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by

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Abstract

The energy Jupiter emits must be transported upwards throught the troposphere. If that transport is accelerated by the prevailing upward motions in the solar driven multicellular meridional circulation, eastward jets develop such as observed in the equatorial region. But if that vertical transport is impeded by the prevailing downward motions in the meridional circulation, the atmosphere "reacts" and tends to maintain the process through the development of hurricanes. Dynamically induced by solar differential heating, an ordered latitudinal structure with alternating "stability" and "instability" is impressed on the troposphere to form alternating zonal strata where hurricanes are "forbidden" and "permitted", respectively.

INTRODUCTION

The first theoretical discussion of the Great Red Spot (GRS) in the Jovian surface was presented by Hide (1961). His idea was based on the analogy with a Taylor column which can be produced by moving a cylindrical object in a rotating liquid. But the solid surface, which is prerequisite to the formation of a Taylor column, does not exist on Jupiter, and several other ideas have since been proposed such as the floating island model (DeMarcus and Wildt, 1966), the terrestrial tropical cyclone model (Kuiper, 1972) and the soliton model (Maxworthy and Redekopp, 1976).

The application of the soliton model to GRS has been developed further in detail (Maxworthy et al., 1978). This involves nonlinear solutions of the baroclinic potential vorticity equation and yields planetary solitary waves which reproduce various features of the GRS as observed with ground based telescopes. The detailed dynamical and thermal structures of the GRS obtained by experiments on Pioneer 10 and 11 and Voyager I and II, however, are difficult to reconcile with the model. In this model, the GRS is regarded as a localized anomaly near the tropopause and not as a deep-seated circulation. Furthermore, the thermal structure of the GRS observed by the IRIS experiments (Hanel et al. 1979 a, b) does not fit the present soliton model.

During more than a century, the theory of the tropical cyclone in the terrestrial atmosphere has been developed in parallel with detailed observations made from aircraft and satellites. Using the results of numerical simulations performed by Ooyama (1969), Kuiper (1972) has emphasized the similarity between the GRS and the tropical cyclone. As described by Fendell (1974), the spatial structure of a tropical cyclone consists basically of four domains; i.e. frictional boundary layer, rapid swirling region, eyewall and eye. The energy of the cyclone is sustained by the latent heat release of water vapor supplied from the bottom, the ocean surface, which is carried by the action of a rapid swirl into the eyewall, forming the hot tower (Malkus and Riehl, 1960). In contrast to the GRS, the life of the tropical cyclone in the earth's troposphere is relatively short, usually less than three weeks due to the loss of water vapor-heat supply after the landing. But if the earth's surface were completely covered with water and the rotation rate of the earth were faster, the life of the tropical cyclone would be presumably much longer.

It has recently been suggested that the prevailing equatorial jets on Jupiter and Saturn can be understood in the framework of a zonally symmetric circulation driven by solar differential heating (Mayr and Harris, 1981). In that model the troposphere below the cloud top is perceived to be convectively unstable; a superadiabatic temperature lapse rate is required to carry planetary energy from the interior to higher altitudes where radiation to space becomes important. Under this condition, the upward motions in the large scale meridional circulation (of the Ferral-Thomson type) is then capable of trapping dynamic energy at low latitudes, which, energetically, provides the basis for sustaining equatorial superrotation. The banded wind field on Jupiter is interpreted as an interference pattern between the energy and momentum balances above and below the clouds. At lower altitudes energy and momentum are effectively advected toward the equator; at higher altitudes they are advected away from the equator. In the intermediate region the dynamic signatures from both regimes are mixed due to vertical advection and diffusion.

Being true that the troposphere of Jupiter is convectively unstable, we propose that the great red spot and the white and brown ovals are hurricanes or cyclones whose formation and latitudinal stratification are controlled by the prevailing multicellular meridional circulation which in turn is driven by solar differential heating.

HURRICANE

We consider an atmosphere with temperature distribution illustrated in Figure 1a. In the troposphere at lower altitudes the lapse rate is superadiabatic.

Energy is released locally, and due to thermal forcing a local circulation develops with rising motions in the center. Horizontal cross sections of temperature, pressure and velocity fields are illustrated. At the bottom, below the heat source, conservation of mass requires a pressure minimum, and, obeying the thermal wind equation, the horizontal motions are cyclonic. At higher altitudes the temperature enhancement prevails and due to thermal expansion the pressure increases; the result is that the motions become anticyclonic. In the upper troposphere and stratosphere which are convectively stable the upward motions cool the gas and a temperature mimimum develops. But due to vertical expansion from below, the pressure continues to be enhanced and the circulation continues to be anticyclonic. Higher up adiabatic cooling prevails. The pressure eventually decreases so that the motions may again become cyclonic and a secondary circulation forms with subsidence in the center.

This interpretation is borne out by the infrared measurements from the Voyager spacecraft (Hanel et al., 1979 a,b). Near the 1 bar pressure level there is virtually no temperature signature from the great red spot. We are in a transition region between energy supply through convection in the troposphere below (which is unstable) and convective cooling by the upward motions in the upper troposphere above (which is stable). Higher up near the tropopause, the infrared measurements show that the red spot is significantly colder than the surrounding medium.

In the temperature observations we are apparently seeing the secondary signature of the hurricane's heat engine, the implication being that the red spot is deeply rooted inside the lower troposphere. At these lower levels, the prevailing zonal circulation is presumably weaker considering that it is driven by solar differential heating (Mayr et al., 1981), and this may in part explain why the red spot moves slowly in longitude. Moreover, in the lower troposphere the time constant for diffusion can be long, the heat engine is therefore very effective and the hurricane can persist over a long period of time.

The analogy with the terrestrial hurricane (Kuiper, 1972) suggests that the process has the tendency to be self sustaining. Upward motions once initiated would continue to supply latent energy from below which in turn is fueling the motions. A necessary condition is again that the troposphere is convectively unstable which should be satisfied on Jupiter (and Saturn). Instead of dispersing energy as is the case under stable conditions, the upward motions in the center of the disturbance are capable of concentrating or trapping the energy. This increases the efficiency of the heat engine and has the effect of extending it to lower altitudes, thereby reaching down into the energy reservoir of the planet.

FORMATION AND LATITUDINAL STRATIFICATION.

In summary, to maintain the hurricane the troposphere must be convectively unstable. The larger the superadiabatic lapse rate is the more efficient is the heat engine. The greater the stress is on the dynamic system the more energetic is the dynamic response.

We consider the energy equation in simplified form

$$\alpha T + Wc_p \left(\frac{\partial T}{\partial r} + \Gamma\right) = Q \tag{1}$$

where α is an effective cooling coefficient which includes vertical and horizontal heat conduction and

T, temperature

c_p, specific heat at constant pressure

W, vertical velocity

Γ, adiabatic lapse rate which may be "moist"

r, radial distance from the center of the planet

Q, heat input.

Applying perturbation theory

$$T = T_o + \Delta T_o + \Delta T$$
$$W = \Delta W_o + \Delta W \tag{2}$$
$$Q = Q_o + \Delta Q_o + \Delta Q$$

yields

$$\alpha \Delta T + \Delta W \, c_p \underbrace{\left(\frac{\partial T_o}{\partial r} + \Gamma\right)}_{S_o} + \Delta W \underbrace{c_p \frac{\partial \Delta T_o}{\partial r}}_{\Delta S_o} + \Delta W_o \, c_p \frac{\partial}{\partial r} \Delta T = \Delta Q \tag{3}$$

where

T_o, ΔT_o, globally and zonally averaged temperatures

ΔT, temperature perturbation

ΔW_o, zonally averaged vertical velocity

ΔW, velocity perturbation, $\Delta W \propto \Delta T$

Q_o, ΔQ_o, globally averaged and zonally averaged heat source

ΔQ, heat input perturbation which includes the release of latent energy.

Parameterizing $\frac{\partial}{\partial r} \Delta T \sim \frac{\Delta T}{h}$ and assuming $h > 0$ in the troposphere we obtain

$$\Delta T = \frac{\Delta Q - \Delta W\, c_p \left(\frac{\partial T_o}{\partial r} + \Gamma + \frac{\partial \Delta T_o}{\partial r}\right)}{\alpha + \Delta W_o\, \frac{c_p}{h}} \tag{4}$$

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

On the global average, small scale convection must carry planetary energy from the interior to higher altitudes where radiation to space becomes important (Figure 1a). The resulting (negative) stability, S_o, depends on the eddy diffusivity, and for Jupiter with $K = 10^6$ it is on the order of $S_o \sim -10^{-6}$ near the cloud top. Relatively small changes in the zonally averaged temperature distribution, ΔT_o (r, θ), can therefore significantly affect the global scale latitudinal variations in the tropospheric stability $S = S_o + \Delta S_o$.

Infrared measurements at the 0.8 bar pressure level on Jupiter (Hanel et al., 1979 a,b) show near 20° and 60° a precipitous decrease in temperature toward higher latitudes, and at the 0.15 bar level there is some indication, that, averaged over longitude, the temperature has a minimum near 20°.

Considering zonal symmetry, this temperature structure can be understood as the consequence of solar differential heating and resultant energy redistribution in a multicellular Ferrel-Thomson circulation (Mayr and Harris, 1981). In the troposphere (with $S_o < 0$), the prevailing upward motions $\Delta W_o > 0$ at the equator supply energy to the ambient medium and bring about greater stability ($\Delta S_o > 0$), easing the tension on the dynamic system (Figure 2). At the same time, energy, which otherwise would contribute to fuel the disturbance is convected to higher altitudes (see the second term in the denominator of (4)) which again eases the tension or decreases the heating efficiency. The consequence of both effects is that the disturbance slows down. If the temperature increase is so large that it brings about stability

$(S > 0)$, the disturbance dies. It is less likely therefore that hurricanes develop in the equatorial region which is consistent with observations.

At low latitudes near 20° where downward motions occur in the prevailing meridional circulation, energy is removed from the surrounding ambient medium. As the temperature decreases the atmosphere becomes less stable $(\Delta S_0 < 0)$, building up a tension to resupply the energy (Figure 2). In parallel, the prevailing downward winds from above retain the energy that otherwise would be convected to higher altitudes (second term in the denominator of (4)) which further increases the tension or the heating efficiency of the disturbance. The consequence of both effects is that the disturbance accelerates, and a hurricane can readily develop. The great red spot and brown ovals are indeed observed along longitude bands near 20° (Smith et al., 1979). We suggest that the multicellular meridional circulation also contributes to stratify the white ovals at higher latitudes (Figure 3).

The Voyager observations (Smith et al., 1979) indicate that there may be some order in the color of Jovian hurricanes. While the great red spot and many of the brown ovals occur at lower latitudes, the white ovals except those near the GRS occur preferentially at high latitudes. A major factor is probably the global scale distribution in temperature which tends to fall off toward higher latitudes due to the decreasing solar heat input.

Another reason might be that the hurricanes at lower latitudes are rooted deeper and are more energetic. The downward motions in the prevailing meridional circulation are stronger at low latitudes-where most of the solar energy is absorbed and under the guiding action of the Coriolis force - and are more effective in reducing the tropospheric stability and retaining latent energy at lower altitudes. Moreover, the higher temperatures at low latitudes would tend to increase the abundance of cloud material which provides the latent energy for driving the hurricane. As the efficiency of the heat engine increases due to the hurricane's depth and the enhanced instability in the surrounding ambient medium, the temperature inside the hurricane and below the cloud top increases to the point where it can be observed in the brown ovals (Hanel et al., 1979 a,b). At these temperatures, the cloud material can no longer condense sufficiently and we can see down through the funnel of the hurricane. The reduction in condensation thereby acts as a negative feedback mechanism and limits the available amount of latent energy. Compared with the white oval, the upward motions inside the deeper and more energetic brown oval are probably larger. Even though there is less condensed material inside the brown oval, the rate at which latent energy is deposited there could still be larger than in the less energetic and more shallow white oval.

Latitudinal cross sections of the prevailing temperature and zonal wind fields are illustrated in Figure 3. It is assumed that the temperature variations reflect the pressure variations, and geostrophy is assumed to hold. In the equatorial region, the temperature (pressure) decrease toward higher latitudes produces the eastward equatorial jet near 10^o; the temperature increase toward the equator produces the westward motion around 25^o. In between, presumably, a temperature minimum lies (or a minimum in the vertical temperature gradient), where the atmosphere is less stable and a hurricane can develop such as the great red spot. This scenario is supported by observations over 100 years showing that the GRS is slowly moving forth and back in longitude (Hide, 1966) as if it were locked to the wind reversal. The mean values of the GRS-drift are approximately -17^o/year (retrograde) and 27^o/year (prograde) based on the system II longitude of Jupiter. A contributing factor may be that the large size of the GRS (~ 10^o in latitude) can cover both velocity directions. On the other hand, the locations of the

GRS were 70° and 100° in system III during the Voyager I (1 February 1979) and Voyager II (23 May 1979) encounters, respectively, which gives a very large -0.5°/day retrograde drift of the GRS within a short period of time (Smith et al., 1979). Consistent with our interpretation, the Voyager observations indicate that the white and brown ovals tend to move eastward in the direction of the prevailing atmospheric superrotation.

CONCULSION

In summary, a relatively simple picture emerges of the atmospheric circulation on Jupiter. On average, small scale convection is transporting heat from the planetary interior to higher altitudes where radiation to space becomes important. At low latitudes upward motions induced by the absorption of solar radiation effectively "funnel" some of this energy, and angular momentum, into the equatorial region to form the prevailing equatorial jets, much like hurricanes are formed on a much smaller scale. Near and certainly above the tropopause the atmosphere is stable. Heat due to insolation is conducted to lower altitudes where molecular excitation permits reradiation. Energy and momentum carried upwards are diverted in the upper leg of the meridional circulation toward higher latitudes, closer to the rotation axis which induces eastward motions. Due to the large rotation rate of the planet, through the Coriolis force, the meridional motions are deflected vertically, and the global scale Hadley circulation is broken up into smaller cells. Latitudinal bands with upward and downward motions form with large eastward and smaller westward jets in between.

Against the background of a convectively unstable troposphere, the general condition exists for the formation of hurricanes. The prevailing large scale circulation increases that stability in regions of rising motions near the equator and it decreases that stability in regions of descending motions near 20° latitude, for example. A latitudinal structure with alternating "instability" and "stability" is impressed on the troposphere, which forms alternating zonal strata where hurricanes are "permitted" and "forbidden", respectively (Figure 3). Solar heating in the "forbidden" equatorial region forces energy upwards through vertical motions, thus releasing the tension,that, ordinarily, could drive hurricanes. Conversely, the descending motions near 20°, where the great red spot and brown ovals are observed, force energy downwards and enhance the tension in the ambient medium, which leads to the development of hurricanes.

The energy Jupiter radiates to space must be transported upwards through the troposphere. If that transport is accelerated by the prevailing upward motions in the (solar driven) meridional circulation, eastward jets develop such as those in the equatorial region. But if that vertical transport is impeded by the prevailing downward motions in the multicellular meridional circulation, the atmosphere "reacts" and tends to maintain the process through the development of hurricanes.

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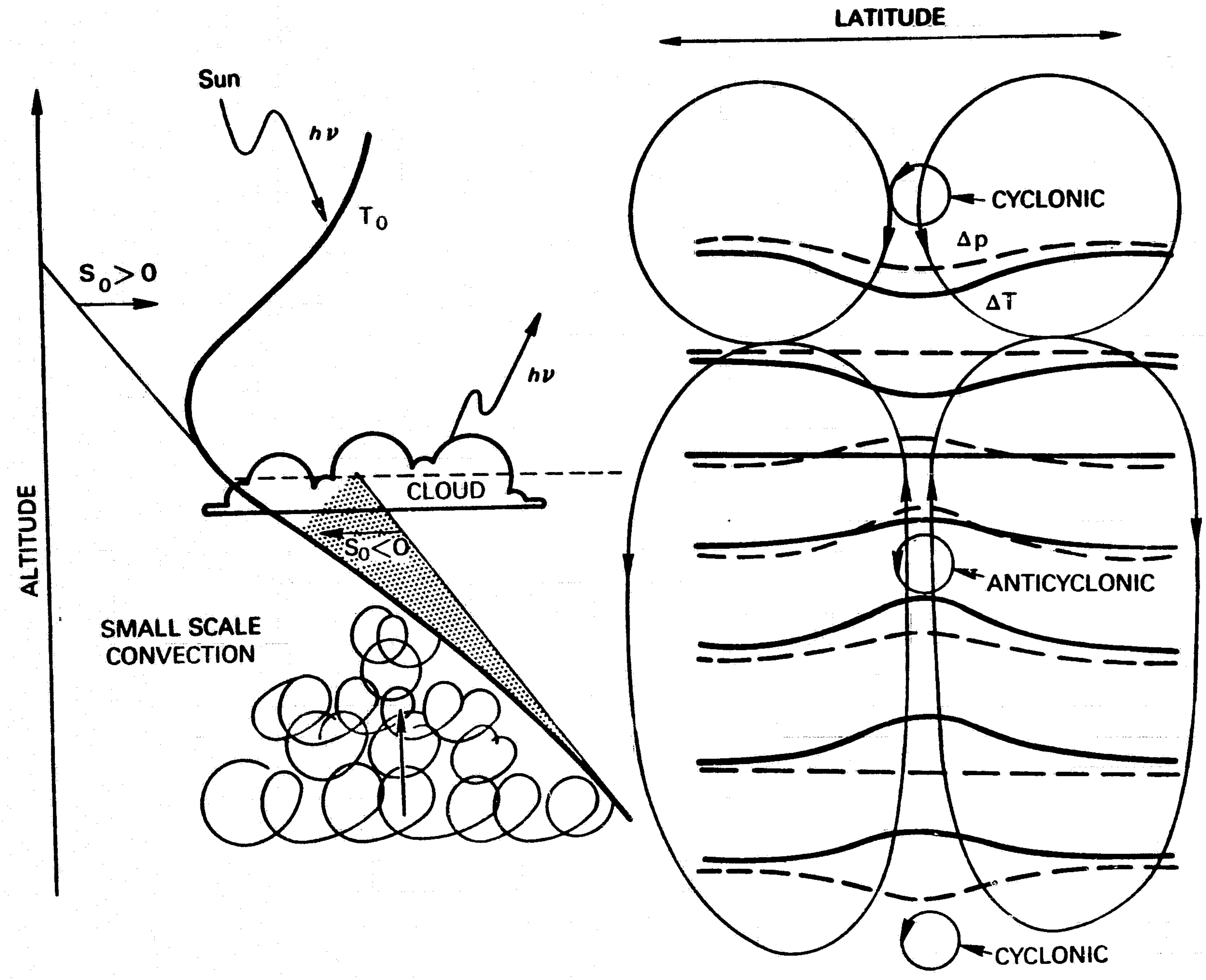
Figure Captions

Figure 1: Left side; schematic illustration of the average conditions in the energetics of the Jovian atmosphere. In the troposphere, the temperature distribuiton is assumed to be superadiabatic. The energy the planet emits must be supplied by small scale convection. Above the tropopause the solar input dominates and energy is carried downwards where it is reradiated. Right side; schematic illustration of the temperature and pressure fields in a hurricane. Within the troposphere the upward motions induced by a disturbance supply latent energy which sustains the motions. Above the tropopause adiabatic cooling prevails, energy is dispersed out of the hurricane and it cools down. This may reverse the motions into the cyclonic direction and a secondary circulation with subsidence may form at the top.

Figure 2: Schematic illustration of the circulation induced changes in the tropospheric stability. The right hand side represents the equatorial region where solar heating drives upward motions that relieve the thermodynamic tension and increase the stability. Hurricanes are therefore less likely to occur or "forbidden". The left hand side represents a region of subsidence, near 20° latitude for example. Here the downward motions build up thermodynamic tension and decrease the tropospheric stability. Hurricanes are therefore more likely to occur or "permitted".

Figure 3: Schematic illustration of the relationships between the multicellular meridional circulation (top), the zonal circulation (middle) and the relative temperature variations, in the troposphere (bottom). Rising motions (light arrows in the meridional circulation) increase

the stability and the temperature is elevated (e.g. in the equatorial region). Downward motions (dark arrows in the meridional circulation) decrease the stability and the temperature is depressed (e.g. near 20° latitude). In between, the temperature or pressure fall off toward higher laitutdes driving eastward jets. Poleward of the temperature minimum a westward jet can develop. The hurricane forms in the convergence zone in between. Due to the multicellular structure of the meridional circulation (caused by the large Coriolis force and relatively small negative stability in the troposphere) alternating strata develop where 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 may become less intense. Note that the anticyclonic motions inside the hurricane near or below the cloud tops are embedded in a flow regime which is cyclonic, thus swirls or wake effects develop.


LATITUDE
Sun
$h\nu$
T_0
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CLOUD
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ALTITUDE
SMALL SCALE CONVECTION
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ANTICYCLONIC
CYCLONIC

Figure 1

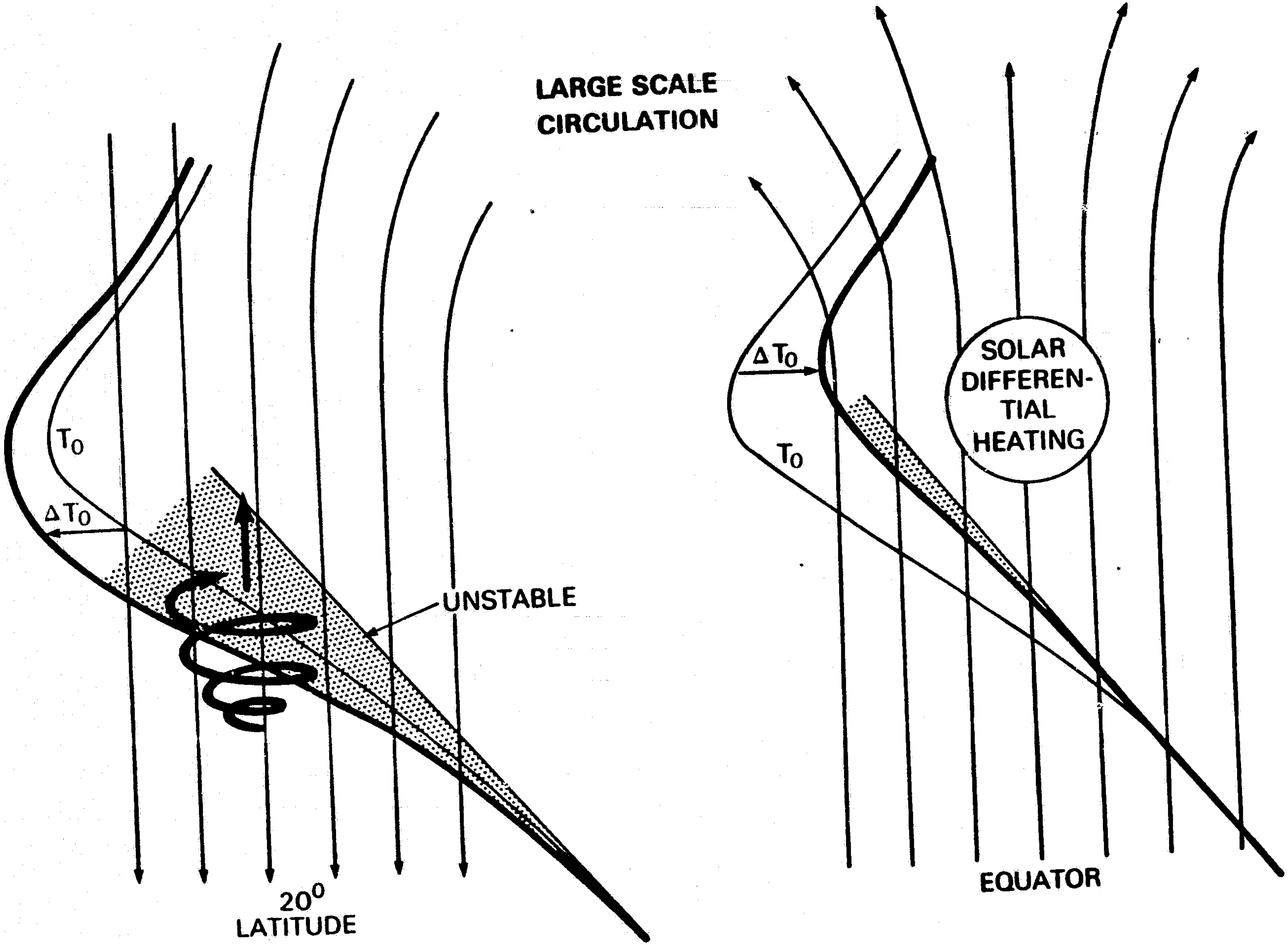
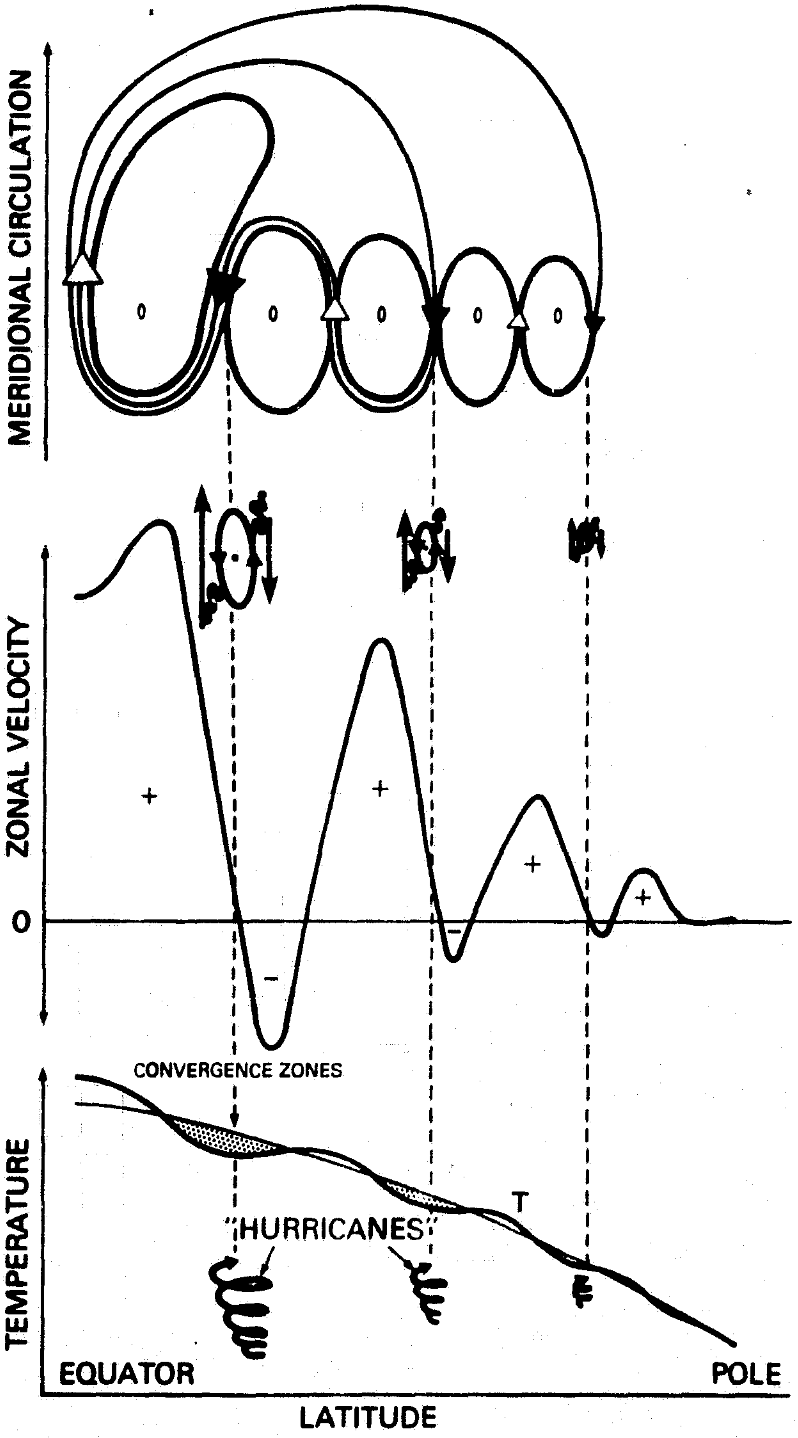

LARGE SCALE CIRCULATION
T_0
ΔT_0
UNSTABLE
20^0 LATITUDE
ΔT_0
T_0
SOLAR DIFFEREN-TIAL HEATING
EQUATOR

Figure 2


MERIDIONAL CIRCULATION
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ZONAL VELOCITY
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CONVERGENCE ZONES
TEMPERATURE
T
"HURRICANES"
EQUATOR
POLE
LATITUDE

Figure 3