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Non-linear simulations of Saturn's 2010 Great White Spot

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1. Introduction

We have little information on the vertical structure of Saturn's atmosphere below the visible cloud deck, i.e., for pressure levels higher than ~500 mbar, in particular of the zonal wind vertical shear and vertical thermal structure. Our knowledge of Saturn's thermal vertical structure is also very limited. Voyager [1] and Cassini radio occultation experiments [2] have probed Saturn's thermal structure down to ~1.5 bars. In both results the planet's thermal profile tends towards an adiabat near the 1 bar level with oscillations of the static stability around the neutral state at the deeper levels. The presence of stable long-lived vortices [3] and continuous convective activity, suggest that vertically stable and unstable regions must coexist. Planetary-scale rare convective events, or Great White Spots (GWS) in Saturn [4], may give us more clues on the higher tropospheric vertical structure. The dynamical evolution of the atmospheric disturbance generated in the region by the storm, and the dynamical evolution of the disturbance itself at the visible cloud deck may be used as a benchmark. Numerical models may try to determine the vertical model structure which best reproduces the observed dynamical behavior of the storm. In this work we present the results of non-linear numerical simulations of the last 2010 GWS which explore the vertical structure of the upper Saturn's troposphere.

2. The atmosphere model

We used the Explicit Planetary Isentropic Coordinate (EPIC) atmospheric model [5], which solves the non-linear Navier-Stokes equations for a rotating, hydrostatic atmosphere assuming that air parcels move adiabatically, where Ertel's potential vorticity (PV) is conserved. In this case PV can be used as a tracer to visualize atmospheric motions if the fluid is inviscid. The free parameters of our model atmosphere are the vertical thermal profile, the zonal wind system, and the vertical thermal structure of the atmosphere. By exploring the parameter space we expect to get insight into the hidden vertical structure of the higher troposphere in Saturn. Our model included the lower stratosphere from 10 mbar down to 10 bar, the water condensation level, where the vigorous convective activity of the 2010 storm may have originated [6].

In our numerical experiments, we used zonal winds retrieved at the cloud top level (~500 mbar) [7]. From the visible layer down to the deeper layers we assumed different values of the vertical wind shear ranging from no shear to an increase of 1.2 times every scale height. We also experimented with different values of the vertical static stability, from almost a neutral atmosphere to values for N^2 as high as $0.7x10^{-4}$ s^{-2}. We modeled the energy injected in the atmosphere by the storm by introducing a Gaussian heat pulse whose intensity, size, and latitude location were also free parameters. Finally, we explored the effect of varying energy deposition by introducing the heat pulse in all or some of the lower layers. The final goal of our simulations was to find the parameter combination which best reproduces the storm's morphology and dynamical activity observed at the visible cloud deck. The 2010 GWS event is a very complex phenomenon which also disturbed a big region of the planet, whose detailed dynamics below the cloud top level is uncertain, and the EPIC model is an approximation to the real atmosphere. We, therefore, proceeded to obtain the combination of free parameters that were able to reproduce the most important observed storm features. We may then assemble all of them in a more general picture of the storm and Saturn's high troposphere properties. This piecewise approach will allow us to make progress and reveal several properties of the actual storm.

3. Simulation results

During the initial stages of the storm which span between two and three weeks after the storm outbreak detection [8], simulations proved to be very sensitive to latitude location, and were able to reproduce very well the initial development of the storm if the perturbation was placed at the north latitude of ~38º, which is fully consistent with measurements [8]. Simulations also proved to be strongly dependent of the thermal vertical structure of the atmosphere. For high Brunt-Väisälä values simulations yielded unrealistically unstable atmospheres with unobserved large vortices. An important general result was that the atmosphere was highly unstable if the perturbation was injected in all the layers (the vertical domain was discretized in 8 layers), generating a chain of long-lived vortices that are not observed in the real disturbance, which has a turbulent nature. We could only mimic this behavior by injecting the heat pulse in the lower layers of our model. Vertical wind shear did not have a large impact on simulations results, but they favored atmospheres with increasing winds at least as high as 1.1 times per scale height.

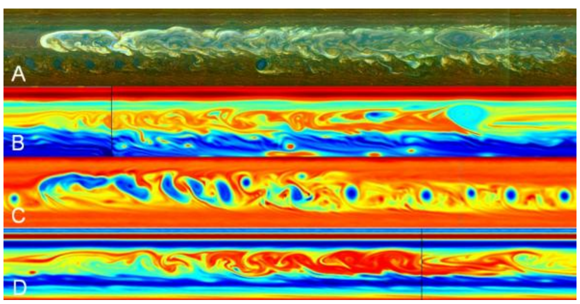

Figure 1: A: Real disturbance observed by Cassini after 120 days of the outbreak. B: EPIC simulation PV map after 80 days after injecting a heat pulse at 4 bars. C: EPIC simulation PV map after 60 days when heat injection is at all the layers, D: The same as B after 120 days.

4. Summary

Non-linear simulations of the 2010 GWS can reproduce most of its observed morphological and dynamical properties. Simulation results suggest that energy injection was very vigorous throughout all the upper troposphere during the initial stages of the storm, during the first two to three weeks. They also point out that energy deposition at the uppermost layers of the troposphere, close to the visible cloud top, had to be lower than that injected at deeper layers close to the water condensation level, otherwise the weather layer becomes unstable with the generation of large vortex chains at ~40ºN. Simulations also point out that the atmosphere must be close to a neutrally stable. Increasing winds with depth are also compatible with the numerical experiments.

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