Reprinted from Nature, Vol. 297, No. 5864, pp. 295-299, May 27 1982

The range and unity of planetary circulations

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Altering the rotation rate, obliquity and diurnal period of an Earth-like model atmosphere produces a wide range of circulation forms, some of which resemble those observed on Venus, Mars, Jupiter, Saturn and (perhaps) on Uranus and Neptune. These unified solutions suggest: that Jupiter and Saturn resemble a larger, faster-spinning Earth and possess a stress-bearing or momentum-exchanging sublayer; that easterly winds prevail in Uranus' summer hemisphere; and that Venus resembles a slowly rotating Earth if diurnal heating variations are included.

FROM Venus to Neptune, the motions of the planetary winds are being explored and subjected to theoretical analysis and prediction. On Earth, Mars and Jupiter the winds appear to exhibit similar arrangements and to obey similar laws[1–3]. These affinities stem mainly from the constraints placed on large-scale motion by planetary rotation[4,5]. To learn more about the influence of rotation on the structure of the planetary winds and to determine the range of circulation forms, we evaluate in this article the response of a representative (Earth-like) model atmosphere to changes in rotation rate, obliquity and diurnal period.

Our numerical experiments show that an Earth-like atmosphere, when placed in the rotational configuration of another planet, displays that planet's form of motion: Jupiter, Uranus and Venus appear to behave like rapidly rotating, oblique and slowly rotating Earths, respectively—despite thermodynamical and other differences. This suggests that the basic meteorology of the Solar System is relatively simple, unified and Earth-like, even though more complex meteorologies are needed for understanding the finer details of individual planetary circulations. The solutions thus provide an elementary indication of the dynamical laws and processes acting in the various planetary atmospheres.

Modelling

Our standard climate simulation model (GCM) integrates the equations of atmospheric motion, thermodynamics and conservation of mass and moisture in space and time, using spectral transform techniques in the horizontal and finite differencing in the vertical. For the radiative heating and cooling calculations, the normal annual-mean distribution of albedo, ozone, carbon dioxide and cloud cover are described as functions of latitude and height, while the variation of water vapour is predicted. The solar declination has its annual-mean values except when we examine obliquity and diurnal effects. For generality, the GCM has a simplified flat, uniformly moist (swamp) surface of zero heat capacity and excludes all ice-related processes. Moist convective adjustment represents small-scale convection and helps maintain vertical (hydrostatic) stability. A quadratic drag law determines the momentum and heat exchanges at the surface. (Full particulars of this GCM may be found in refs 6–9.) Solutions are discussed in terms of the relative rotation rate $\Omega^* = \Omega/\Omega_E$; where $\Omega_E = 7.292 \times 10^{-5}\,s^{-1}$ is the present terrestrial value. θ_p denotes planetary obliquity.

Dependence on rotation rate at equinox

Varying the rotation rate over a wide range of values ($\Omega^* = 0$–8) produces jets of diverse form and scale in the model atmospheres (Fig. 1). The jets are circumglobal and permanent in form, except at very low rotation rates ($\Omega^* < 1/64$).

The double maximum of the idealized terrestrial zonal flow stems from the overlapping of the tropical and extratropical jets at $\Omega^* = 1$ (Fig. 1*d*). These two basic jet forms are more independent and more obvious at higher rotation rates, because the baroclinic eddies are then smaller and more localized. Increased rotation rates also make the tropical jets narrower and the extratropical jets more numerous and more zonally aligned. At $\Omega^* = 8$, the tropical jet is centred on the equator (Fig. 1*a*).

In general, the mean meridional circulations consist of a direct (Hadley) cell equatorward of the tropical jet core, a weaker indirect cell in the poleward part of that jet, and assorted weaker cells in the extratropical jets. But at lower rotation rates ($\Omega^* \leq 1/4$) the baroclinic eddies cease to exist and a Hadley cell occupies the whole hemisphere (Fig. 1*g–j*). (The 'tropics' is defined as being that region influenced by the Hadley circulation. It extends from the equator to 15° N when $\Omega^* = 8$ and to 90° N when $\Omega^* \leq 1/4$.)

The equator-to-pole surface temperature difference generally increases with the rotation rate, from a minimum at $\Omega^* = 0$ to a maximum value (determined by the radiative equilibrium balance) approached at $\Omega^* = 8$, Table 1. A secondary minimum occurs at $\Omega^* = 3/4$ when baroclinic eddies peak in efficiency.

Dependence on obliquity at solstice

During solstice, a planet with a 10° obliquity and terrestrial rotation rate exhibits little latitudinal temperature variation, or motion, in its summer hemisphere (Fig. 2*c*). However, when the obliquity exceeds 20° the summer pole receives the greatest solar heating, resulting in strong pole-to-pole temperature gradients and extensive easterlies (with speeds up to 180 m s^{-1}) and eddies in the summer hemisphere (Fig. 2*a*, *b*). At $\theta_p = 90°$, a strong temperature inversion in the winter hemisphere excludes eddies from that region. Higher rotation rates reduce the width and amplitude of all currents and also reduce the tendency of temperature maxima to move to higher latitudes as obliquity increases (Fig. 2*d–f*). Consequently, the summer easterlies intrude less across the equator and the flow in the winter hemisphere retains its equinoctal characteristics: a pre-eminent tropical jet and multiple extratropical jets. Interhemispheric heat transport, by the baroclinic eddies and the mean meridional circulation, balances radiative cooling in the unheated winter hemisphere (Table 2).

Dependence on diurnal period

The diurnal variation in the solar heating plays a fundamental role in shaping the circulation of an Earth-like planet only at low rotation rates ($\Omega^* \leq 1/16$).

Table 1 Surface temperatures (K) at the equator and pole of the model atmosphere as a function of relative rotation rate

Ω^*	0	1/8	3/4	1	2	4	8
T_s Equator	292	300	300	305	305	305	310
T_s Pole	280	255	275	270	265	235	230

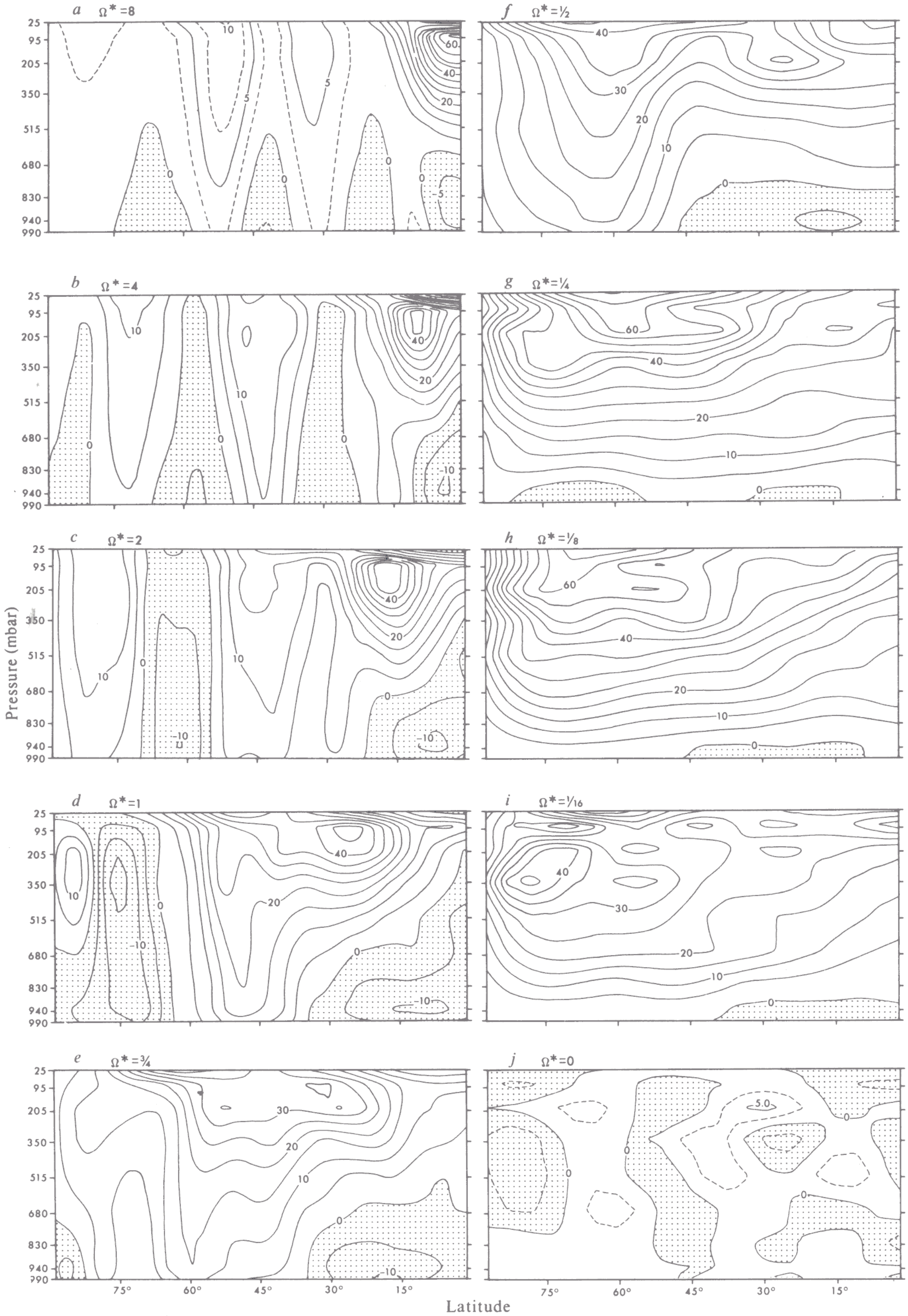

Fig. 1 The mean zonal flow of an Earth-like model atmosphere (subject to the annual-mean heating parameters) at different relative rotation rates, Ω^*. Similarities may exist between Jupiter, Saturn, Uranus, Neptune and *a–c*. Easterly winds are shaded; the main contour interval is 5 m s^{-1} and the supplementary one, 2.5 m s^{-1}. Pressure is used as the vertical coordinate. Calculations use a hemispheric sector, 120° in longitude, and horizontal rhomboidal spectral resolutions of 42 waves for the experiments in *a–e* and 15 waves for those in *f–j*.

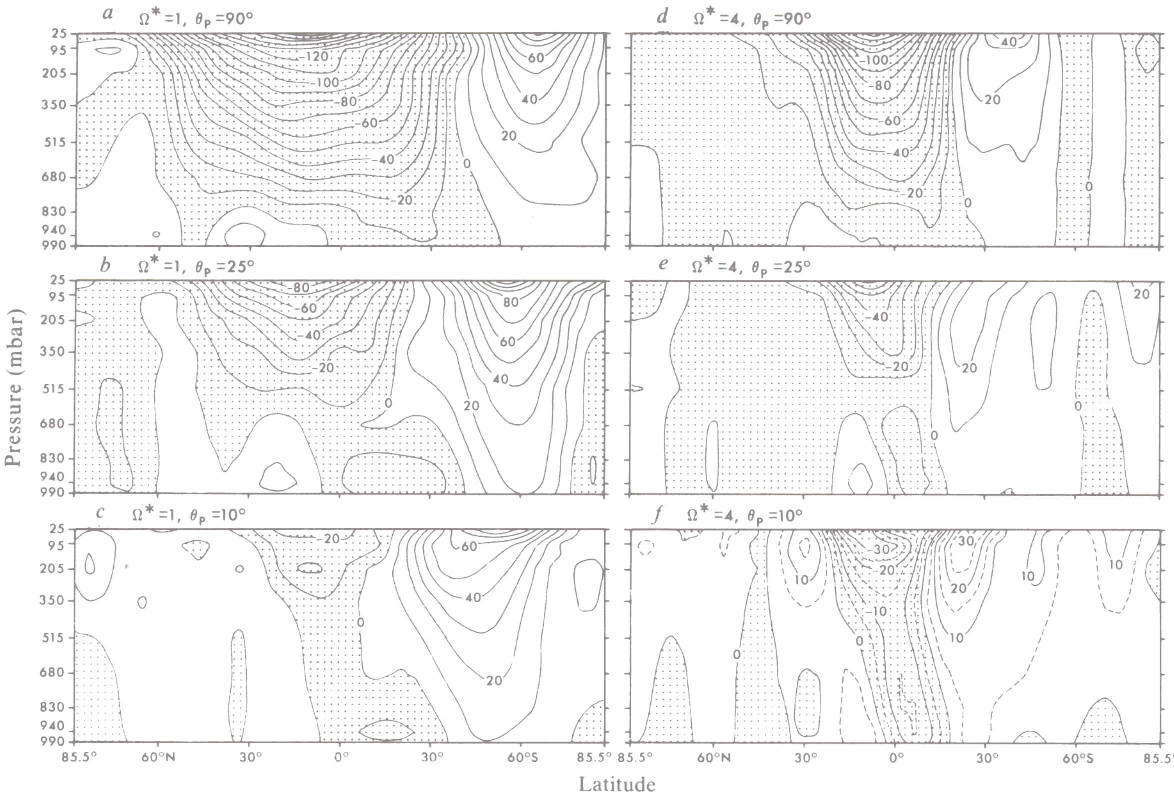

Fig. 2 The mean zonal flow of an Earth-like model atmosphere at different obliquities (θ_p) and relative rotation rates (Ω^*). Similarities may exist between Earth, Mars and *b*, between Uranus and *d*, between Saturn, Neptune and *e*. The solar constant is reduced to 3/4 or 1/2 its normal value when $\theta_p = 25°$ or 90°. The Sun is permanently at the northern hemispheric solstice (left side). Easterlies are shaded; the main contour interval is 10 m s^{-1} and the supplementary one, 5 m s^{-1}. Calculations use a global crescent, 120° in longitude, with a resolution of 15 waves (the solutions are preliminary and of reduced accuracy for the $\Omega^* = 4$ cases).

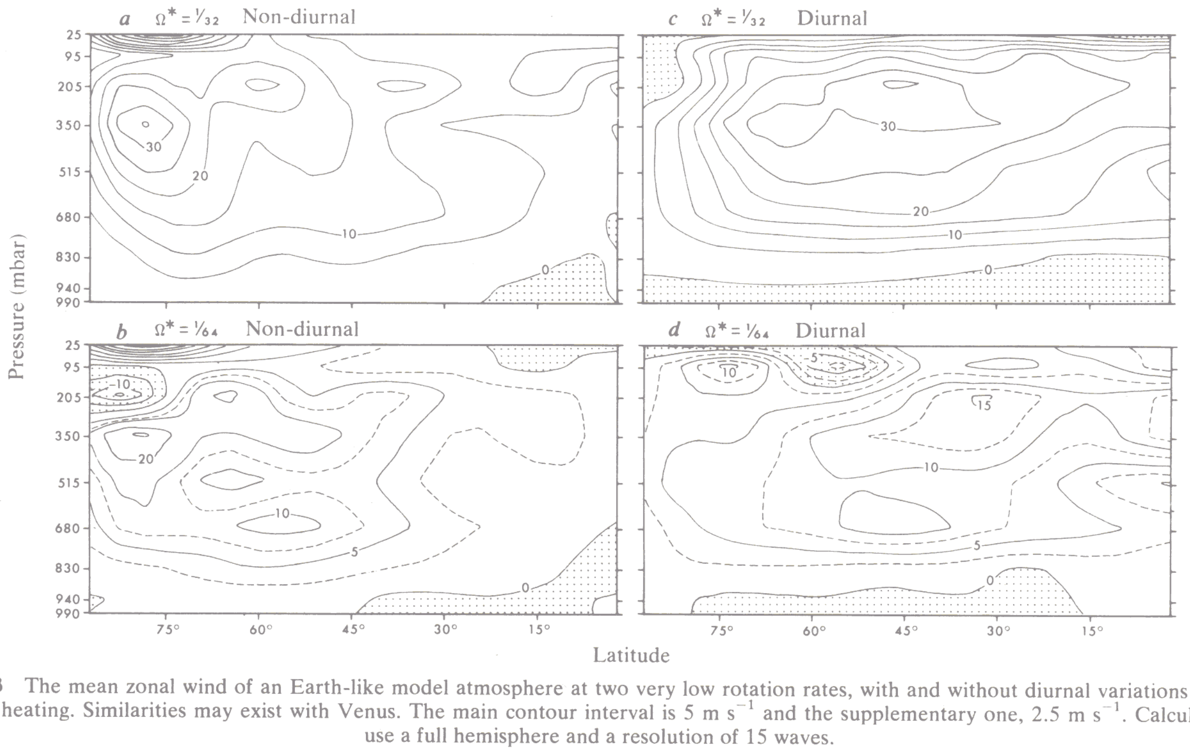

Fig. 3 The mean zonal wind of an Earth-like model atmosphere at two very low rotation rates, with and without diurnal variations in the solar heating. Similarities may exist with Venus. The main contour interval is 5 m s^{-1} and the supplementary one, 2.5 m s^{-1}. Calculations use a full hemisphere and a resolution of 15 waves.

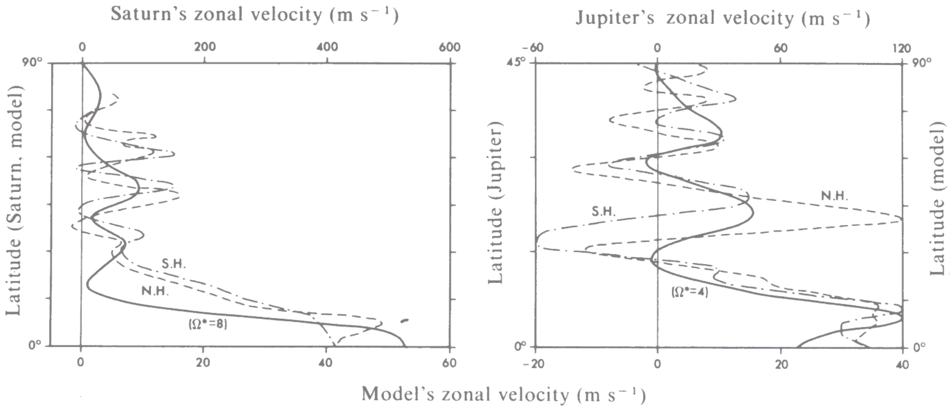

Fig. 4 Latitudinal profiles of the mean zonal velocities of northern and southern hemispheres (NH, SH) and rapidly rotating Earth-like model atmospheres. Adapted from Voyager data[17,18] and from Fig. 1*a*, *b* (at 205 mbar): *a*, Saturn and model at $\Omega^* = 8$; *b*, Jupiter and model at $\Omega^* = 4$. Scales are arbitrary.

As the rotation decreases towards these low rates in the nondiurnal system, the axis of the simple tropical (Hadley) jet that now constitutes the entire zonal flow moves poleward until a limit is reached at 80° latitude (Fig. 1*i*). At very low rates ($\Omega^* = 1/32$, $1/64$), geostrophy declines and the zonal flow weakens and becomes more complex (Fig. 3*a*, *b*).

Introducing diurnal variability into the very slowly rotating systems changes their narrow polar jets into broad global currents (Fig. 3*c*, *d*). The equatorial and subtropical westerly maxima (15 m s^{-1}) produced by the diurnal processes represent powerful currents for a planet whose surface rotates at <7 m s^{-1} (when $\Omega^* = 1/64$).

When $\Omega^* = 1/32$, the diurnal processes are wave-like and moderate; it may then be valid to regard the broad zonal current as being the result of the equatorward redistribution (by the waves) of momentum inherent in the polar jet of the nondiurnal state[10]. When $\Omega^* = 1/64$, the diurnal processes are so strong, and the nondiurnal jet so weak, that there may be no simple association between the diurnal and nondiurnal zonal flows[11].

Planetary implications

Earth: The hybrid mix of tropical and extratropical jets that occur at $\Omega^* = 1$ gives Earth the most complex of meteorologies. However, the thermal inertia of the oceans and ice caps reduces the strong seasonal variability normally associated with such an oblique planet. Only in the summer stratosphere are the warm polar temperatures and strong easterlies realized. The influence of obliquity may have been greater during Earth's ice-free-periods, when Ω^* and θ_p were perhaps double their present value[5], and the circulations were as depicted in Figs 1*c*, 2*b*.

Mars: Despite great differences in mass and composition, the martian and terrestrial atmospheres have similar forms of circulation. Lacking oceans, however, Mars has greater seasonal variation and, at solstice, the temperature and velocity distributions predicted by a Mars-like GCM[3] resemble those given by our simplified Earth model (Fig. 2*c*).

Venus: Venus' zonal circulation consists of a broad retrograde current that varies almost uniformly with latitude and step-like with height. Velocity maxima occur near the equator and in midlatitudes[12–14]. This form of circulation is also exhibited by our Earth-like model when the rotation is very slow and the diurnal heat cycle is included (Fig. 3*d*). Thus Venus seems to behave meteorologically like a slowly spinning, diurnally heated Earth. The diurnal heating component drives the quasi-horizontal turbulent exchanges that determine the form of the zonal wind[11] while the nondiurnal heating component drives the meridional exchanges that determine the amplitude of the zonal wind[10].

If we confine the solar heating more to the model's stratosphere, by inserting a high level opaque cloud, a more complex meridional circulation (multiple pole-to-equator cells) occurs but the zonal circulation remains basically unaltered. This suggests that the high level of heat deposition on Venus plays no fundamental role in determining the form of the zonal wind but is vital to the form of the meridional circulation. Stronger winds occur for Venus than for the model mainly because of the greater depth and density of its atmosphere[15].

Jupiter: Both Jupiter and the Earth-like GCM (when $\Omega^* = 4$) have circulations consisting of a pre-eminent tropical jet and multiple, highly zonal extratropical jets and assorted eddy fields (Fig 4*b*). If Jupiter does indeed resemble a larger, faster spinning Earth in its meteorology[2], then we predict that easterly trade winds occur in the lower tropical atmosphere and that Hadley and ageostrophic meridional circulations support the cloud band constituents.

Tropical jets cannot exist if the surface momentum exchange (drag) is excluded, so Jupiter must have a stress-bearing or momentum exchanging sublayer of some sort to be Earth-like in its tropical meteorology. The sublayer needed for tropical jet formation may not be uniform. Solitary topographic bumps (representing magnetic loops, rafts, icebergs, mountains or whatever)[16] inserted into the anticyclonic shear zones of the analogue circulations produce a long-lived anticyclonic vortex,

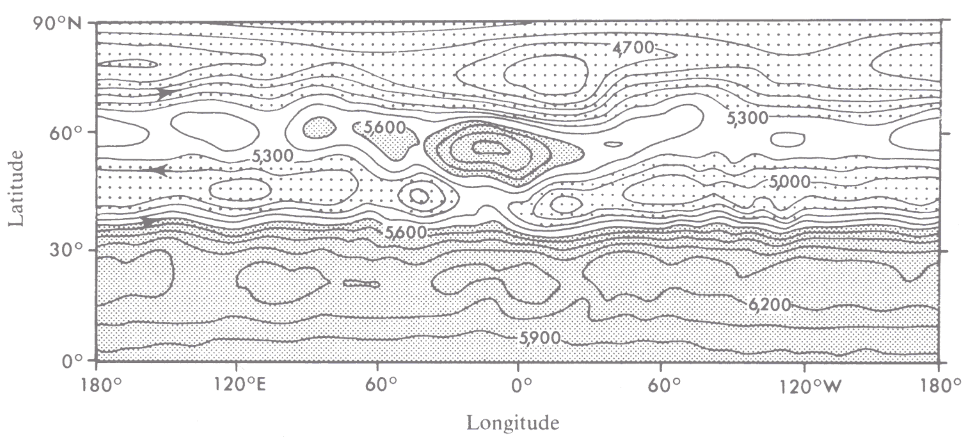

Fig. 5 The singular vortex resembling the Great Red Spot is produced by a topographic surface anomaly in a rapidly rotating ($\Omega^* = 4$) Earth-like model atmosphere. The 1-km high 'mountain' is centred near the latitude (53°) of zero mean flow (in a geostrophic, anticyclonic-shear zone) and at 0° longitude. Contours of the 500-mbar geopotential surface (a streamfunction) are plotted at intervals of 150 m with shading for values below 5,300 m and above 5,600 m.

Table 2 Surface temperatures (K) at summer and winter poles of the model atmosphere as a function of obliquity and relative rotation rate

Ω^*	1	1	1	4	4	4
θ_p	10°	25°	90°	10°	25°	90°
T_s Summer pole	300	310	310	280	320	310
T_s Winter pole	220	180	150	210	180	110

Reduced solar constants (Fig. 2) prevent the temperatures from exceeding 325 K at the summer pole.

together with a stagnant wake, a current reversal and secondary vortices (Fig. 5). This flow arrangement resembles that of the Great Red Spot (GRS). Topographic vortices of GRS scale are highly stable because they obey the planetary geostrophic (Burger) equations which, in contrast to the more familiar quasi-geostrophic equations, do not admit dispersive linear-wave solutions (Williams, G. P. and Pacanowski, R., in preparation). Thus, in this Earth-like meteorological view, the existence of the tropical jet and the genesis and permanence of the GRS all point (consistently) towards the presence of some sort of (irregular) sublayer on Jupiter. Such a possibility seems remote but is not inconceivable.

Saturn, Uranus and Neptune: Similar physical configurations should give all the outer planets similar meteorologies and, at least near equinox, zonal circulations like Jupiter's. Observations of Saturn's equatorial circulation reveal some basic differences from Jupiter that may be due to seasonal or other parametric differences (Fig. 4*a*). A velocity maximum at or near the equator, and a smaller relative amplitude to the extratropical jets, imply that Saturn resembles more an Earth-like atmosphere with $\Omega^* = 8$, than one with $\Omega^* = 4$. The greater strength and extent of Saturn's all-powerful equatorial jet may be due to the wider Hadley cell favoured by a deeper atmosphere.

At solstice, the large obliquity of Saturn and Neptune could lead to easterly winds dominating their summer hemispheres, if the internal heat sources do not reduce the seasonal variations. The extreme obliquity of Uranus and its lack of internal heat sources make the onset of a polar hot spot and powerful easterly winds and eddies inevitable in its summer hemisphere.

Conclusions

The element of unity seen in the above set of solutions suggests that relatively simple principles govern all the known planetary circulations and that these laws can be deduced best by evaluating a comprehensive atmospheric model rather than by trying to reason from individual facts of nature. The extent of planetary unity can be explored relatively simply: by looking for easterly winds deep in Jupiter's tropics or in the summer hemispheres of the other major planets.

We thank S. Manabe for guidance, and B. G. Hunt for stimulating correspondence. The study was initiated while G.P.W. was a visitor at the Department of Applied Mathematics and Theoretical Physics and Darwin College, Cambridge. P. Tunison, W. Ellis, M. Zadworny drafted the figures; B. M. Williams typed the manuscript.

Received 1 November 1981; accepted 23 March 1982.

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