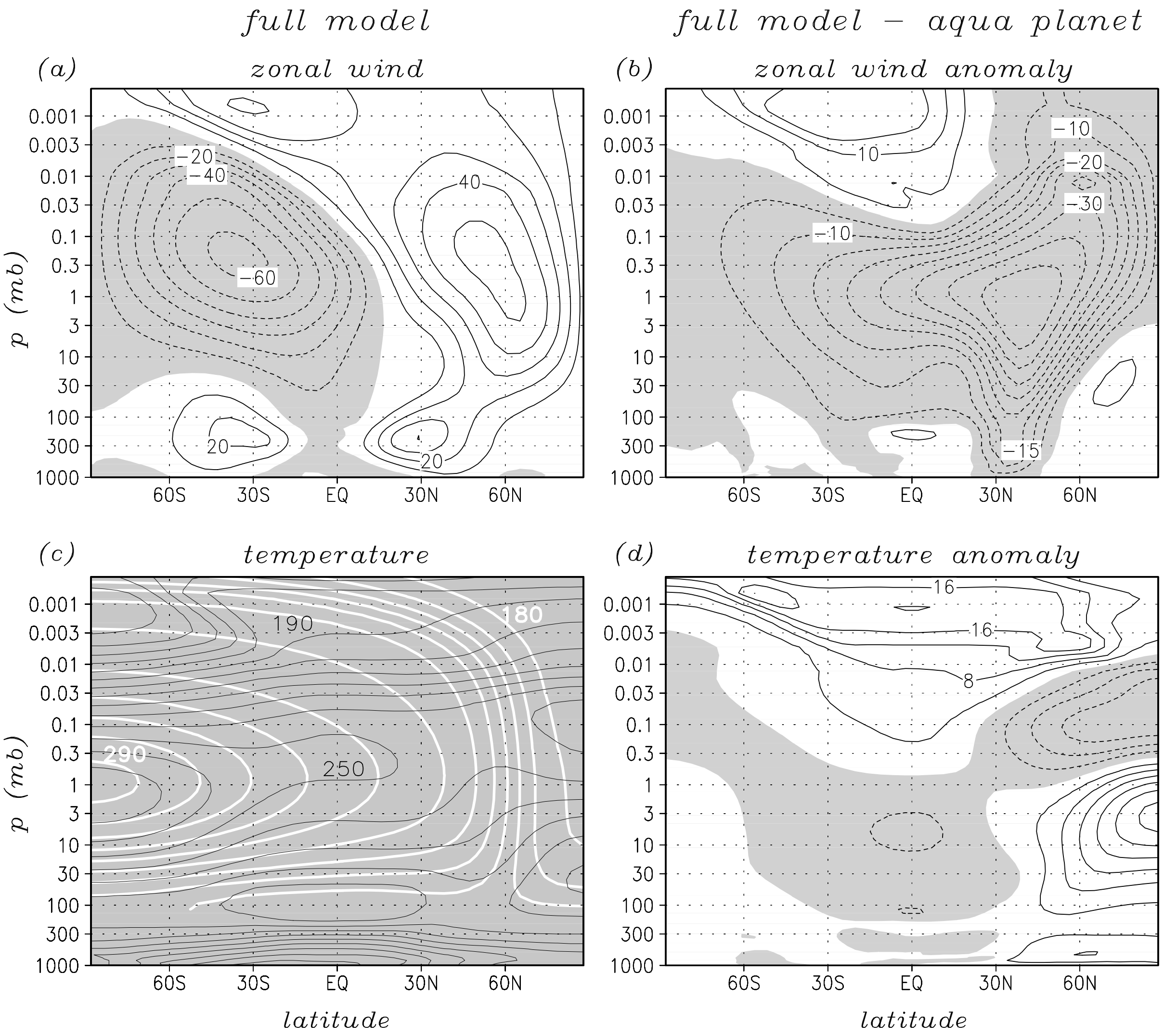

Figure 2: Zonal–mean zonal wind and temperature in the full wave forcing experiment (lhs panels, contour intervals 10 ms^{-1} and 10 K) and corresponding differences from the equivalent aqua–planet simulation (rhs panels, contour intervals 5 ms^{-1} and 4 K). In (a),(b),(d), the zero contours are not drawn and negative values are shaded. White contours in (c) show the equilibrium temperature T_E in the middle atmosphere (contour interval 10 K).

relaxation) do no more balance each other. We rather have to take the direct thermodynamic effects owing to IGW break–down into account. In the present model, these are due to IGW–induced diffusion of potential temperaure (applied with Prandtl number 2), energy deposition and frictional heating owing to IGW–induced momentum diffusion. The sum of these heating rates is displayed in Figs. 3c and d for the aqua–planet and the full wave forcing experiment. In addition, Figs. 3a and b show corresponding dynamic heating rates (adiabatic heating plus advection) due to the resolved planetary–scale flow, which to a good approximation represent adiabatic heating by the residual circulation in either case.

The direct IGW heating rates, which are dominated by cooling due to vertical diffusion of potential temperature, become substantial above 0.01 mb or so. Thus, the temperature signal in the upper mesosphere reflects the residual of the changes in dynamic heating and the direct IGW effects. In the winter mesosphere, heating due to the former as well as cooling due to the latter are strongly reduced as a result of stationary wave forcing, with the first effect being dominant.

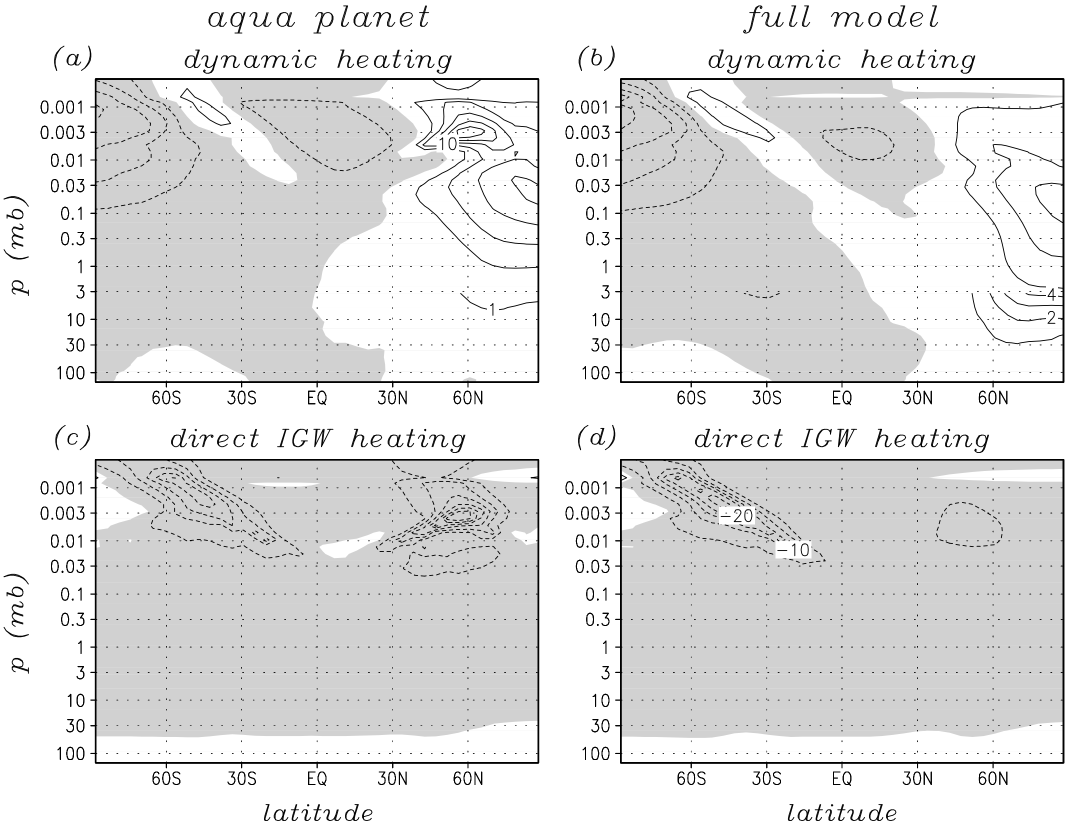

Figure 3: Climatological zonal–mean heating rates owing to advection and adiabatic heating by the resolved planetary–scale flow (abbreviated as dynamic heating, upper panels) and direct heating owing to IGW saturation (the sum of energy deposition, heat diffusion plus and dissipation, lower panels). Results from the equivalent aqua–planet simulation and the full wave forcing experiment are displayed on the left and right hand side panels, respectively. The contour interval is 1 Kd^{-1} below 3 mb and it is 5 Kd^{-1} above that level. Zero contours are not drawn and negative values are shaded.

The situation is more complicated in the summer mesosphere. Computing the differences in Figs. 3b,d from Figs. 3a,c reveals that the higher temperatures in the southern upper mesosphere are consistent with reduced dynamic cooling, hence with a globally reduced upper level residual circulation. This remote coupling between ascent in the summer mesosphere and gravity wave drag in the winter mesosphere is to some extent analogous to the extratropical planetary wave pump in the stratosphere.

Present model results furthermore suggest that gravity wave effects in the MLT may be much stronger in austral winter than in boreal winter. Hence, the strong difference between summer and winter as observed in the northern hemisphere may be absent in the southern hemisphere.

4. References

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