# CONJECTURE ABOUT A HURRICANE SYSTEM IN THE JOVIAN ATMOSPHERE

H. G. MAYR, K. MAEDA, and I. HARRIS
*Laboratory for Planetary Atmospheres, NASA/Goddard Space Flight Centre, Greenbelt, Maryland, U.S.A.*

(Received 10 August 1984)

**Abstract.** Kuiper (1972) had suggested that the Great Red Spot (GRS) of Jupiter is a giant hurricane. We present further arguments in support of this idea and propose that it may also apply to the smaller vortices such as the white and brown ovals (barges). Our estimates indicate that the spin-down time-constants for these Jovian vortices are significantly shorter than the observed lifetimes. Thus, the motions must be sustained through the continued release of internal energy. In analogy with the CISK mechanism for the terrestrial hurricane, transport of water vapor, which is observed on Jupiter, may provide the latent energy to fuel the motions. The energy the planet emits must be transported upwards; therefore its troposphere should be convectively unstable. In such an atmosphere, the proposed solar driven meridional circulation is multicellular, of the Ferrel-Thomson type. If the energy transport from the planetary interior is accelerated by the upward motions in the circulation, eastward zonal jets develop such as observed in the equatorial region. But if the upward flow of energy is impeded by the prevailing downward motions in the meridional circulation (which occur, for example, near 20° latitude), we propose that the convective instability is amplified. The conditions then are more favorable for the development of hurricanes which may appear in the form of the GRS and the white and brown ovals. The GRS with its large size and long life time (indicating that it is very deep) is unique, and we suggest that it may have been induced by meteor impact.

## 1. Introduction

Recently, a number of models have been proposed to describe the Great Red Spot (GRS) in the Jovian atmosphere (see references in Gehrels, 1983). In this paper, we shall expand on the idea of Kuiper (1972) who emphasized the similarity between the GRS and the terrestrial tropical cyclone or hurricane.

The accepted theory for the development of the terrestrial hurricane is due to Charney and Eliassen (1964) and Ooyama (1969). The mechanism is characterized by the Conditional Instability of the Second Kind (CISK) which requires that the lower layer in the Earth's tropical atmosphere is conditionally unstable, i.e., unsaturated and wet-super-adiabatic. When a vorticity develops, convergence of horizontal flow brings moisture into the centre and forces ascension with release of latent heat; this process, in turn, refuels the motions.

To first order, the alternating zonal wind bands and the equatorial jet on Jupiter can be understood in the framework of a quasi-zonally symmetric circulation with anisotropic eddy diffusion (Mayr and Harris, 1983; Mayr *et al.*, 1984). In this model the circulation is induced by solar differential heating, and the troposphere below the cloud top is perceived to be weakly convectively unstable. A multicellular meridional circulation (of the Ferral-Thomson type) then develops which can produce a banded zonal wind field.

*Earth, Moon, and Planets* 32 (1985) 183–192. 0167–9295/85/0322–0183$01.50.

Being true then that the Jovian lower troposphere is convectively unstable, we shall present here further arguments in support of Kuiper's idea about the similarity between the GRS and the terrestrial hurricane and suggest that it may also apply to the observed white and brown ovals (barges). Moreover, we shall propose that the formation and latitudinal stratification of these vortices are controlled by the multicellular meridional circulation.

## 2. Comparative Spin Down Times

The spin down time of vortex systems can be estimated based on the conservation of mass flow inside the vortex and divergent flow from the top of the vortex (Holton, 1979). It is given (in sec) by

$$\tau = h\left(\frac{2}{Kf}\right)^{1/2}, \tag{1}$$

where $h$ is the vertical depth of the vortex (cm), $K$ is the vertical eddy diffusion coefficient (cm$^2$ sec$^{-1}$), and $f = 2\Omega \sin\theta$ is the Coriolis parameter for the planetary angular velocity $\Omega$ (sec$^{-1}$) at the latitude $\theta$.

In Table I the spin down times are estimated for the terrestrial tornado and hurricane and for Jupiter's GRS and its white and brown ovals. The characteristic depth of the tornado is known to be on the order of 1 km and that of the hurricane is about 10 km. For Earth it is reasonable to adopt a vertical eddy diffusion coefficient of about $10^5$ cm$^2$ sec$^{-1}$.

On Jupiter there are no direct observations revealing the depths of the vortices. Considering that the observed horizontal dimension $d$ of the vortex can reach, as an upper limit, the Rossby diameter of deformation (Holton, 1975), the depth of a vortex can be estimated

TABLE I

For the Jovian vortices, the depths parameters are estimated from the Rossby radius of deformation which yields the ratio $R$. Adopting eddy diffusion coefficients which are consistent with energetic considerations, the time constants for spin-down can then be evaluated.

| | Tornado | Hurricane | Red Spot | White<br>Brown Ovals |
|---|---|---|---|---|
| Diameter, $d$ (km) | 10 | 800 | 20000 | 5000 |
| Depth, $h$ (km) | 1 | 10 | 400 | 200 |
| Radio, $R = d/h$ | 10 | 80 | | |
| Stability, $S$ (K km$^{-1}$) | | | $-0.1$ | $-0.1$ |
| $R \sim \frac{2}{f}\ \frac{Sg}{T}\Big)^{1/2}$ | | | 50 | 25 |
| Latitude | 40 | 15 | 20 | 40 |
| $f$ | $9.3 \times 10^{-5}$ | $3.8 \times 10^{-5}$ | $1.2 \times 10^{-4}$ | $2.2 \times 10^{-4}$ |
| $K$ (cm$^2$ sec$^{-1}$) | $10^5$ | $10^5$ | $10^4$ | $10^5$ |
| $\tau = h\left(\frac{2}{Kf}\right)^{1/2}$ | $4.6 \times 10^4$ sec<br>13 hr | $7.2 \times 10^5$ sec<br>8 d | $5.2 \times 10^7$ sec<br>1.6 y | $6 \times 10^6$ sec<br>2.3 mo |
| Observed | $\geqslant 3$ hr | 30 d | $> 300$ y | $\geqslant 4$ mo |

$$h \leqslant \frac{df}{2\left(\frac{Sg}{T}\right)^{1/2}}, \tag{2}$$

where $T$ is the temperature, $g$ is the gravitational acceleration and $S = \partial T/\partial z + \Gamma$ the stability, ($z$ is the altitude and $\Gamma$ the adiabatic lapse rate). Based on the observed latitudinal structure of the zonal velocity field, the average stability can be estimated to be on the order of $S_0 \sim -0.2\,\mathrm{K\,km^{-1}}$ near the one bar pressure level (Mayr *et al.*, 1984). Given this stability, the vertical eddy diffusion coefficient is then determined from the observed radiative emission of the planet and yields a value of about $K \sim 3 \times 10^5$. For the vortices in Jupiter's atmosphere which develop below the cloud cover, the eddy diffusion coefficients should be smaller, and we adopt values of $10^4$ for the deeper GRS and $10^5$ for the shallower white and brown ovals. Lower down, with the larger density, a smaller temperature gradient suffices to transport the energy. Thus we choose also a smaller magnitude for the stability, $S_0 = -0.1\,\mathrm{K\,km^{-1}}$.

Our estimates for the spin down time of the tornado gives a value of 13 hr which is sufficiently long to account for the observed life time of the disturbance. However, the observed life times of the terrestrial hurricane and Jovian vortices are much longer than the estimated time constants for spin down. This suggests, therefore, that these vortices are sustained for some time through the continued release of energy.

## 3. Internal Heat Source

As described by Fendell (1974), once a hurricane develops into a significant size near the equator (5°–20° latitude), warm, moist air converges toward the center of the vortex. By conservation of mass flow in the frictional boundary layer above the tropical ocean surface, the moist warm air ascends inside the vortex where water vapor releases the latent heat, forming the hot tower (Malkus and Riehl, 1960). Due to this heat release, a positive feedback develops, and the ascending motions inside the hurricane are further accelerated. Air flowing outward from the top subsides in the surrounding area and carries warm water vapor into the bottom of the hurricane, refuelling the heat-engine. This type of interaction, involving a large scale feedback mechanism, has been characterized by the earlier mentioned Conditional Stability of the Second Kind (CISK) after Charney and Eliassen (1964) and Ooyama (1969). The necessary condition for this process is that, inside the large vortex and at the bottom of the vortex (eye) and eyewall, the atmosphere is conditionally unstable, i.e., the temperature lapse rate is between the dry adiabatic ($\sim -10\,\mathrm{K\,km^{-1}}$) and the wet adiabatic ($\sim -6\,\mathrm{K\,km^{-1}}$).

## 4. Origin of the Jovian Vortices

In Figure 1 we show oblique views of large scale vortices in the atmospheres of Jupiter and Earth. On the top (a) is a picture of the Great Red Spot, taken from Voyager I in March 1979 (Smith *et al.*, 1979). On the bottom (b) is a picture of the hurricane Irah

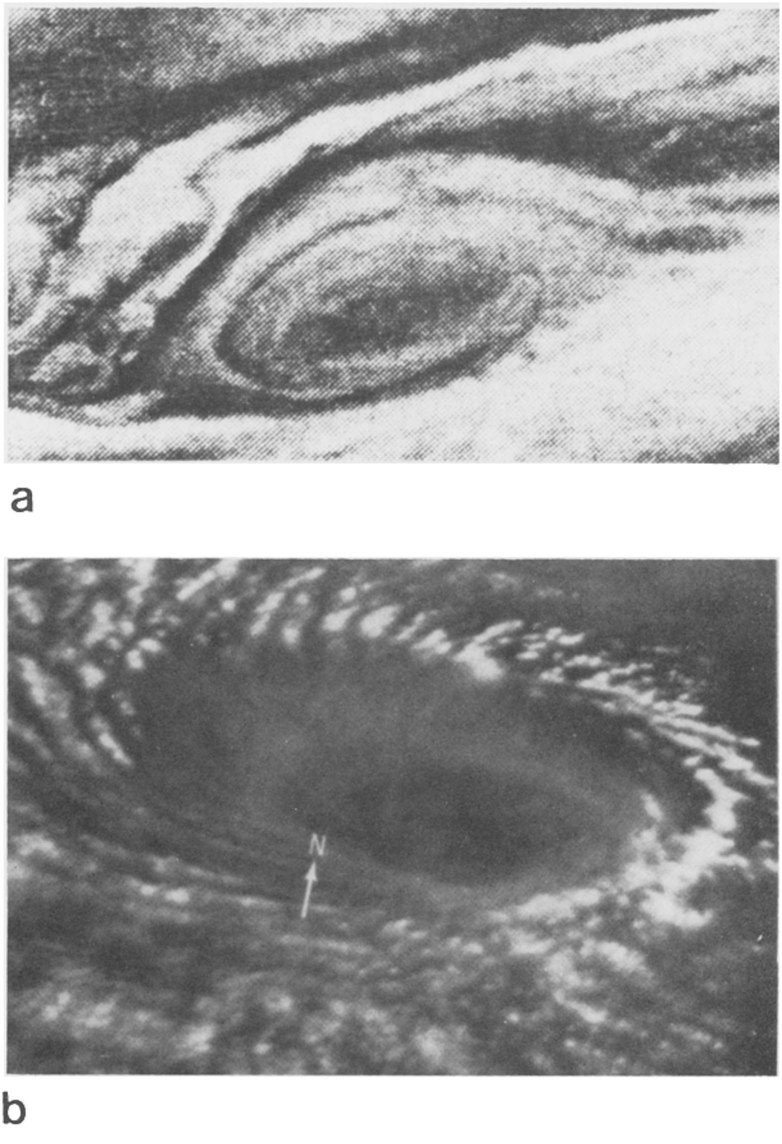

Fig. 1. Oblique views of Jupiter's Great Red Spot taken from Voyager I in March 1979 (Smith *et al.*, 1979) on the top (a) and the hurricane Irah taken from sky lab on September 24, 1973 (NASA SP-380, 1977) on the bottom (b).

taken from sky lab on September 24, 1973 (NASA SP-380, 1977). The sense of the rotation at the top of these vortices is both anticyclonic, i.e., counter-clockwise for the GRS which is located in Jupiter's southern hemisphere (~ 20° S) and clockwise for hurricane Irah which appeared in the northern hemisphere (18° N, 107.8° W). The longitudinal diameters for the GRS and the hurricane are approximately 23 000 and 800 km, respectively.

The similarities between these large vortex systems also extend to their thermal structures and dynamical processes which sustain the motions. In Figure 2a, we show the vertical temperature distributions inside and outside of the GRS which were derived from the infrared measurements on Voyager I (Hanel *et al.*, 1979a). The dashed portions were extrapolated and indicate that, below the 1 bar pressure level, the temperature and negative temperature lapse rate (smaller stability) are probably larger inside the disturbance.

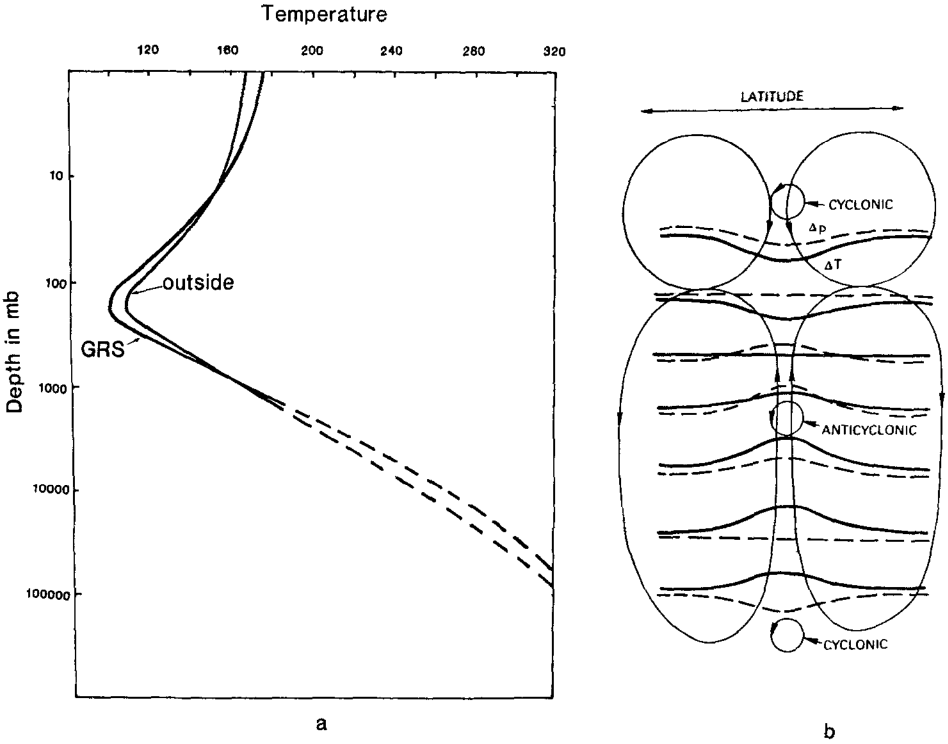

Fig. 2. (a) Vertical temperature distributions inside and outside of the GRS derived from the infrared measurements on Voyager I (Hanel *et al.*, 1979a); the dashed portions are extrapolated. (b) Proposed schematic cross sections of temperature (full lines), pressure (dashed lines), and flow fields in a Jovian hurricane; note that in the upper troposphere, the horizontal temperature perturbations associated with the disturbance may be small, while significant pressure gradients can persist which drive the vortex.

Cross sections of temperature, pressure and velocity fields are illustrated in Figure 2b. Conservation of mass requires that below the heat source the flow is toward the center. This in turn requires a pressure minimum which leads to cylonic motions. At higher altitudes, we postulate that heat is released and the pressure increases in the center;

consequently, the motions become anticyclonic. Still higher up, in the upper troposphere and lower stratosphere which are convectively stable due to solar heating, the upward motions in the center of the vortex cool the gas, and a temperature minimum develops. Due to vertical expansion from below, however, the pressure continues to be enhanced and the circulation continues to be anticyclonic. Eventually, in the upper stratosphere, adiabatic cooling may prevail, so that the pressure decreases and the motions again become cyclonic, forming a secondary circulation with subsidance in the center.

This scenario seems to be borne out by the infrared measurements on Voyager I (Hanel *et al.*, 1979a). Near the 1 bar pressure level there is virtually no temperature signature from the GRS, suggesting that the observations come from a transition region which is influenced by energy supply in the troposphere below (unstable) and adiabatic cooling by the upward motions in the upper troposphere (stable). Higher up near the tropopause, the infrared measurements show that the GRS is significantly colder than the surrounding medium, indicating that adiabatic cooling prevails.

We have seen from Table I that the time constant for the spin-down of the GRS is much too short to explain the maintenance of this vortex for hundreds of years. As in the case of the terrestrial hurricane, some internal heat source must sustain the motions, and we suggest (following Kuiper, 1972), that, in analogy with the CISK mechanism, the GRS as well as the smaller vortices in the Jovian atmosphere are driven by the release of latent energy from water vapor.

The IRIS experiment (Hanel *et al.*, 1979a, b) indicates the existence of water in the lower Jovian atmosphere. Thus, the release of latent energy from the condensation of water vapor is plausible. Condensation of water vapor takes place at around 270 K which is at the pressure level of about 10 bar. Internal heating should become important at altitudes on the order of 100 km below the temperature cross over shown in Figure 2a. However, the ascending air inside the GRS must originate further below which is consistent with our estimate for the depth of this vortex (Table I).

## 5. Latitudinal Stratification

We consider the energy equation in simplied form

$$\alpha T + W c_p \left( \frac{\partial T}{\partial z} + \Gamma \right) = Q, \tag{3}$$

where $\alpha$ is an effective cooling coefficient which includes vertical and horizontal eddy heat conduction, $c_p$ is the specific heat at constant pressure, and $Q$ is the heat input. Applying perturbation theory

$$\begin{aligned} T &= T_0 + \Delta T_0 + \Delta T \\ W &= \Delta W_0 + \Delta W \\ Q &= Q_0 + \Delta Q_0 + \Delta Q, \end{aligned} \tag{4}$$

yields

$$\alpha \Delta T + \Delta W c_p \left( \frac{\partial T_0}{\partial z} + \Gamma \right) + \Delta W c_p \, \frac{\partial \Delta T_0}{\partial z} + \Delta W_0 c_p \frac{\partial}{\partial z} \Delta T = \Delta Q, \qquad (5)$$

where

| | |
|---|---|
| $T_0, \Delta T_0$ | globally and zonally averaged temperatures; |
| $\Delta T$ | temperature perturbation; |
| $\Delta W_0$ | zonally averaged vertical velocity; |
| $\Delta W$ | velocity perturbation, $\Delta W \propto \Delta T$, |
| $Q_0', \Delta Q_0$ | globally averaged and zonally averaged heat sources, |
| $\Delta Q$ | heat input perturbation which includes the release of latent energy. |

Parameterizing $(\partial/\partial z)\Delta T \sim \Delta T/h$ and assuming $h > 0$ in the lower troposphere, we obtain

$$\Delta T = \frac{\Delta Q - \Delta W c_p \left( \frac{\partial T_0}{\partial z} + \Gamma + \frac{\partial \Delta T_0}{\partial z} \right)}{\alpha + \Delta W_0 \frac{c_p}{h}}, \qquad (6)$$

representing the condition inside the disturbance. For a source $\Delta Q > 0$ the disturbance in the vertical velocity is positive $\Delta W > 0$.

In the Jovian atmosphere, the average stability, $S_0$, is relatively small; thus, relatively small changes in the zonally averaged latitudinal temperature distribution, $\Delta T_0(r, \theta)$, can significantly affect the latitudinal variations in the tropospheric stability ($S = S_0 + \Delta S_0$). Indeed, infrared measurements from the 0.8 bar pressure level on Jupiter (Hanel *et al.*, 1979a, b) show considerable structure in the latitudinal temperature distribution. Plateaus are seen, with the temperature decreasing precipitiously toward higher latitudes near 20° and 60°. At the 0.15 bar level there is some indication, that, averaged over longitude, the temperature has a minimum near 20° latitude. This temperature structure may be understood as the consequence of solar differential heating and the resultant energy redistribution by the multicellular Ferrel–Thomson circulation (Mayr and Harris, 1983; Mayr *et al.*, 1984).

In the troposphere (with $S_0 < 0$), the *prevailing* upward motions ($\Delta W_0 > 0$) around the equator, for example, supply from below energy to the ambient medium and bring about greater stability ($\Delta S_0 > 0$). Energy, which otherwise may contribute to fuel a disturbance is advected to higher altitudes (see the second term in the denominator of (6)), the consequence being that *localized disturbances* are suppressed. It is less likely therefore that hurricanes develop in the updraft regions of the prevailing meridional circulation.

On the other hand, near 20° for example, where downward motions occur in the prevailing meridional circulation, energy is removed from the surrounding ambient medium and transported to lower altitudes. As the temperature decreases, the atmosphere becomes less stable ($\Delta S_0 < 0$), which is the prerequisite for replenishing the latent energy (Figure 3). The prevailing downward winds from above retain the energy that otherwise would be advected to higher altitudes (second term in the denominator of (6)),

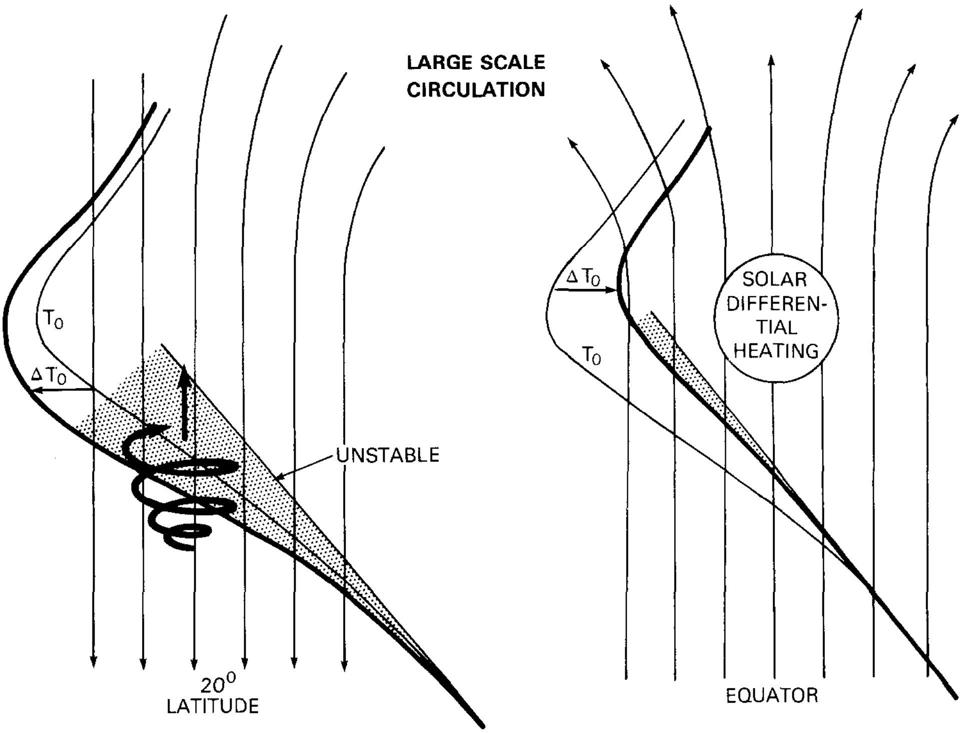

Fig. 3. Schematic illustration of the changes in the tropospheric stability induced by the multicellular meridional circulation (thin vertical lines). The right hand side represents the updraft region near the equator, for example; and similar conditions should occur in certain bands at higher latitudes. Because of the enhanced stability, hurricanes are not likely to develop in these regions. The left hand side illustrates the conditions in regions where subsidence occurs, near 20° latitude for example. Here, the downward motions decrease the stability and local disturbances in the form of hurricanes may develop.

the consequence being that localized disturbances will be accelerated, and hurricanes can develop. The great red spot and brown ovals are indeed observed along latitude bands around 20° (Smith *et al.*, 1979). It is assumed here that the prevailing wind system (with eastward motions equatorward and westward motions poleward, see Figure 4) is responsible for the observed cyclonic motions surrounding the brown ovals (Morrison and Samz, 1980), and that the motions deep inside the brown oval are anticyclonic. We suggest that the multicellular meridional circulation also determines the latitudinal stratifications observed in the white ovals.

Latitudinal cross sections of the prevailing temperature and zonal wind fields are illustrated in Figure 4. The temperature (pressure) decrease toward higher latitudes can produce (assuming geostrophy) the eastward equatorial jet near 10°. Around 25°, the temperature decreases toward the equator and can produce the westward motion. In between, presumably, a temperature minimum lies (or a minimum in the vertical

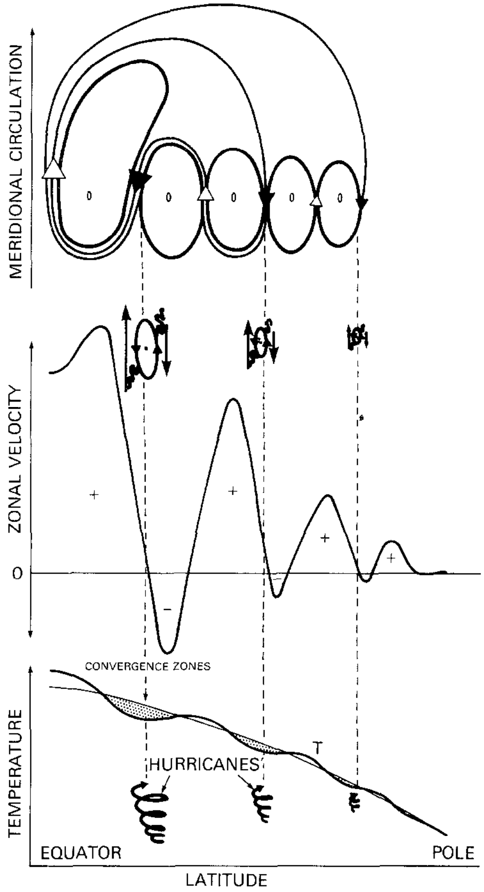

Fig. 4. Illustration of the relationship between the multicellular meridional circulation (top), zonal circulation (middle) and relative temperature variations (bottom) in the lower troposphere. Rising motions (light arrows) increase the temperature at higher altitudes, and the stability is enhanced (e.g. in the equatorial region). Downward motions (dark arrows) decrease the temperature at higher altitudes, and the stability is reduced (e.g. near 20° latitude). In between, the temperature (pressure) falls off toward higher latitudes, driving eastward jets. Poleward of the temperature minimum, a westward jet can develop. The hurricane would tend to form in the shear region of the zonal velocity field in between. Due to the multicellular structure of the meridional circulation, this alternating pattern continues at higher latitudes, thus alternating strata develop in which hurricanes are 'permitted' or 'forbidden'. Since the meridional circulation weakens toward higher latitudes, the differentiation between the forbidden and permitted regimes also weakens, and the hurricanes become less intense. The anticyclonic motions inside the hurricane are embedded in a prevailing flow regime which is cyclonic. However, this relationship only applies to the altitude regime in which the hurricane is generated.

temperature gradient), where the atmosphere is less stable, and a hurricane can develop such as the great red spot and the brown ovals.

In this model, the anticyclonic motions inside a Jovian hurricane are perceived to be embedded in a prevailing zonal velocity field which is cyclonic (swirls and wake effects may develop as illustrated in Figure 4). Our discussion about the hurricane's position relative to the zonal circulation, however, applies to the altitude regime in which the vortex is created. One should therefore not expect that Figure 4 correctly represents the hurricanes' position relative to the observed zonal velocity field which portrays only the conditions at higher altitudes near the top of the visible clouds.

The locations of the GRS were 70° W and 100° W in system III during the Voyager I (1 February 1979) and Voyager II (23 May 1979) encounters, respectively. This gives a very large $-0.27^\circ$ day$^{-1}$ retrograde drift of the GRS within a short period of time (Figure 1 in Smith *et al.*, 1979), which is consistent with the 100 yr mean drift ($1.05 \times 10^4$ deg between 1850 and 1950). As illustrated in Figure 4, this direction is opposite to that expected from the observed zonal circulation and may indicate that the latitudinal structure in the prevailing circulation is changing significantly over the large depth of the GRS. Consistent with our interpretation (Figure 4), however, the Voyager observations show that the shallow white and brown ovals tend to move eastward in the direction of the prevailing atmospheric jets.

The existence of the GRS has been known since its discovery by Casini in 1665. On Jupiter, this huge, long lived vortex is unique. Speculating about its origin, we suggest that an enormous meteor might have plunged into the southern tropical zone where the dynamical conditions are favorable for maintaining a vortex.

## Acknowledgements

We are indebted to Joanne Simpson, R. A. Hanel and R. E. Hartle for helpful discussions.

## References

Charney, J. G. and Eliassen, A.: 1964, *J. Atmos. Sci.* **21**, 68.

Fendell, F. E.: 1974, 'Tropical Cyclones', in (H. E. Landsberg and J. Van Mieghem, eds.), *Advances in Geophysics* **17**, 2–100.

Gehrels, T.: 1983, *Jupiter*, University of Arizona Press, (in press).

Hanel, R., Conrath, B., Flaser, M., Kunde, V., Lowman, P., Maguire, W., Pearl, J., Pirraglia, J., Samuelson, R., Gautier, D., Gierasch, P., Kumar, S., and Ponnamperuma, C.: 1979a, *Science* **204**, 972.

Hanel, R., Conrath, B., Flaser, M., Herath, L., Lia, V., Samuelson, R., Gautier, D., Gierasch, P., Horn, L., Kumar, S., and Ponnamperuma, C.: 1979b, *Science* **206**, 952.

Holton, J. R.: 1975, *The Dynamic Meteorology of the Stratosphere and Mesosphere*, American Meteorological Society.

Holton, J. R.: 1979, *An Introduction to Dynamic Meteorology*, Academic Press.

Kuiper, G. P.: 1972, *Sky and Telescope I.* **43**, 4, II, **43**, 75.

Malkus, J. S. and Riehl, H.: 1960, *Tellus* **12**, 1.

Mayr, H. G. and Harris, I.: 1983, *Astron. Astrophys.* **121**, 124.

Mayr, H. G., Harris, I., and Chan, K. L.: 1984, *Earth, Moon, and Planets* **30**, 245.

Morrison, D. and Samz, J.: 1980, *Voyage to Jupiter*, NASA-publication SP-439.

Ooyama, K.: 1969, *J. Atmos. Sci.* **26**, 3.

Smith, B. A., Beebe, R., Boyce, J., Briggs, G., Carr, M., Collins, S. A., Cook II, A. F., Danielson, G. E., Davies, M. E., Hunt, G. E., Ingersoll, A., Johnson, T. V., Masursky, H., McCauley, J., Morrison, D., Owen, T., Sagan, C., Shoemaker, E. M., Strom, R., Suomi, V. E., and Veverka, J.: 1979, *Science* **206**, 927.