19.5 ATMOSPHERIC RESPONSE TO MID-LATITUDE THERMAL FORCING: A MECHANISM FOR CHANGES IN CLIMATE REGIMES?

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1. INTRODUCTION

There is evidence of systematic changes in the background mean state of the atmosphere over recent decades. One such change is in the mean latitude of the southern mid-latitude high pressure belt (HPB), which has moved southward by 2-3 degrees over the past 50 years at the longitude of Eastern Australia. Such secular changes may cause changes in the response of the atmosphere to topographic and thermal forcing, and in consequence, cause local changes in climate regimes. Resonances exist in the atmospheric response, and changes in the background flow which cause a move through a resonance may change the predominant forced wind anomaly from, say northerly to southerly, or vice versa.

In this paper I describe an analysis of forced disturbances in a highly baroclinic atmosphere, where the mean wind velocity at the ground is small. This approximates the situation under the mid-latitude high pressure belt. A mid-latitude beta-plane model is used, which suppresses latitudinal variations. Resonances exist in this system, and the results suggest that the climate is sensitive to variations in mean conditions including the position of the HPB.

2. THE MODEL

We consider a mid-latitude beta-plane with x eastward and y northward, with an eastward mean flow in geostrophic hydrostatic balance

$$U_a(y,z) = -\frac{1}{f\overline{\rho}_a}\frac{\partial \overline{p}}{\partial y}, \quad \frac{\partial \overline{p}}{\partial z} = -g\overline{\rho}_a, \tag{1}$$

where the overbar denotes mean conditions. The linearised potential vorticity equation for the disturbance pressure p' is then

$$\left(\frac{\partial}{\partial t} + U_a\frac{\partial}{\partial x}\right)\varsigma + B^* p'_x = f^2 g\left(\frac{\overline{\rho}_a F_H}{N^2}\right)_z, \tag{2}$$

where F_H is a heating function,

$$\varsigma = p'_{xx} + p'_{yy} + \frac{f^2}{N^2}\left(p'_{zz} + \frac{1}{H_s}p'_z\right), \tag{3}$$

$$B^* = \beta - U_{yy} - \frac{f^2}{N^2}\left(U_{azz} - \frac{1}{H_s}U_{az}\right), \tag{4}$$

provided N and scale height H_s are constant with height z. This notation is fairly standard, and is mostly the same as that used in Baines & Cai (2000). The linearised condition at the ground including topography and Ekman friction then gives

$$\left(\frac{\partial}{\partial t} + U_a\frac{\partial}{\partial x}\right)\left(p'_z + \frac{g}{c_s^2}p'\right) - \left(U_{az} - \frac{N^2}{g}U_a\right)p'_x + C_D\frac{U_a N^2}{f^2}\nabla^2 p' = \overline{\rho}_a\left(F_H - N^2 U_a h_x\right), \quad \text{at } z = 0 . \tag{5}$$

Topographic forcing appears through the lower boundary condition via the topography $z = h(x,y)$, and thermal forcing appears in both the main equation and the lower boundary condition. C_D is a surface drag coefficient. This system has similarities with forcing of lee waves in non-rotating stratified flows, as described below. For present purposes we consider mean velocity profiles that have the form

$$U_a(z) = U_a(0)e^{z/a}, \quad 0 < z < H_T,$$
$$= U_a(H_T) = U_a(0)e^{H_T/a}, \quad z > H_T, \tag{6}$$

where H_T denotes the tropopause height.

3. RESPONSE TO ZONALLY PERIODIC FORCING

We consider solutions to (2), (5) of the form

$$F_H = F_H(0)e^{-\alpha z}e^{ikx}\cos ly, \; p' = p'(z)e^{ikx}\cos ly, \quad 0 < z < H_T, \tag{7}$$

where F_H vanishes above the tropopause. As described by Held (1983), these solutions are propagating in the stratosphere if the wavelength is sufficiently long, but otherwise (and for the conditions of interest here) are confined to the troposphere. For the profile (6), the solution has the form

$$p'(z) = AJ_\nu\left(\lambda e^{-z/2a}\right) + BY_\nu\left(\lambda e^{-z/2a}\right) + F_s\frac{(1+\alpha H_s)}{k}\left(\frac{a}{H_s}\right)^2 \Im(z), \tag{8}$$

where J_ν and Y_ν are Bessel functions,

$$\lambda = \frac{2Na}{|f|}\left(\frac{\beta}{U_a(0)}\right)^{1/2}, \nu^2 = \left(2 - \frac{a}{H_s}\right)^2 + \left(\frac{2Na}{f}\right)^2\left(k^2 + l^2\right), \tag{9}$$

A and B may become large close to a resonance, but $\Im$ does not. The lowest mode may be identified with the barotropic mode, and may become large when the forcing wavelength is near its resonant wavelength (~ $\left(\overline{U}_a / \beta\right)^{1/2}$), where the response changes sign (Held 1983). Positive reinforcement of the Antarctic Circumpolar Wave depends on the mid-latitude zonal flow being on the long wavelength side of this resonance.

If Ua(0) is small ($\leq$ 1 m/sec), other modes with more complex vertical structure may become resonant, being trapped in the low velocity region beneath the shear zone above (Geisler & Dickinson 1975).

4. RESPONSE TO ISOLATED FORCING

The response to thermal or orographic forcing that is isolated in the x-y plane may be calculated by double Fourier integrals. Essentially, this is done by multiplying the above periodic solutions with the Fourier transform of the forcing, and taking the Fourier inverse. This gives a wave field that, for each subcritical mode, consists of a lee wave field and upstream columnar disturbances. The amplitudes of these features may be large when the surface velocity is small. These equations have mathematical similarities to those describing stratified flow past isolated topography in non-rotating flow (Baines 1995).

5. CONCLUSIONS

In baroclinic environments where the surface velocity is small, heating (or orographic forcing) can force a response comprising several modes with different vertical structure. This response may be relatively large, affect both the upstream and downstream environments, and be sensitive to the details of the background state. In particular, variations in the background state may cause changes in the climate in the vicinity of the mid-latitude high pressure belt. Some numerical experiments to examine the effects of latitudinal variations are planned.

6. REFERENCES

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