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Baroclinic Instability on Hot Gas Giant Planets

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Abstract

We investigate baroclinic instability under conditions applicable to hot extrasolar giant planets. Using a global general circulation model (GCM) which solves the primitive equations, we show that large-scale jets similar to those observed in current GCM simulations of hot gas giant planets are baroclinically unstable at a wide range of latitudes. For jets located at latitudes away from the equator, the growth rate and the most unstable mode are in good agreement with linear analysis. For jets located at or near the equator, the instability is strong at the jet flanks, rather than at the core. Thus, baroclinic instability is significant for understanding characteristics of hot gas giant planet atmospheres. We also demonstrate that the instability is not captured in simulations with low resolution and/or high artificial viscosity.

1. Background

Baroclinic instability is a generic instability process that occurs in rotating stably-stratified fluids, subject to a meridional temperature gradient. By thermal wind balance, the gradient induces a vertical shear in the mean flow (e.g., [1]). The instability is important as it gives rise to the large- and meso-scale weather systems on the Earth and other planets in the Solar System. For extrasolar planets, the instability could serve as a source of turbulence, which has been invoked as initial conditions in some simulations (e.g., [2]). More importantly, it is a source of variability which could be observed remotely.

Baroclinic instability on extrasolar planets has not been studied thus far. In this work we use an advanced pseudospectral GCM to perform an extensive study of the stability and nonlinear evolution of a balanced jet on an extrasolar planet. For concreteness, we present here the result corresponding to the close-in planet HD209458b and focus on the stability of high-speed (typically $\sim$1000 $\mathrm{m\,s^{-1}}$) eastward jets at the equator and westward jets at high latitudes. Wide jets of such strengths is a robust feature of GCM simulations of tidally-synchronized extrasolar giant planet atmospheres (e.g., [3]; [4]; [5]). The jets, which are gradient-wind balanced, are perturbed initially by an infinitesimal disturbance and allowed to evolve freely thereafter. The nonlinear calculations have been validated against previous baroclinic instability calculations for the Earth (e.g., [6]). We also derive growth rate and phase speed spectra using linear theory and compare the linear results with full nonlinear simulation results.

2. Results

2.1 Linear Analysis

According to our linear analysis, the growth rate of the instability is reduced for a jet located at low latitudes, compared with a jet located at high latitudes. Near the equator, where the deformation length scale becomes too large to accommodate baroclinic waves, the linear theory predicts stability. In general, the linear analysis agrees well with the full nonlinear calculations, at the early stages of the unstable evolution.

2.2 Nonlinear Evolution

Full nonlinear calculations show much richer behavior, as expected. For example, broad equatorial eastward jets are unstable. The instability takes place at the jet flanks, where there is still a significant vertical shear to satisfy the necessary condition for instability. The jet core is stable, unlike in the jets situated at higher latitudes.

The unstable flow resulting from the equatorial jet is illustrated in Figure 1. It shows relative vorticity of the flow after 26 planetary rotations in polar stereographic view, centered on the North Pole. At the shown time, the instability is well developed, with sharp fronts rolling up nonlinearly into cyclones (areas of positive vorticity anomaly, shown in red).

Broadly, we find that the most unstable mode for a

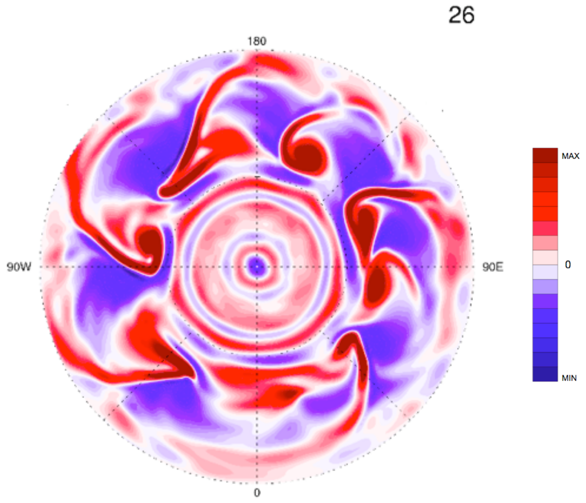

Figure 1: Polar stereographic view of the relative vorticity at the 975 mbar level of the eastward equatorial jet 26 planetary rotations after applied small perturbation. The max/min contour level is $\pm 1.5 \times 10^{-5} \mathrm{m}^2\,\mathrm{s}^{-2}$ and the contour interval is $6 \times 10^{-7} \mathrm{m}^2\,\mathrm{s}^{-2}$.

mid- or high-latitude westward jet is 3. For a broad equatorial jet, the most unstable mode is 7, which is manifested at the jet flanks (see Figure 1). We also observe that westward jets tend to be more stable, compared to their eastward counterparts, and requires much stronger vertical shear for instability.

2.3 Numerical Convergence

By performing the simulations described above with a wide range of horizontal resolution (from T21 to T170, corresponding to 64×32 and 512×256 grid points in physical space, respectively), we find that the calculations do not converge for resolutions below T85. Furthermore, we find that baroclinic instability does not occur if the artificial viscosity coefficient used in the calculation is too high. A high artificial viscosity is often used to stabilize numerical simulations against strong forcing in current studies of extrasolar planet atmospheres. Given this, baroclinic instability is unlikely to be captured in current simulations even when conditions are favorable for the instability. This poses a serious issue in current flow modeling studies of extrasolar planet atmospheres.

3. Summary and Conclusions

We have used HD209458b as a paradigm hot extrasolar planet to investigate the significance of baroclinic instability on such planets. Baroclinic instability is known to play an important role in weather, general circulation, and large-scale variability on Solar System planets. We have found jet profiles plausible for such planets to be unstable in our high-resolution simulations. Significantly, the instability can only be captured if the resolution is sufficiently high and if the numerical viscosity is carefully chosen.

In this work, effect of heating from the host star has not been incorporated and the calculations performed are adiabatic. While this may be reasonable for deep regions in the atmosphere, diabatic forcing needs to be included for higher altitude regions. Also, we have focused mainly on the instability and subsequent evolution in isolation. The full effect of baroclinic instability on the mean flow on hot extrasolar planets remains to be studied. These issues will be addressed in future work.

Acknowledgements

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