The Role of Momentum Fluxes in Shaping the Life Cycle of a Baroclinic Wave

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ABSTRACT

The wide disparities in baroclinic wave development between spherical and Cartesian geometry are investigated with the purpose of assessing the role of the eddy momentum fluxes. Differences are already significant at the linear stage, as momentum fluxes are predominantly poleward in spherical geometry and predominantly equatorward in Cartesian geometry. More important, the low-level flux convergence is displaced poleward on the sphere and equatorward on the plane. On the sphere, these circumstances lead to rapid poleward movement of the low-level zonal-mean jet. The anticyclonic horizontal shear region expands as the jet feeds back on the momentum flux. The wave breaks anticyclonically and quickly zonalizes. In the Cartesian life cycle, the equatorward displacement of the flux convergence is counteracted by the mean meridional circulation and there is consequently a weaker feedback with the horizontal shear. The wave breaks, in this case cyclonically, but then takes much longer to zonalize. On the sphere, the angular velocity gradient in uniform westerly or easterly flow adds a separate mechanism for converting eddy kinetic energy to zonal mean, further hastening the zonalization process.

It is possible to change the sign of the eddy momentum flux and the sense of the breaking in either geometry by slightly changing the basic flow. For example, cyclonic roll-up on the sphere can be obtained by adding weak cyclonic barotropic shear, as highlighted in a recently published study. Similarly, the addition of anticyclonic barotropic shear in a Cartesian simulation leads to anticyclonic wave breaking. An easterly jet on the sphere allows cyclonic breaking, but the wave still zonalizes rapidly, as in the case of a westerly jet. The persistence of the nonlinear eddies in these diverse experiments is not well correlated with the minimum value of the refractive index for Rossby waves, as suggested in the referenced study. It is proposed that the longevity of residual vortices after wave breaking is determined not by the sign of the vorticity or the breadth of the waveguide, but by the sign of the momentum flux and the geometry of the model.

1. Introduction

In order to characterize the interaction between mean flow and baroclinic eddies, most studies have focused on the finite-amplitude development of normal modes in a zonally symmetric baroclinic jet. Such waves grow exponentially at all altitudes for a few days depending on the initial amplitude and then progressively enter a nonlinear stage from the bottom up. Nonlinearity eventually stops the growth of the wave. This equilibration process[1] can often be characterized as strongly cyclonic or strongly anticyclonic, according to the predominant meridional tilt of the wave prior to equilibration or the sign of the vorticity between the two main barotropic zonal-mean jets that are created. Snyder et al. (1991), Nakamura (1993), and Rotunno et al. (1994) have discussed the tendency of baroclinic waves in Cartesian models to exhibit cyclonic (SE–NW) tilt. Observations (Starr 1968; Peixoto and Oort 1984) and modeling studies on the sphere (Hollingsworth 1976; Simmons and Hoskins 1978) have documented predominantly poleward momentum fluxes, associated with anticyclonic (SW–NE) tilt. In this study, we analyze the differences, due to model geometry, between the two extreme types of equilibration.

Differences due to geometry have never been investigated systematically using multilevel models. While the solutions in both Cartesian and spherical geometry exhibit common features like lower- and upper-level frontogenesis, occlusion, and wave breaking, there are major differences in morphology, starting with the aforementioned meridional eddy tilt, that significantly

[1] Since "wave breaking" is commonly understood to imply turbulent energy transfer to smaller and larger scales, we use "equilibration" to refer to a terminal process that may or may not involve such a cascade.

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