# MOIST CONVECTIVE STORMS IN THE ATMOSPHERES OF JUPITER AND SATURN

*Atmospheric storms in Jupiter and Saturn*


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**Abstract** Moist convective storms might be a key constituent of the global energy budget in the atmospheres of the Giant Planets. The storms extract their energy from the release of latent heat produced in the condensation of water which is only abundant hundreds of kilometers below the observable cloud deck. Because these atmospheres are made of hydrogen and helium, dry air is lighter than moist parcels, providing a strong stabilization against vertical motions in the atmosphere. However, very large-scale convective storms have been observed in the atmospheres of the giant planets. Among them, Jupiter is the most convectively active, showing frequent storms with sizes on the order of 3000 km that occasionally trigger planetary scale disturbances. Observations from Voyager, Galileo and Cassini spacecrafts confirm the overall convective activity of Jupiter through observations of lightning flashes below the upper ammonia cloud deck. The energy associated to these storms is large enough to constitute a relevant fraction of the total internal heat source of the planet. Although Saturn presents a more quiescent atmosphere where storms are rarely observed, about once every 30 years, a giant storm has been observed to develop with sizes of 20000 km also triggering a planetary scale disturbance. We will review the current observational background of these giant storms in both Jupiter and Saturn presenting also numerical results obtained by different teams in simulating this vigorous meteorology. In both planets water storms may develop upward velocities of 50-150 m/s. The interaction of the storms with the powerful winds are not clear. In Saturn the giant storm of 1990 could have played a key role in originating the recently discovered change of 200 m/s in the broad and intense equatorial jet.



**Keywords:** Jupiter, Saturn, Atmospheres, Dynamics; Atmosphere; Meteorology

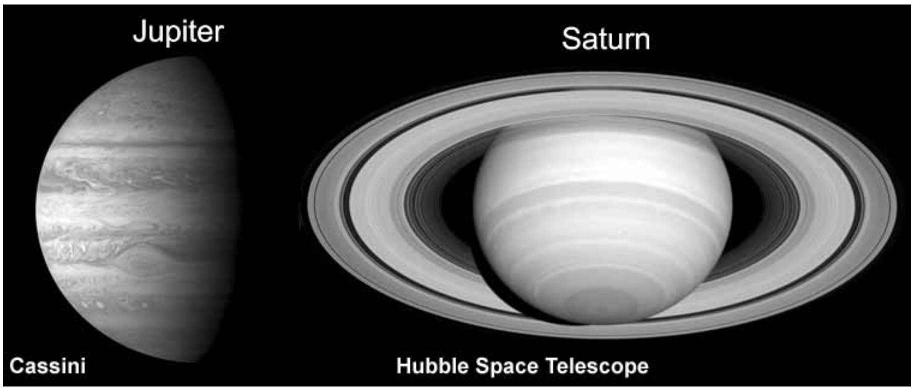


*Figure 1.* Visual aspect of the upper clouds of Jupiter and Saturn.

## Introduction

The giant planets are fluid objects. They have no solid surfaces and their atmospheres gradually become denser in the interior until the distinction between gas and liquid becomes meaningless. In this chapter we will discuss the formation of convective storms in the upper atmospheres of Jupiter and Saturn. Water is in both cases the main candidate for powering the convective structures. Uranus and Neptune have also cloud structures of probable moist convective origin made of methane (Stoker and Toon, 1989).

In the tropospheres of Jupiter and Saturn the range of temperatures and chemical composition allow the formation of three distinct cloud layers. The main atmospheric features are observed in the upper cloud, close to the 1 bar level, giving the planets their caracteristic visual aspect (Figure 1). The vertical cloud structure can be studied in terms of simple thermochemical models based on the Clausyus-Clapeyron equation (Sánchez-Lavega et al. 2004a). There are three main clouds expected to form. The upper cloud is made of ammonia condensed particles, below there are an intermediate ammonia hydrosulfide cloud and a lower and denser water cloud deck (Weidenschilling and Lewis, 1973). The particle density and the vertical location of the cloud depend on the condensable abundance and may vary from one location to other. The overall cloud structure is summarized on Figure 2. The water cloud is specially interesting because water has a large latent heat. In both planets the atmospheres are heated not only by the solar insolation but also by the release of internal heat remanent from their planetary formation. For Jupiter and Saturn this heat is equivalent to 1.7 and 1.8 the heat absorbed from the Sun.

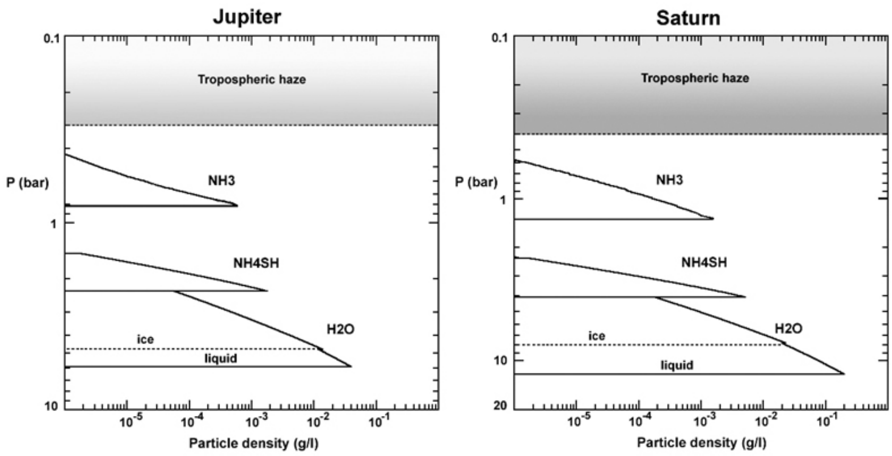


*Figure 2.* Average vertical cloud structure in Jupiter and Saturn. The upper hazes are derived from the observations and are probably of photochemical origin. The lower curves correspond to thermochemical calculations representative of the average cloud structure. Differences in cloud levels in both planets are mainly due to the colder temperatures of Saturn with respect to Jupiter with temperatures at the tropopause near the 100 mb level of 113 and 84 K respectively and, 170 and 135 K at P=1 bar near the top of the nearly adiabatic deeper atmosphere.

# 1. Observations of convective storms in Jupiter and Saturn

## Jupiter

Ground-based observations have shown the regular development of mid-scale storms (1.000-5.000 km) at specific latitudes with the ocassional development of planetary scales disturbances triggered by the appearance of convective clouds (Sánchez-Lavega et al. 1996). The Voyagers and the Galileo and Cassini spacecrafts have obtained detailed observations of these convective features together with the detection of lightning strikes in long-term exposures of the night side of the planet (Little et al. 1999). The lightning have been show to reside on deep levels of $\sim$ 5 bars close to the expected water cloud deck. In some cases day side images of the lightning regions show convective clouds in the upper levels implying an activity which extends 150 km (Gierasch et al. 2000). The frecuency of lightning strikes, the planetary area covered by the associated storms and the large energy released in the condensation of water and vertical ascension have led to these authors to suggest that a significant proportion of Jupiter's inner heat could be transported to the upper troposphere by means of moist convective storms (Ingersoll et al. 2000). Therefore, the storms migh be an important constituent of the overall atmospheric dynamics of these planets.

### Saturn

Mid-scale bright clouds of probable convective origin arise occasionally at the Equator and at mid-latitudes and were best viewed during the Voyagers flybys in 1980-1981. Very rarely, about once every 30 years, a giant storm arises on the planet (Sánchez-Lavega, 1982; Sánchez-Lavega and Battaner, 1987). The last one, known as the 1990 Great White Spot (GWS) developed a 20,000 km size massive cloud system over a period of a month and evolved into a planetary scale disturbance (Sánchez-Lavega et al. 1991; Barnet et al. 1992). One of the mysteries of these storms is at which cloud layer they originate and how the seasonal cycle of 29.5 years of Saturn can influence their development. The other main mystery is if the large storms arising in Saturn's equator in the early 90s could have changed the local winds as to explain the wind decrease of 200 m/s in the equatorial current found between the Voyagers data obtained in 1981 (Sánchez-Lavega et al. 2000) and the 1994-2004 Hubble Space Telescope observations of Saturn (Sánchez-Lavega et al. 2003, 2004b).

## 2. Modelling moist convective storms

For any hydrogen based atmosphere, condensables are almost 7-8 times heavier than the hydrogen-helium atmospheric air with mean molecular weight $\sim 2.2$ g mol$^{-1}$) and the ascension of humid air is obstructed by the difference on molecular weight between dry and humid air. This factor alone is responsible for the main difficulties in originating moist convection in the giant planets. The development of moist convection becomes a competition between the heating produced by the condensation of volatiles in their vertical ascension and the heavier humid air.

Stoker (1986) developed the first quantitative model of moist convection for the Jupiter atmosphere. Her model was a 1D thermodynamical model of a raising parcel subject to entrainment with outside colder air. This basic model allowed to place upper limits for the vertical velocities and cloud tops to be expected in Jupiter storms. This model produced intense storms under favorable conditions (high relative humidity of water) able to fit the cloud tops observed by the Voyagers in the equatorial plumes. The model was also applied by Sánchez-Lavega and Battaner (1987) to study the onset of the 1990 GWS finding water storms were able to fit the cloud tops in the GWS only under favorable conditions.

Yair et al. (1992, 1995) performed 2D dynamical models of convective storms in Jupiter. Their results suggested very weak convection unable to be the cause of most of the meteorological phenomenology assumed to be of convective origin in Jupiter. This discrepancy can be explained by realising their initial conditions were typical of Earth cumulus development and may be also of average conditions in Jupiter which were shown to be very disfavorable for the development of storms in Jupiter, but probably not of the few spots where convective cumulus grow.

Hueso and Sánchez-Lavega (2000) developed a 3D model of moist convection for the giant planets by fully integrating the Navier-Stokes equations under the anelastic approximation. The microphysics were approached in the model by assuming condensation acts instantaneusly removing a fixed proportion of the condensed particles. The model has been applied to the water and ammonia clouds of Jupiter and Saturn. In the jovian atmosphere their results suggest that under favorable atmospheric conditions water based moist convective storms develop and can become very energetic, being able to ascend 150 km from the 5 bar level to the observed cloud tops of 200-400 mbar at storm locations. Expected vertical velocities are on the order of 50-150 m/s. Ammonia on the other hand does not show the same activity since the clouds form in a more stable part of the atmosphere and its lower abundance and low latent heat do not allow for strong convective motions. The water based updrafts can ascend very fast because, contrary to the Earth case, they have a lot of vertical space to accelerate progresively. These simulations encompased an area an order of magnitude smaller than real observed storms. Hueso et al. (2002) presented a 2D model of the cloud tops in which they integrated the mass continuity equation with divergent sources and Coriolis forces to try to reproduce observations of large scale storms observed by the Voyagers. The results of these two works are partially summarized on Figure 3.

Simulations of single cell storms in the atmosphere of Saturn were presented by these authors more recently (Hueso and Sánchez-Lavega, 2004). In Saturn's colder atmosphere ammonia clouds are at lower levels where the static stability of the atmosphere is not so high and ammonia storms are possible. Still much more intense convection can be attained if the updrafts originate at the water cloud deck buried down at 9 bars, 300 km below the observed cloud tops. As in Jupiter's case, the large vertical space allowed to the convective updrafts translates in powerful motions with updrafts on ther order of 150 m/s. These results are summarize on Figure 4.

Because convection depends very strongly on the initial conditions both studies performed several simulations under different atmospheric conditions varying basic factors as the environment relative humidities, total weight of the condensates and total water and ammonia abundances. A brief summary of the sensitivity analysis of storms in both planets is presented on Table 1.

The main difficulty in originating water storms in both planets is the environment relative humidity which must be higher than 75% and 80% in Jupiter and Saturn respectively for water convection to originate. Under a lower hu-

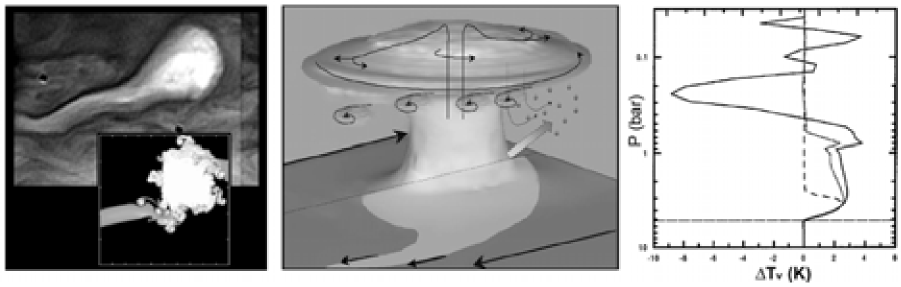


*Figure 3.* Jupiter storms, observations and models. The left image shows a mature stage of a South Equatorial Belt perturbation. The storm core is 5000 km wide. An inset shows results of simulating this particular storm by using a 2D model composed of 120 storm cells. The characteristics of the 2D storm cells are taken from more detailed 3D calculations. The center image shows the 3D structure of water storms on Jupiter. The right pannel is reserved to display the virtual temperature differences between the storm and its environment, being this thermal difference the atmospheric engine powering storm convection.

mid environment, convection can not initiate because, in spite of the release of latent heat, saturated air is heavier than the environment colder air. Also, precipitation must act efficiently in both planets or the saturated updraft would get negative buoyancy caused by the weight of the condensed particles. A precipation efficiency able to lose $\sim 25\%$ of the total condensates is required in both planets to develop moist convection. The total water abundance is also a key factor in determining convection strength but unfortunately this factor is not well constrained by the observations. Cloud tops at storm locations in Jupiter have been found to lie higher than 400 mbar in Jupiter and close to 200 mbar in Saturn's Great White Spots. This constrains weakly the deep water abundances. Jupiter storms can be explained with water abundance as low as 0.2 solar, while a higher deep water abundance would yield stronger convection more difficult to initiate. In Saturn the GWS cloud tops could be explained by water storms but also by ammonia clouds if ammonia were overabundant with 10 times solar abundance.

## 3. Storm locations and wind relation

Storms in Jupiter have only been found in regions of cyclonic shear close to a minimum in the wind speed. They are specially abundant in the South Equatorial Belt (SEB) at 16° S at the turbulent wake of the Great Red Spot and at some less frequent at the North Equatorial Belt (NEB) at 16° N. In Saturn most of the smaller scale storms in the last years have been observed at latitudes of $42^\circ$ North and South with large scale storms arising in the equator in 1990 and 1994. Since storms are so energetic they may interact with the zonal wind

| $Abundance$ | $h$ **(%)** | $f_c$ | $W_{max}$ (m/s) | $P_{top}$ (mb) | $Time$(hr) |
|---|---|---|---|---|---|
| Jupiter water storms | | | | | |
| 2.0 | 99 | 0 | 210 | 100 | 1.1 |
| 1.0 | 99 | 0 | 145 | 140 | 1.4 |
| 1.0 | 99 | 0.25 | 115 | 200 | 1.5 |
| 1.0 | 99 | 0.50 | 75 | 250 | 2.0 |
| 1.0 | 75 | 0 | 70 | 330 | (*) |
| 1.0 | 50 | 0 | 30 | 500 | (*) |
| 0.2 | 99 | 0 | 50 | 250 | 2.2 |
| Saturn water storms | | | | | |
| 3.0 | 99 | 0 | 260 | 120 | 3.1 |
| 1.0 | 99 | 0 | 150 | 210 | 4.2 |
| 1.0 | 90 | 0 | 140 | 240 | 3.1 |
| 1.0 | 80 | 0 | 90 | 400 | (*) |
| 1.0 | 99 | 0.2 | 100 | 310 | 3.5 |
| 1.0 | 99 | 0.5 | 60 | 530 | 5.4 |
| Saturn ammonia storms | | | | | |
| 10.0 | 99 | 0 | 90 | 240 | 1.1 |
| 3.0 | 99 | 0 | 40 | 390 | 1.1 |
| 1.0 | 99 | 0 | 15 | 500 | 1.5 |

*Table 1.* Main characteristics of simulated storm convective plumes under different atmospheric properties. Abundances are measured relative to solar composition, $h$ is the atmospheric relative humidity, $f_c$ is the proportion of condensate particles carried upward by the storm with (1-$f_c$) the proportion of condensates that instantaneously rains out of the parcel, $W_{max}$ is the maximum ascending velocity attained by the storm, $P_{top}$ is the higher level where cloud material arrives and $Time$ is the average time to develop a mature stage convective cell. Note: (*) denote cases in which convection could be initiated only under large initial thermal perturbations and could not sustain long-term convection. The appearance of these cases close to stable convective storms means that convection, though difficult to initiate, must be very energetic once the required conditions are met.

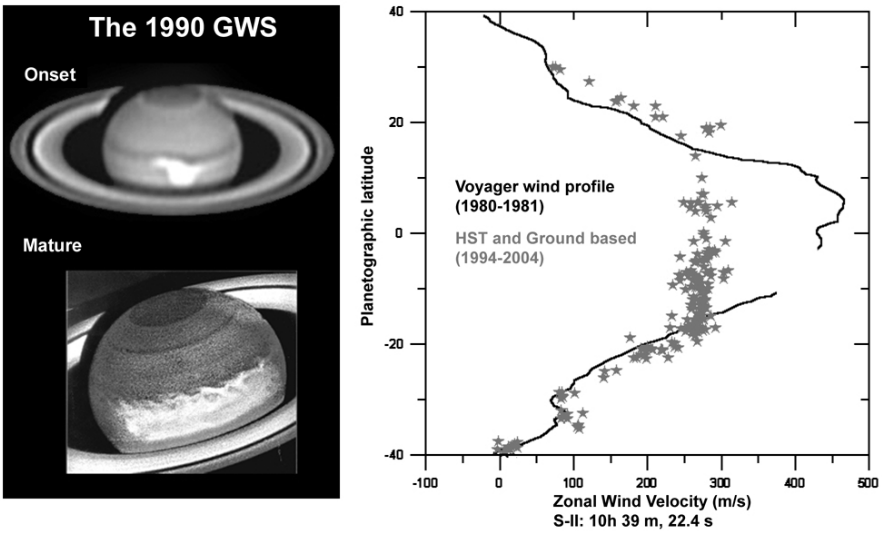


*Figure 4.* On the left: Images from the 1990 Great White Spot onset and mature stages. Images are from the Pic du Midi 1m telescope and the Hubble Space Telescope. On the right: Saturn's equatorial wind profile at two different periods from data obtained with the Voyagers in 1980-1981 and ground-based and Hubble Space Telescope observations on the 1994-2004 period.

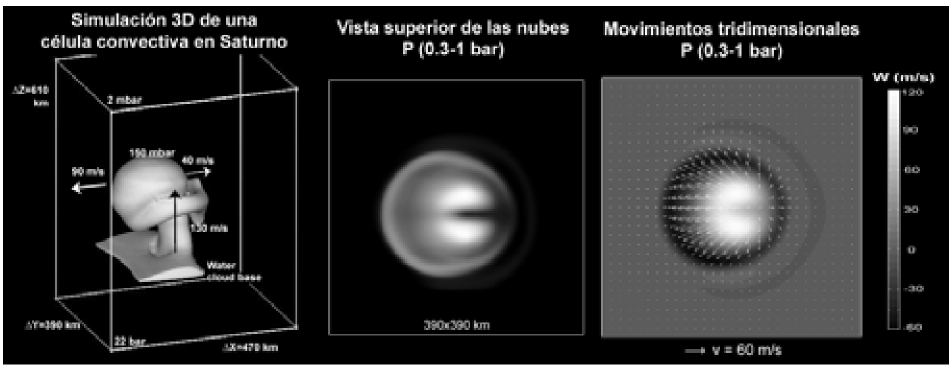


*Figure 5.* Detailed schema of an equatorial Saturn storm simulation. The left figure shows the 3D structure of a water-ammonia cloud storm cell. The center image is an XY map of cloud density in the 0.3-1 bar levels and shows how a 400 km storm would be seen in high resolution observations. The right image shows the vertical and horizontal motions expected if the upper flow is not turbulent. A net conversion of upward momentum to westward momentum is clearly seen in the simulation, a consequence of the three-dimensional Coriolis forces.

system powering or weakening it. Saturn's equator has indeed experienced a dramatic wind change since the Voyager observations (Sánchez-Lavega et al. 2003, 2004b). The change seems to have originated after the 1990 storm (Figure 4).

Our simulations show that equatorial updrafts ascending from the water cloud base at 9 bars take enough time to be deflected to the west by means of Coriolis forces transforming up to a 10% of their kinetic energy to westward momentum (see Figure 5). An order of magnitude evaluation of this effect, compatible with the size and intensity of the 1990 GWS, seems to indicate that the storm may have directly decreased the equatorial winds by 20-30 m/s with a larger contribution of kinetic energy to turbulent motions. In order to produce a larger change of the order of the observed decrease ($\sim 200$ m/s) the GWS convective core should have stayed active for a whole year and most of the equatorial atmospheric material initially at 9 bars should have had to be transported to the upper troposphere. On the other hand, if the 1990 GWS was indeed a giant storm system at the upper ammonia cloud there would not have being any significant momentum transformation because of the lower vertical scales involved. The 1990 storm may however have altered deeply other atmospheric properties that eventually contributed to change the equatorial winds and overall dynamics. A work devoted to the exploration of the mechanisms responsible for the wind change will be presented elsewhere.

## 4. Conclusions

We have presented the basic phenomenology of convective storms forming in the atmospheres of Jupiter and Saturn. Detailed three-dimensional models have been used to explore the dynamics of such storms finding that only water can be responsible of Jupiter's convective storms while Saturn may have both water and ammonia storms. Saturn's ammonia storms may exhibit characteristics typical of water storms if ammonia is abundant enough in the atmosphere (10 times solar). In both, Jupiter and Saturn, Coriolis forces may transform upward momentum in the storms to zonal motions with an efficiency of the released energy of $10\%$ in the equator. The relationship between the overall zonal winds and the moist convective activity remains obscure due to the complexity of the problem and the unknowns of some basic atmospheric properties like water abundance and overall planetary convective activity.

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