Global GCM simulations of Jupiter's atmosphere

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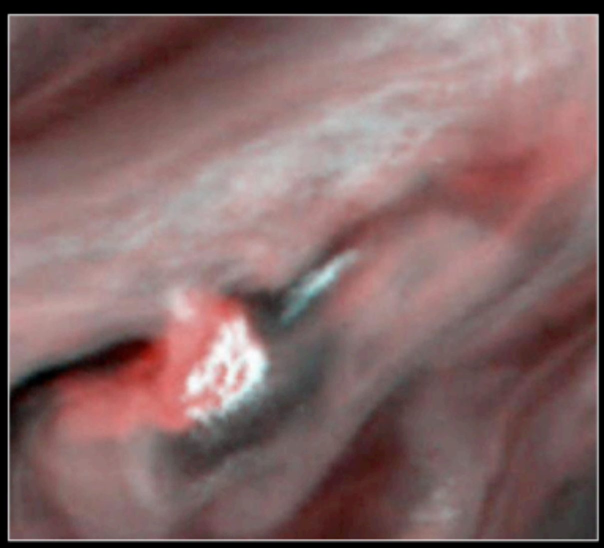
Introduction

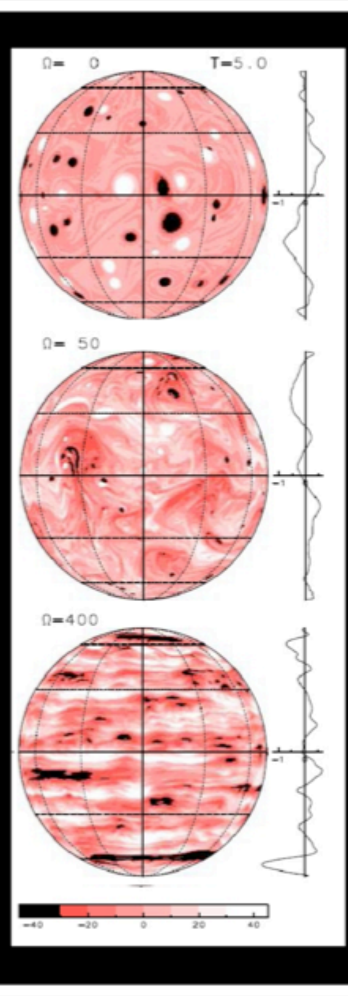
The giant planets have long been recognised as some of the best natural laboratories for studying planetary fluid dynamics.

Nevertheless, we still only poorly understand the mechanisms responsible for the formation and maintenance of the ubiquitous zonal jets on these planets, of which Jupiter's are the most spectacular example (see background image).



Of particular interest is how energy is injected into the system at small scales to drive the eddies and jets. Observations of lightning on the giant planets (left) suggest that moist convection might be the dominant small-scale process responsible [ref. I00].

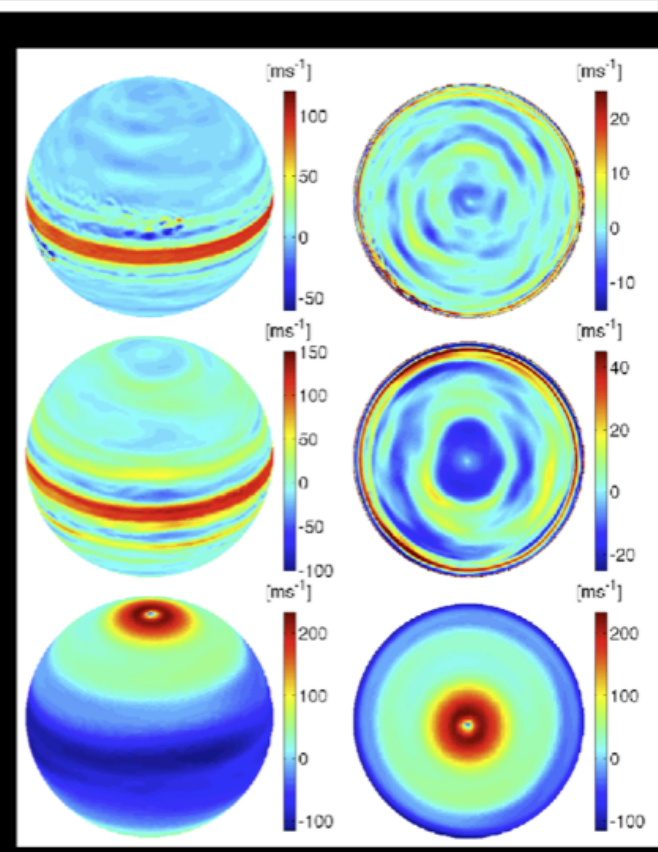
Water storm cloud north west of the Great Red Spot. The image is about 7000 km by 5000 km (NASA / Galileo) [B98, Fig. 6].



Relative vorticity for three 2D non-divergent simulations with different rotation rates [S09, Fig. 3]

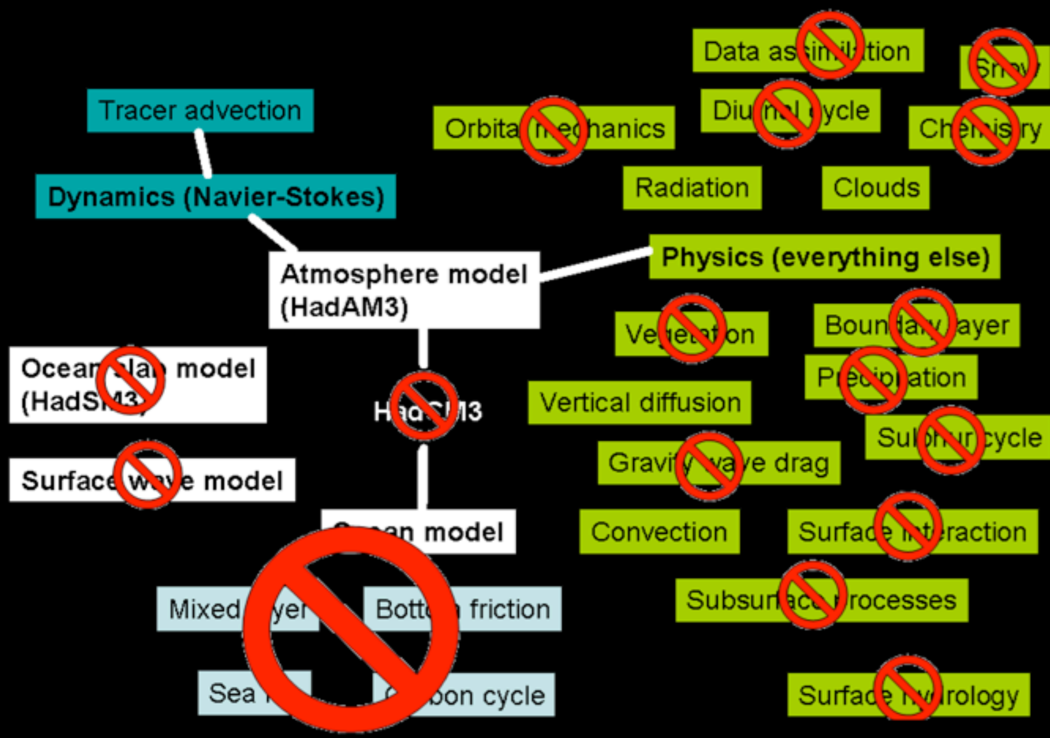
These jets can be reproduced qualitatively using idealised models such as the 2D non-divergent barotropic vorticity equations on a sphere (left), and recently using quasigeostrophic and simplified general circulation models (GCMs, right). The strength and direction of the giant planets' equatorial jets are not yet fully understood, however. Simple models suggest a preference for retrograde flow, but Jupiter's and Saturn's are prograde.

Recent work with a limited-area Jupiter general circulation model (GCM) developed in Oxford has focused on that planet's troposphere and stratosphere, including the effects of moist convection [Z09]. We report on our progress in extending this model to a global domain. We soon hope to be able to resolve the zonal jets on a global scale and hence investigate Jupiter's atmospheric dynamics using a more realistic model.



Zonal wind profiles for Jupiter, Saturn, and Uranus/Neptune from GCM simulations including latent heating [L10, Fig. 2]

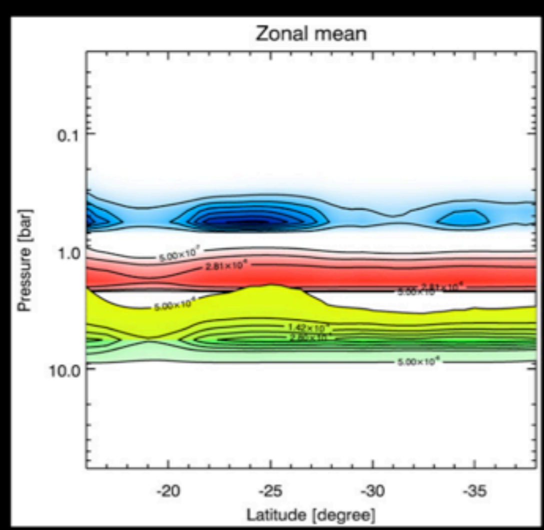
Model



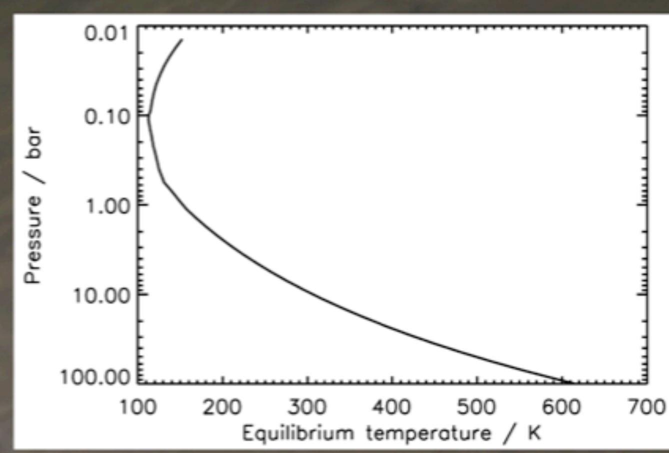
Structure of the Met Office Unified Model, showing components removed for the Jupiter model.

A GCM for giant planet atmospheres has been developed in Oxford over the last decade [Y04] based on the dynamical core of the UK Met Office Unified Model. This model is primarily known to the public via the BBC's weather forecasts, and the particular version of the model we use is well known in the scientific community through the *climateprediction.net* project.

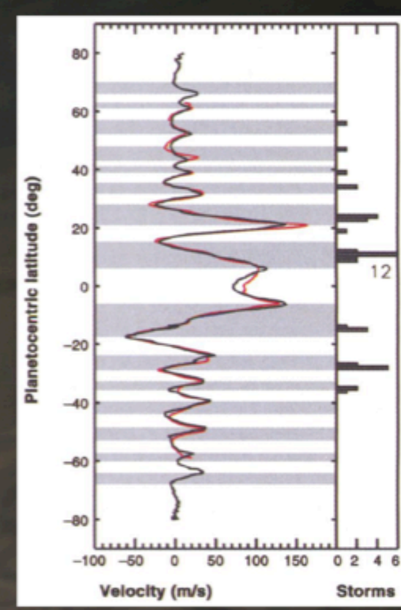
Our model solves the primitive equations in sigma coordinates for the jovian troposphere and stratosphere (100 to 0.01 bars).



Typical vertical distribution of cloud species in the Jupiter limited area model. Blue is NH_3-ice, red is NH_4SH-solid, yellow is H_2O-ice, and green is H_2O-liquid [Z09a, Fig. 1a].



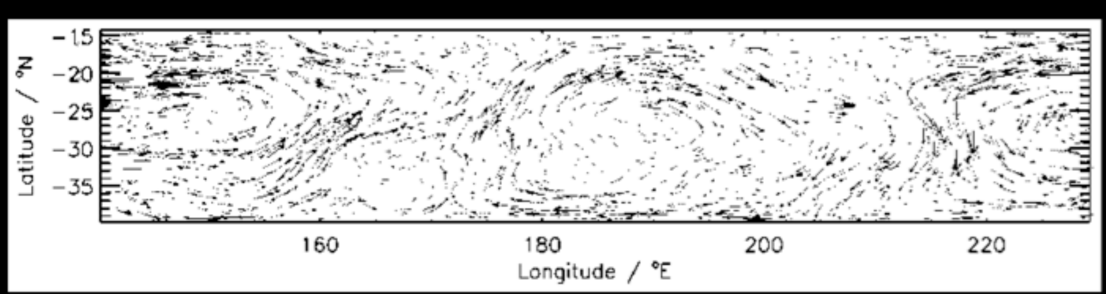
Equilibrium temperature profile used in the models, from Cassini data [R06, Fig. 3a] above the 1 bar level, and adiabatic below.



Zonal mean zonal wind speeds measured by the Cassini spacecraft (black) [P03, Fig. 1]. The red line is the equivalent measured by Voyager 2 [L86].

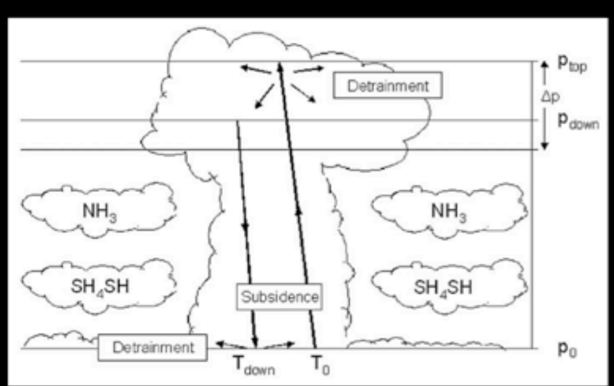
All the Earth-specific physical parameterizations have been removed (above), and simple equivalents added for Jupiter:
- Newtonian cooling of potential temperature
- Passive cloud tracers (NH_3 currently included, but no latent heat feedback)
- Richardson number-based vertical mixing
- Dry adiabatic adjustment
- Moist convection (currently inactive)
- Rayleigh damping of zonal velocity towards an observed profile (to be deactivated in the future)

Most work to date has been based on a limited area model, periodic in longitude, including the south equatorial and temperate belts and the Great Red Spot [Z09] (above right and below).



Typical limited area model velocity field around 1 bar at t + 970 days. Resolution is 0.5 degrees in latitude and longitude.

Our current work is focused on testing and validating a global version of this model, and configuring it for a cluster in Oxford. The model is still very much in the testing phase. Once this parallel version is set up, giving us up to 512 processors to run simulations on, we intend to re-activate the moist convection component and perform spin-up experiments from random initial conditions.

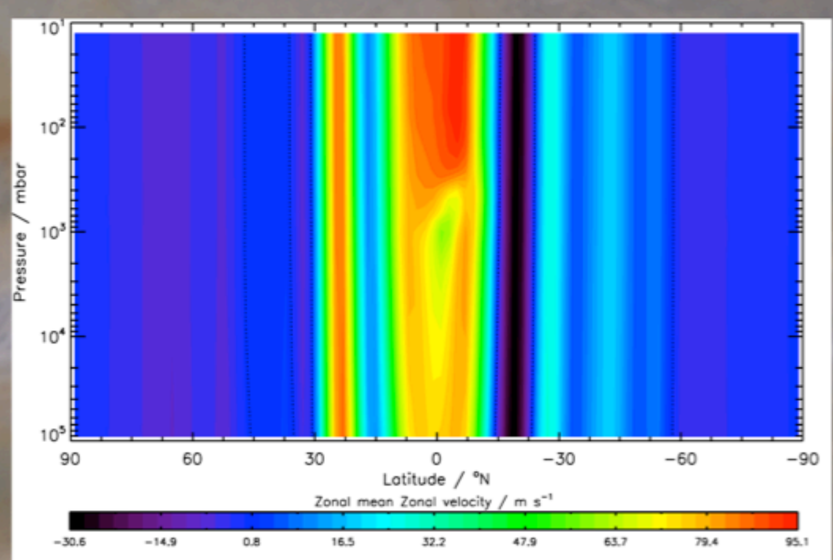


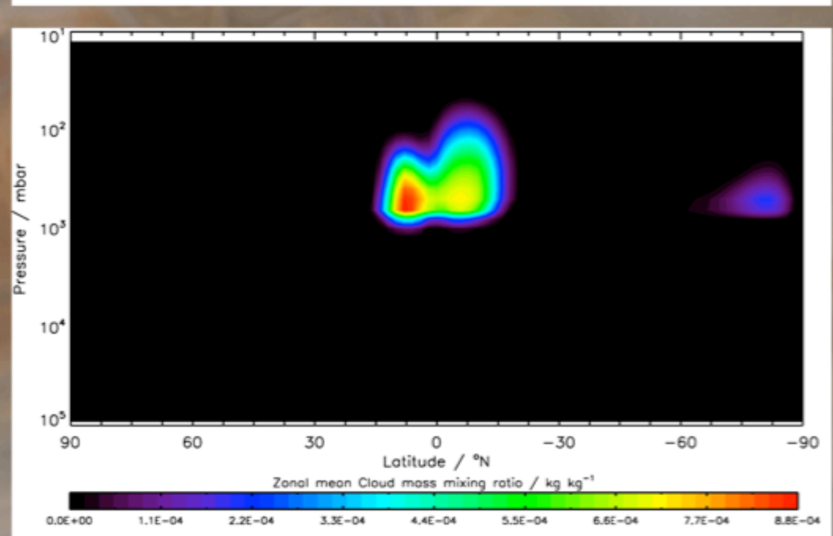
Schematic of our moist convection parameterization for Jupiter based on the Carnot cycle. Not yet included in the global model [Z09b, Fig. 1].

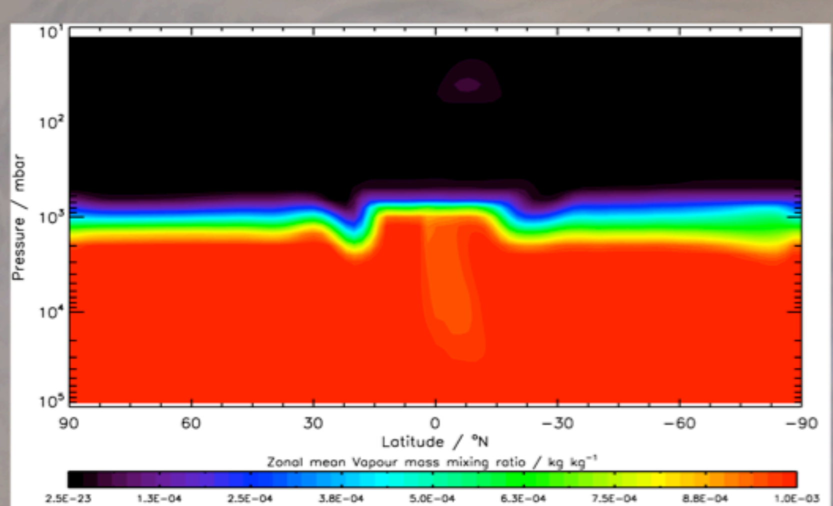
Example global simulation

The figures show results from an example run using the global model, with a resolution of two degrees in latitude and longitude. Both Newtonian cooling and Rayleigh damping are activated, with radiative and dynamical timescales of about six and 60 Earth days respectively. The equilibrium temperature field (Cassini data) is a function of pressure only, and the equilibrium velocity field (Voyager data) is a function of latitude only (both shown above). Both upper and lower boundaries are free-slip, i.e. they have no velocity boundary condition.

Without velocity forcing zonal jets do form (with a retrograde jet at the equator) but are extremely weak, as there is nothing explicitly driving the flow at small scales.







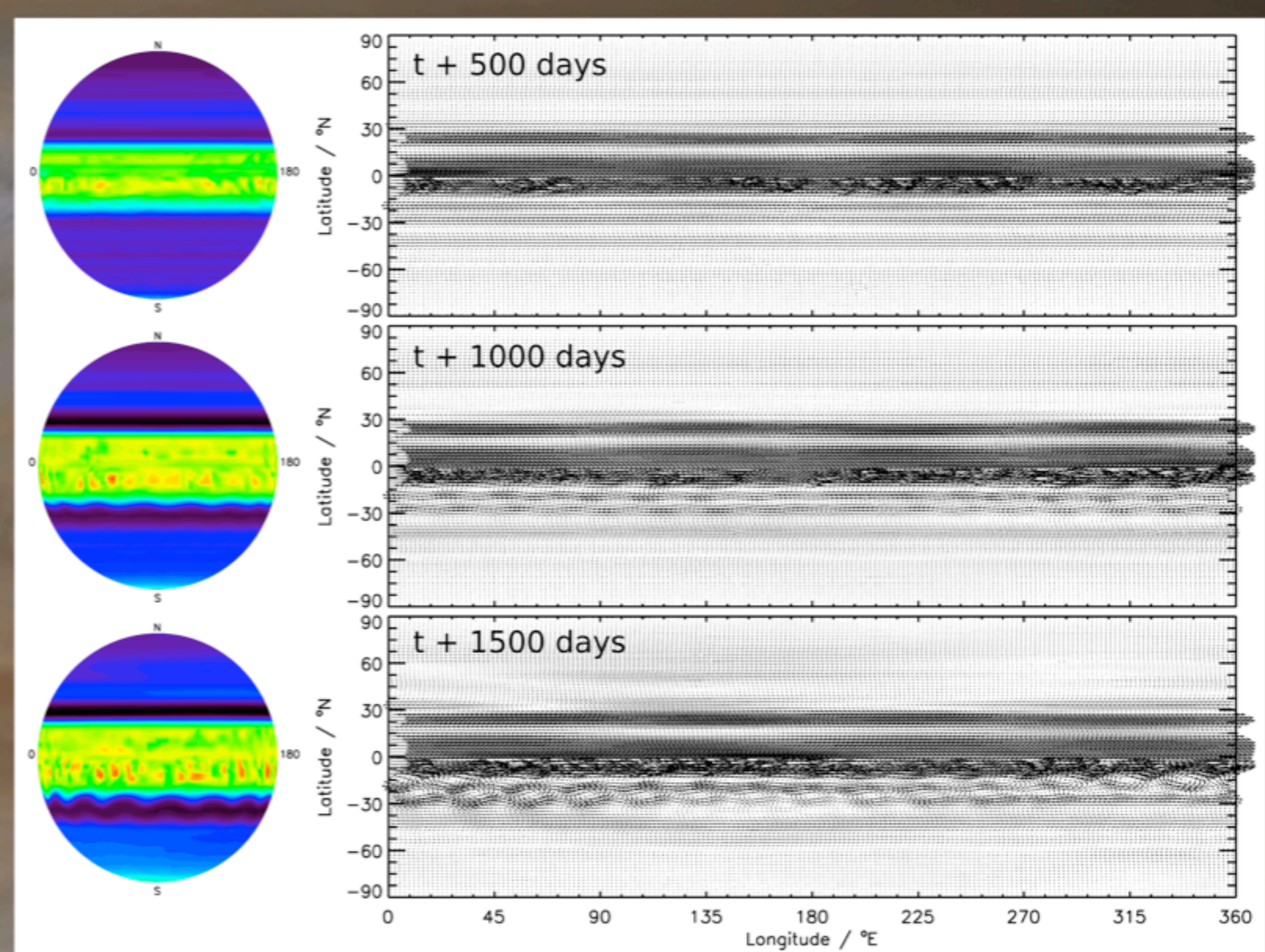
Vertical sections through three fields showing zonal mean quantities at t + 1500 days.

Top: zonal mean velocity.

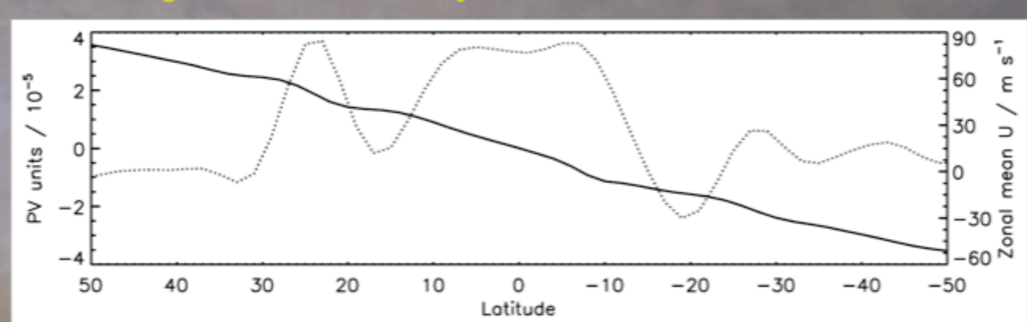
Middle: NH_3-ice (cloud) concentration.

Bottom: NH_3-vapour concentration.

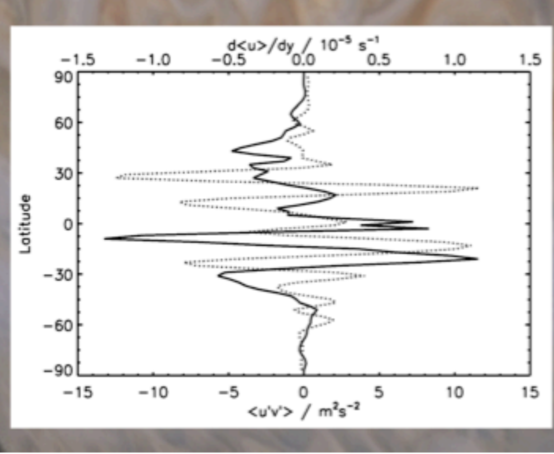
NH_3-vapour concentration (left) and horizontal velocity field (right) at p = 800 mbar at three different times during the model run. Vapour concentrations range from zero (black) to 830 ppmm (red).

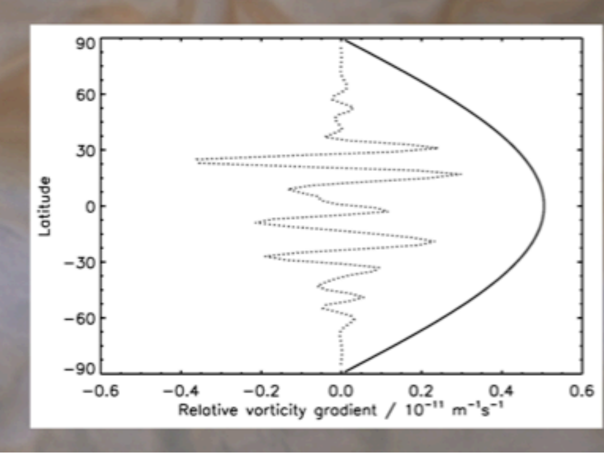


Zonal mean Ertel potential vorticity (solid) on the 177 K potential temperature surface (with p_0 = 1 bar) and barotropic component of zonal velocity (dotted) at t + 1500 days. Regions of positive zonal velocity correlate with high PV shear, and negative zonal velocity correlate with low PV shear.



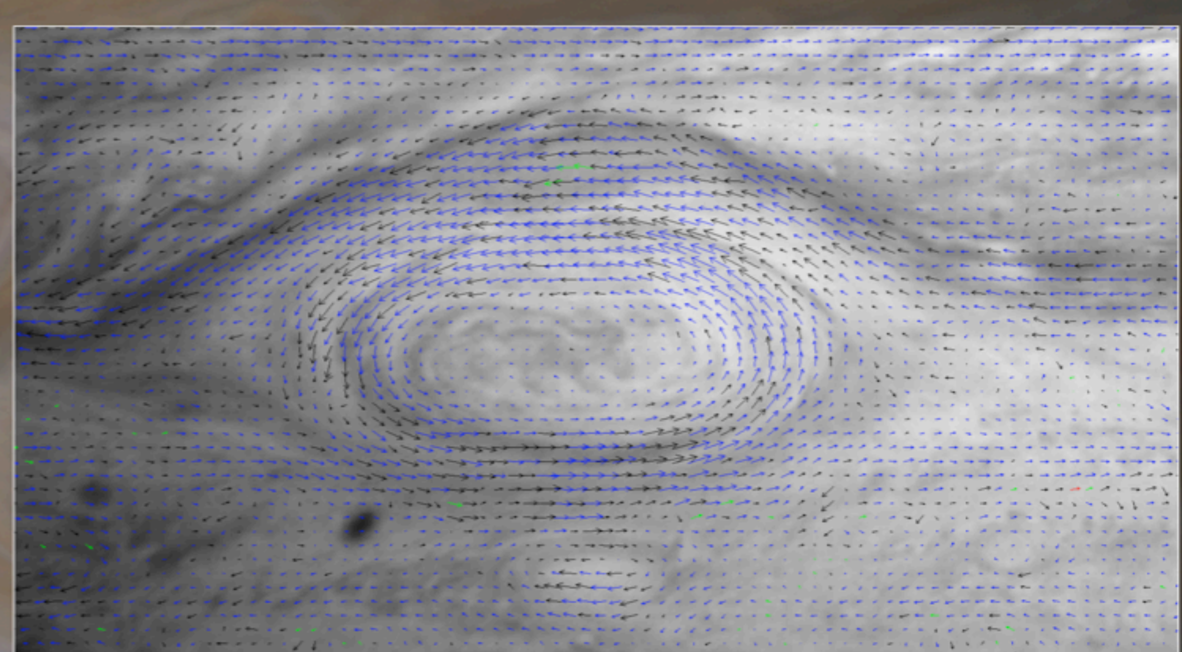
Diagnostic quantities based on the 800 mbar velocity field at t + 1500 days. Left: eddy momentum flux (solid, bottom axis) and gradient of zonal mean zonal velocity (dotted, top axis). When these are correlated (as they are in observations) it implies that eddies transfer energy to the zonal jets. Right: relative vorticity gradient (dotted) and beta parameter (solid). Relative vorticity exceeding beta implies a barotropically unstable velocity profile, and this is also seen in observations. It is perhaps not surprising that our model profiles do not resemble the observed profiles, as the model does not resolve the deformation radius and hence even interactions between the largest vortices are unresolved. With higher resolution we expect to improve this aspect of the model.





Observations

Observational data from Jupiter is needed to test our model and initialise model runs. Currently we are working on data from the Cassini flyby of Jupiter in 2000. Using correlation image velocimetry (CIV) we can track cloud features in the atmosphere and recover horizontal velocity fields (below). We hope to combine these with the thermal wind equation and a vertical temperature profile to produce 3D horizontal velocity fields.



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Velocity field around the Great Red Spot from CIV analysis. Image is about 47000 km by 28000 km; RMS velocity is ~55 m/s [image NASA / Cassini].

Future directions

Our immediate goals are to
- Configure and run the model on a large cluster
- Re-activate the moist convection parameterization
- Perform spin-up experiments with moist convection
- Run at resolutions below 0.5 degrees
- Add an equator-pole temperature gradient induced by differential solar heating

On a longer timescale we plan to
- investigate turbulent properties of the flow
- use observational data for validation and initialisation
- extend the model to other planets

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