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# Super- and sub-rotating equatorial jets: Newtonian cooling versus Rayleigh friction

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Observations of Jupiter and Saturn show super-rotating (prograde) equatorial jets that have persisted for decades. Shallow water simulations run in the Jovian parameter regime reproduce the mixture of robust vortices and alternating zonal jets seen in Jovian cloud decks, but until recently the equatorial jet was invariably sub-rotating (retrograde). Recent work has obtained super-rotating equatorial jets, but only by using models for radiative cooling to supplement the usual frictional dissipation. We present a theory that explains both sets of simulation results by calculating the meridional transport of zonal momentum induced by trapped equatorial Rossby waves. These waves transport no momentum in the absence of dissipation, because the zonal and meridional velocity components are 90 degrees out of phase, as for evanescent waves on a homogeneous background. Dissipation changes this phase relation between the two velocity components to create a net momentum transport. Radiative Newtonian cooling creates a net transport of eastward zonal momentum towards the equator and an eastward acceleration in the zonally averaged zonal momentum equation, while linear Rayleigh friction creates a net transport of eastward zonal momentum away from the equator. The former result is consistent with the previous findings of Andrews and McIntyre (1976) because they considered waves with large vertical wavenumber in a stratified fluid, while shallow water theory describes the opposite limit of zero vertical wavenumber. Our findings provide a mechanism to explain the directions of the equatorial jets seen in forced-dissipative shallow water simulations with isotropic forcing and the two alternative forms of dissipation. The latitudinal structure of the momentum flux for the lowest trapped wave mode is also consistent with the positions of the two "horns" of maximal eastward velocity either side of the broad Jovian equatorial jet. Finally, we present the thermal shallow water equations as an alternative model for Jovian atmospheres. These equations extend standard shallow water theory by treating the reduced gravity as an advected scalar representing a spatially-varying buoyancy contrast between the two layers in the equivalent barotropic interpretation. This allows us to introduce Newtonian cooling in the separate evolution equation for the buoyancy, while existing work places the cooling in the shallow water height equation. Simulations of this thermal model also produce super-rotating equatorial jets, and they show a more realistic distribution of jet speeds that gradually decay with latitude. The previous model produced a concentrated equatorial jet with little motion at higher latitudes. Extending our Rossby wave theory to the thermal model, we again find that radiative cooling creates a net transport of eastward zonal momentum towards the equator, while Rayleigh friction creates a net transport of eastward zonal momentum away from the equator.