6B.6 TIME DEPENDENT ENERGY BUDGET FOR QUASI-STATIONARY CONVECTIVELY COUPLED MODES

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1. INTRODUCTION

In this paper we analyze the time varying energy budget for the quasi-stationary, equatorially trapped, 4-day modes described and documented in Tomas and Webster (2002, hereafter, TW1). TW1 find that in many ways, the modes are well described as a superposition of the largest scale mixed Rossby gravity and inertia gravity waves and the zonal mean oscillation lying on the same $n = 0$ dispersion curve derived from shallow water theory. An equivalent depth of 34 m produces the best agreement between observations and theory. Using the relationship between equivalent depth and vertical scale in Holton (1970), a value of $T_\circ = 300°$K and $dT/dz = -6°$K/km, TW1 calculate a vertical scale of approximately 10 km, which is in close agreement with the data. Our interest here is determining the energy sources and sinks of the modes around the time they attain peak amplitude. In particular, we are interested in determining whether the modes are forced by the convection associated with them, and if so, how this forcing compares to other forcing(s). One question we seek to answer is if it is appropriate to describe the modes as CISK-like (Lindzen, 1974).

2. THE DATA AND METHODOLOGY

The data used in TW1 and here are the ECMWF reanalyses on a 2.5° by 2.5° grid and at 13 pressure levels between 1000mb and 100mb made available through the National Center for Atmospheric Research. The period of coverage is the 15 years between 1979-1993 at 6 hourly resolution. The three dimensional distribution of heating was calculated as the residual to the thermodynamic energy equation. Composite averages were constructed using two indices based upon the areally averaged (15°S to 15°N, 160°E to 80°W) meridional divergent wind (v_χ): the upper index, defined as $\left\langle\left\langle v_\chi^{200mb}\right\rangle\right\rangle - \left\langle\left\langle v_\chi^{500mb}\right\rangle\right\rangle$ and the lower index defined as $\left\langle\left\langle v_\chi^{500mb}\right\rangle\right\rangle - \left\langle\left\langle v_\chi^{925mb}\right\rangle\right\rangle$, where the angle brackets designate a horizontal average. In TW1 these indices were shown to be associated with two similar but largely independent modes dominated by fluctuations in the upper and lower troposphere, respectively.

The equations of motion for large scale flow with the vertical coordinate expressed in terms of the log of the pressure (e.g., Holton, 1992) were used to derive equations for the time rate of change of the potential and kinetic energy. These equations were evaluated using the composite averaged data fields. The resulting quantities were then areally averaged and vertically integrated over a volume that envelops the maximum in the time mean of the composite perturbation energy (15°S to 15°N, 160°E to 80°W, 1000mb to 100mb). The analysis was simplified because only a few of the terms in the budget were found to make a significant contribution and those that did not were omitted with very little impact on the results. Additional simplifications resulted from writing the advective terms in flux form and noting that only the meridional flux convergence is large. The resulting equation for the time rate of change of the total energy after simplifications is:

$$\left[\left\langle\left\langle \frac{\rho_o}{2}\left(\left(\frac{R}{NH}\right)^2\frac{\partial T'^2}{\partial t}+\frac{\partial u'^2}{\partial t}+\frac{\partial v'^2}{\partial t}\right)\right\rangle_y\right\rangle_x\right]^z \approx$$
$$\left[\left\langle\left\langle \rho_o\left(\frac{1}{C_p}\left(\frac{R}{NH}\right)^2 T'J' - u'v'\frac{\partial\bar{u}}{\partial y} + u'X' + v'Y'\right)\right.\right.\right.$$
$$\left.\left.\left. + R_{PE} + R_{KE_u} + R_{KE_v}\right\rangle_y\right\rangle_x\right]^z \quad (1)$$
$$-\left[\left\langle \rho_o\left(\left.\frac{v'\phi'}{y_2-y_1}\right|_{y_1}^{y_2}\right)\right\rangle_x\right]^z$$

Here the angle brackets designate a horizontal average and the square brackets designate a vertical integral. R_{PE}, R_{KE_u}, and R_{KE_v} are the residuals corresponding to the potential, zonal kinetic and meridional kinetic energy equations. X' and Y' are dissipation terms, linearly proportional to the zonal and meridional velocities, respectively, with the coefficients chosen such that the sum over the 19 day composite period of the right hand side of each equation (with the residuals set to zero), is zero. The rest of the symbols are standard and in the interest of brevity, the reader is referred to Holton (1992) for their definitions.

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The terms on the left are the time rates of change of the potential, zonal kinetic and meridional kinetic energies, respectively. The first term on the right is a source/sink of potential energy owing to heating. The second term on the right is a conversion between zonal mean and perturbation kinetic energy. The final term is the flux convergence across the north-south boundaries and it represents the work done on the air within the domain but associated with mass redistributions occurring outside the domain.

3. THE RESULTS AND DISCUSSION

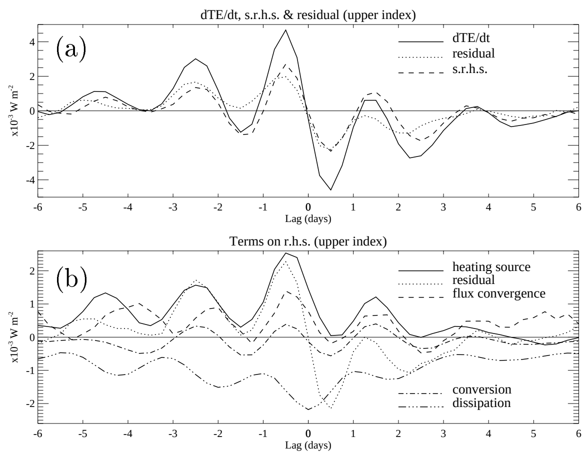

Figure 1: Integrated and averaged energy budget terms for upper index composites.

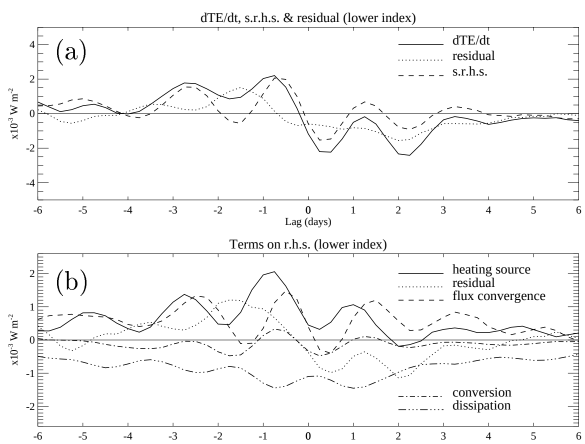

Figure 2: Integrated and averaged energy budget terms for lower index composites.

Figures 1a and 2a show the time rate of change of the total energy (left hand side of eqn. 1), the sum of the terms on the right hand side of eqn. 1 minus the total residual (s.r.h.s) and the total residual for the upper and lower composites, respectively.

For the upper mode case, the time rate of change, the s.r.h.s. and the residual vary in phase with one another and the latter two have roughly comparable amplitudes. The amplitude of the time rate of change at extrema is greater than the s.r.h.s. prior to day 0, and less than the s.r.h.s after day zero. The residual is positive prior to day zero and negative after day zero.

For the lower mode case, the time rate of change and the s.r.h.s. also vary in phase, but the residual does not. The amplitude of the time rate of change is in better agreement with the s.r.h.s. than in the previous case but the residual is not negligible. The residual is positive prior to day zero and negative after day zero.

We find that the there are four sources/sinks of energy (fig. 1b and fig. 2b). For the upper mode, listed in order of largest absolute amplitude attained during the rise and fall of the total perturbation energy, they are (1) a source owing to convective heating correlating with temperature anomalies, (2) a residual (3) dissipation (4) flux convergence across the lateral boundaries, and (5) a conversion between time mean zonal kinetic energy and perturbation zonal kinetic energy. The quantities (2), (3) and (4) rank roughly the same so the order in which they are listed is not particularly important, and in fact is different for the lower mode case.

If the time dependence is removed by summing over the period of growth and decay (1) and (4) make net positive contributions to the energy, (3) makes a net negative contribution and (2) and (5) make little net contribution. We conclude from this result that the modes are forced by the convection associated with them and by the flux convergence across the southern and northern boundaries. The latter is less important for the upper mode case than for the lower mode case. The same conclusion is reached if one considers the time varying behavior, however the interpretation is complicated by the residual. The residual is both positive and negative over the life cycle and its source is unknown. We suspect that the residual results from observations being incorporated into the reanalyses to compensate for deficiencies in first guess simulation. We considered the behavior of the residual in comparison to other forcing(s), but could not conclude precisely what the deficiencies might be. For example, if it were simply a matter of heating being underestimated, the residual would be in phase with the heating source term and would always be positive. The first condition is true for the case of the upper mode but not for the lower mode. The second condition is not true for either case.

4. REFERENCES

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