

Dynamics in Planetary Atmospheric Physics: Comparative Studies of Equatorial Superrotation for Venus, Titan, and Earth

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The long-standing problem of equatorial superrotation in a slowly rotating planetary atmosphere has been solved recently. This article presents a systematic, comprehensive, and analytical examination of the momentum budget that maintains stable superrotational winds in a given planetary atmosphere. After reviewing general approaches used in modeling comparative planetary atmospheres, I describe the major dynamical processes that maintain stable equatorial superrotation for the atmospheres of Venus, Saturn's moon Titan, and Earth. Under appropriate conditions, all three bodies could have equatorial superrotational winds greater than 100 m s^{-1} . Venus' equatorial superrotation of 118 m s^{-1} is maintained at its cloud-top level at $\approx 65 \text{ km}$. My model predicts that, to maintain an equatorial superrotational jet stream in Titan's stratosphere, its main haze layer, which absorbs solar radiation, would need to be centered at an altitude of 288 km (corresponding to 10 Pa pressure). It is hoped that ongoing observations by the Cassini-Huygens mission to Saturn will be able to validate this model prediction. Strong equatorial superrotational winds could also be induced on Earth by optically thick dust clouds, such as those arising from an asteroid impact or extreme volcanic event. Superrotation would greatly enhance meridional transport in the Earth's atmosphere, which could have accelerated the globalization of an environment unfavorable to the survival of the dinosaurs.

THE SCIENCE OF COMPARATIVE PLANETARY ATMOSPHERES

This article gives a brief overview of modeling studies of planetary atmospheric physics, focusing mainly on atmospheric motions associated with dynamics, and reports significant progress in solving the long-standing dynamical problem of equatorial superrotation

in a slowly rotating planetary atmosphere.¹ The discussions are presented from the perspective of comparative planetary atmospheres rather than for a specific planet. The scientific merits of conducting studies of comparative planetary atmospheres are illustrated based on both general rationales and specific examples.

Over the past few decades, our understanding of the planets (including planetary bodies such as Saturn's moon Titan) and their atmospheres has advanced from a highly subjective art to a purely scientific process, supported by a large number of measurements made by various space missions. Our current knowledge indicates that while planetary atmospheres share physical processes, they exhibit diverse characteristics. The goal of modeling comparative planetary atmospheres is to understand a variety of atmospheric phenomena governed by common physical laws.

One way to illustrate the importance of comparative planetary atmospheres is to consider the Earth's atmosphere from first principles. There are two clear-cut methodologies in the physical sciences: (1) theoretical modeling based on observations and (2) laboratory experiments. The first method starts from a set of fundamental physical laws that govern the states and motions of the atmosphere. These physical laws are expressed mathematically and are often analyzed and solved numerically. Solutions are compared with measurements, from which our understanding of the Earth's atmosphere can be steadily improved. The essence of the second methodology is the simulation of processes in the laboratory, where one can control and change the external conditions that govern the behavior of the particular physical system under study. One must therefore be able to reproduce an approximate physical model of the real system in the laboratory where it can be controlled—a requirement that clearly cannot be met for the Earth's entire atmosphere. In fact, atmospheric research is mostly an observational science rather than an experimental science.

With an observational science, the critical process of hypothesis testing is severely curtailed because of our inability to control the external variables in laboratory experiments designed to simulate atmospheric processes. However, planetary atmospheres with remarkably different astronomical conditions, which result in significantly different atmospheres in terms of their physical and chemical properties, serve as ideal "laboratories." They provide a natural set of experiments, allowing us to test our basic understanding of physical processes that are governed by the same set of physical laws, yet under different external conditions. Therefore, comparing and contrasting different atmospheres in the solar system enables us to test our basic understanding of atmospheric processes in general and can also help us gain insight into the Earth's atmosphere. For example, the well-known phenomenon of the Antarctic "ozone hole" was found to be caused by the catalytic destruction of ozone by chlorine and other halogen-containing components. This discovery benefited greatly from theoretical studies of the photochemistry of HCl in the atmosphere of Venus.²

The Earth's atmosphere has been studied extensively, mainly by meteorologists. Yet meteorologists have different objectives and approaches from those studying comparative planetary atmospheres. The main objective of studying Earth's atmosphere is to make better predictions of its future state. In weather forecasting as well as climate prediction, one likes to know the physical state of the atmosphere at any given time. The prediction problem is often treated as an "initial value problem" in mathematical terms. So-called data-model assimilation, which appropriately incorporates current measurements into a continuously running numerical model, often plays an important role in prediction. Conversely, in comparative planetary atmospheres, one often cares more about the physical mechanisms that explain or predict atmospheric phenomena. In these cases of "mechanistic studies," the problem is often treated as a so-called forcing-response problem, and data-model assimilation usually does not enter directly into the formulation and solution procedures in numerical modeling. The physical mechanisms in comparative planetary atmospheres usually include those that explain the causes of atmospheric composition, origin, evolution, and dynamics.

This article focuses mainly on modeling studies of atmospheric motions associated with dynamics and reports on recent progress in solving the long-standing dynamical problem of the equatorial atmosphere rotating much faster than its solid planetary body (superrotation) in a slowly rotating planetary atmosphere.

OVERVIEW OF ATMOSPHERIC MODELING STUDIES

In modeling studies of atmospheric states and motions, significant advances can be made by investigating common atmospheric processes, such as energy balance, the momentum budget, the interaction between waves and the mean flow, etc., as they apply to different planetary settings. Atmospheric features observed on different planets can frequently be explained by understanding common processes governed by common physical laws.

The basic physical laws describing the conservation of momentum, energy, and mass are the same for all planetary atmospheres. The mathematical expressions of these laws are called "primitive equations" (see Box 1, "Invariant Primitive Equations"). Often, one does not solve the complete set of primitive equations directly when studying atmospheric motions. Box 1 gives one example of deriving an important feature of planetary atmospheric motions by a set of simple sign transformations. Numerical models for other planetary atmospheres are usually derived from those for the Earth's atmosphere. An invariant characteristic demonstrated in Box 1 indicates that it is the magnitude rather than the direction of planetary rotation that matters.

BOX 1: INVARIANT PRIMITIVE EQUATIONS UNDER A COORDINATE TRANSFORMATION

The so-called atmospheric primitive equations for the Earth's atmosphere are expressed in spherical coordinates that describe the fundamental conservation laws for atmospheric momentum, energy, and mass,³ that is,

momentum equations

$$\frac{Du}{Dt} - \left(2\Omega \sin \phi + \frac{u \tan \phi}{a} \right) v + 2\Omega w \cos \phi + \frac{uw}{a} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + F_{rx}, \quad (1)$$

$$\frac{Dv}{Dt} + \left(2\Omega \sin \phi + \frac{u \tan \phi}{a} \right) u + \frac{vw}{a} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + F_{ry}, \quad (2)$$

$$\frac{Dw}{Dt} - 2\Omega u \cos \phi - \frac{u^2 + v^2}{a} = -\frac{1}{\rho} \frac{\partial p}{\partial z} - g + F_{rz}; \quad (3)$$

the *thermodynamic energy equation*

$$\frac{D(c_v T)}{Dt} + \frac{p}{\rho} \nabla \cdot \mathbf{V} = Q; \quad (4)$$

and the *continuity equation*

$$\frac{D\rho}{Dt} + \rho \nabla \cdot \mathbf{V} = 0. \quad (5)$$

In these equations,

- a = Earth radius,
- c_v = specific heat at constant volume,
- $c_v T$ = internal energy,
- g = gravity,
- p = air pressure,
- T = air temperature,
- t = time,
- u, v, w = eastward, northward, and upward velocity, respectively,

- \mathbf{V} = velocity vector (u, v, w) ,
- x, y = eastward and northward distance, respectively,
- z = altitude,
- ρ = air density,
- ϕ = latitude, and
- Ω = Earth's rotation rate.

The terms F_{rx} , F_{ry} , and F_{rz} in Eqs. 1–3 and Q in Eq. 4 represent the net forcing to the momentum and internal energy, respectively. The total derivative D/Dt with respect to time t and wind divergence $\nabla \cdot \mathbf{V}$ in spherical coordinates that adopted appropriate approximations for the Earth's atmosphere are defined as follows:

$$\frac{D}{Dt} \equiv \frac{\partial}{\partial t} + u \frac{\partial}{\partial x} + v \frac{\partial}{\partial y} + w \frac{\partial}{\partial z}, \quad (6a)$$

$$\nabla \cdot \mathbf{V} = \frac{\partial u}{\partial x} + \frac{1}{\cos \phi} \frac{\partial(\cos \phi v)}{\partial y} + \frac{\partial w}{\partial z}. \quad (6b)$$

Equations 1–6 can also be applied to studying the atmospheric motions of other planetary bodies. The inclination of the Earth's equator to its ecliptic is 23.45° and its rotational direction is from west to east. Some planets or planetary bodies have negative inclinations. For example, Venus' inclination is -2.7° and Pluto's is -57.54°. Venus and Pluto rotate retrograde with respect to Earth: from east to west.

It can be easily verified that Eqs. 1–5 are invariant after making the following sign transforms: $\Omega \rightarrow -\Omega$, $x \rightarrow -x$, and $u \rightarrow -u$; i.e., if our Earth were rotating from east to west, the magnitude of its atmospheric motion would remain the same except that its wind direction would be reversed. In other words, the atmospheric states as solutions of a rotating dynamical system can be more effectively described by a coordinate system based on a rotating axis rather than fixed east–west coordinates. Therefore, when studying atmospheric motions from the standpoint of comparative planetary atmospheres, one can define prograde (retrograde) wind to be motions in the same (opposite) direction as the rotational direction of a planet. Likewise, prograde (retrograde) acceleration corresponds to a momentum source (sink) that generates (destroys) the east-to-west winds in the atmosphere of Venus and the west-to-east winds in the atmospheres of Earth and Titan.

In terms of the number of space variables explicitly included, the state, structure, and circulation of a planetary atmosphere can be studied by 0-, 1-, 2-, or 3-D models. As the number of model dimensions increases, more realistic physical processes that are often parameterized (i.e., the detailed processes are expressed in terms of simplified empirical formulas with a few bulk parameters) in lower-dimensional models are included. Even though more physical processes are explicitly modeled in a higher-dimensional model, the number of adjustable and empirical model parameters still increases for a fixed number of observations because of the much faster increase in the number of model gridpoints. Therefore, the computational resource requirements increase

dramatically as one proceeds to higher-dimensional models.

There is always a fundamental trade-off between model efficiency and model robustness in terms of choosing the appropriate model dimensionality and the appropriate physical processes to be explicitly included in the model. Three-dimensional models are the most complicated, addressing all interactions among dynamics, photochemistry, radiation, and transport. However, the merit and success of using 3-D models for studying comparative planetary atmospheres depend largely on the availability of data that can be used to initialize and constrain the model; that is, the availability of data provides constraints on the complexity of models. Here, I

give a brief description of atmospheric models in lower dimensions.

Zero-dimensional models describe atmospheric states that are independent of spatial variables (i.e., location). A simple example of a 0-D model is the calculation of the effective temperature T_e of a planet, which is defined by an energy balance between the incoming solar flux and outgoing thermal radiation⁴:

$$\frac{\pi a^2 (1 - a_p) S}{d_{sp}^2} = 4\pi a^2 \sigma T_e^4, \quad (1)$$

where

- a = planet radius (6371 km for Earth),
- a_p = planetary albedo (0.30 for Earth),
- d_{sp} = Sun–planet distance (1.00 AU for Earth),
- S = solar constant at 1 AU (1366 W m^{-2}),
- T_e = effective temperature, and
- σ = Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W m}^{-2}$).

The left-hand side of Eq. 1 denotes the solar energy intercepted and absorbed by the planet disk, whereas the right-hand side denotes the thermal energy radiated back out to space by the planet as a blackbody radiator. Equation 1 can be considered a degenerate form of Eq. 4 in Box 1: $Q=0$.

Table 1 lists several values of the effective temperature T_e and the mean surface temperature T_s for a few selected planets. Because of the greenhouse effect, T_s is often greater than T_e . “Greenhouse effect” refers to the planet’s surface receiving both direct shortwave solar radiation that transparently passes through the air, which would yield T_e , and longwave IR radiation emitted from the air that absorbs and thus prevents the IR radiation from below from returning to space, leading to $T_s > T_e$. The higher T_s than T_e for Jupiter is mainly due to its internal heat source. In addition to Jupiter, Saturn and Neptune also possess substantial internal heat sources compared to the solar energy they receive. For a planet with a very thin atmosphere such as Pluto, T_e is approximately the same as the planetary T_s . For Pluto’s icy surface, I assume a relatively large value of albedo: $a_p = 0.67$. On the basis of the above energy balance equation, it can be found that $T_e = 38.7 \text{ K}$, which is consistent with the value derived from coincident measurements.⁵

One-dimensional models often refer to radiative-convective or radiative-conductive models that determine the vertical (z) thermal structure or photochemical (box) models that determine the vertical distribution of chemicals in the atmosphere. Atmospheric radiative transfer is key to understanding and developing various 1-D models of the vertical thermal structure of planetary atmospheres.⁶ Measured vertical profiles of temperature, air density, and chemical composition provide

Table 1. Effective temperatures T_e and mean surface temperatures T_s for select planets.

	Sun–planet distance, d_{sp} (AU)	Albedo, a_p	T_e (K)	T_s (K)
Venus	0.72	0.77	227.0	750.0
Earth	1.00	0.30	255.0	280.0
Mars	1.52	0.15	217.0	225.0
Jupiter	5.20	0.58	98.0	138.0 ^a
Titan	9.57	0.30	82.0	94.0
Pluto	29.70 ^b	0.67	38.7	38.7

^aAt cloud top (pressure = 1 bar or 10^5 Pa).

^bIn May 1993.

constraints on atmospheric energy exchange, photochemistry, and transport within the atmosphere and possibly also on thermodynamic and chemical states at the lower boundary or in the deep atmosphere. Since the distribution of minor photochemical species often exhibits the largest gradient in altitude, 1-D models are useful tools for interpreting the measurements of minor chemical constituents. Note that the major components of planetary atmospheres are generally uniformly distributed globally, such as N_2 for Earth and Titan, CO_2 for Venus and Mars, and H_2 for giant planets. Therefore, their distribution can often be derived by 0-D models alone on the basis of thermodynamics and from the perspective of solar system evolution.² Since the minor constituents of planetary atmospheres (e.g., O_3 for Earth and Mars, HCl for Venus, and CH_4 for giant planets) vary the greatest in the vertical direction and are sensitive to the vertical thermal and dynamical structure of the atmosphere, a 1-D model is the minimum requirement for determining the vertical profiles of minor species in photochemical-diffusive equilibrium in a planetary atmosphere. Various 1-D models for different planets are presented in a recent monograph by Yung and DeMore.⁷

Two-dimensional models, which contain two spatial variables (altitude and latitude), have been useful tools for mechanistic studies of the atmospheres of Earth and other planets. For a rotating planetary atmosphere, zonal mean (latitude bands averaged across all longitudes) 2-D models can be considered a good trade-off, mainly because large-scale atmospheric structure and circulation vary the least along latitude bands. In a zonal mean 2-D model, atmospheric state variables such as temperature, winds, and chemical species distributions are expressed as functions of time t , latitude ϕ , and altitude z . Current computational capacity allows one to couple complicated photochemistry with dynamics through transport in a 2-D model. However, this kind of model can

only be well tested for the Earth's atmosphere because of the availability of databases of dynamical state variables and chemical species. The most observable and stable dynamical features for planetary atmospheres are zonal jets at various altitudes and latitudes. Important questions in planetary atmospheric dynamics remain: How is an atmospheric jet stream maintained on a particular planet? Why is the jet stream for that planet located at a particular latitude and altitude? What determines the magnitude of the maximum wind at the jet center? Is the observed jet stream a stable, steady physical state or a transient realization of an oscillatory state?

MAINTENANCE OF EQUATORIAL SUPERROTATION IN A PLANETARY ATMOSPHERE

A long-standing problem in planetary atmospheric dynamics is the maintenance of equatorial superrotation in the atmospheres of slowly rotating planets. Strong equatorial superrotational zonal winds of $\approx 100 \text{ m s}^{-1}$ (Fig. 1) were first observed at Venus' cloud-top level in the 1960s,⁸ consistent with an atmospheric angular velocity nearly 60 times greater than the rotation of the solid planet! Several mechanisms have been proposed to explain the generation or maintenance of the superrotation of clouds on Venus.



Figure 1. A UV image of thick clouds on Venus taken by the Pioneer Venus Orbiter (26 February 1979). Venus rotates very slowly, taking 243 days to complete one revolution. By tracking the cloud features, it is found that the clouds travel quickly around the planet, taking only 4 days to circulate once, indicating superrotational winds at the cloud level. Both the winds and the solid planet rotate from east to west, opposite to the direction on Earth. The Y-shaped cloud patterns move from right to left in the figure.

I have already shown in Box 1 the primitive equations for atmospheric motion applicable to all planets. To examine the dynamics of a zonal jet stream, one needs to take a zonal average over Eqs. 1–5 in Box 1 and evaluate the zonal momentum budget of all terms. Since the zonal momentum equation describing the zonal mean winds contains 10 terms (see Eq. 2 below), a rigorous and quantitative study of the superrotation has always been difficult. Most theories have qualitatively or quantitatively described possible mechanisms arising from one or two particular dynamical processes corresponding to one or two terms in the zonal momentum equation. Also, most theories have studied equatorial superrotation based on a set of atmospheric parameters specific to Venus. Two well-known theories that explain the maintenance of Venus' equatorial superrotation are (1) meridional momentum transport from mid-latitudes by eddy mixing^{9,10} and (2) momentum pumping by thermal tides.^{11,12} Careful examination of the existing theories shows that they either have difficulties leading to a contradiction with fundamental physical laws or are incomplete, leading to incorrect predictions of the magnitude of the superrotating winds.

To rigorously solve problems of large-scale circulation, such as equatorial superrotation in a planetary atmosphere, a 2-D model is necessary to describe the zonally averaged winds. By taking a zonal average of the flux form of Eq. 1 in Box 1, I arrive at the following mean zonal momentum equation¹:

$$\begin{aligned}
 \rho \bar{u}_t = & - \frac{1}{a \cos^2 \phi} (\overline{\rho v' u' \cos^2 \phi})_\phi - (\overline{\rho w' u'})_\zeta - \rho \bar{w} \bar{u}_\zeta \\
 \text{(I)} & \qquad \qquad \text{(II)} & \qquad \qquad \text{(III)} & \qquad \text{(IV)} \\
 & - 2 \Omega \cos \phi (\rho \bar{w}) - \alpha_R \rho \bar{u} + 2 \Omega \sin \phi (\rho \bar{v}) \\
 & \qquad \qquad \text{(V)} & \qquad \text{(VI)} & \qquad \text{(VII)} & \qquad \text{(2)} \\
 & - \frac{(\bar{u} \cos \phi)_\phi}{a \cos \phi} \rho \bar{v} - \frac{\overline{\rho w' u'}}{a} - \frac{\rho \bar{w} \bar{u}}{a}, \\
 & \qquad \qquad \text{(VIII)} & \qquad \text{(IX)} & \qquad \text{(X)}
 \end{aligned}$$

where the overbars and primes denote the zonal averages and deviations from them, respectively. I have also replaced the momentum drag term F_{rx} by a Rayleigh frictional drag term $-\alpha_R \rho \bar{u}$ with the Rayleigh frictional coefficient α_R . Equation 2 shows that the mean zonal momentum equation contains 10 terms (I–X), each representing a different dynamical process contributing to the momentum sources and sinks. These terms have never been systematically and self-consistently evaluated in the same dynamical frame. Therefore, the exact physical mechanism that maintains equatorial superrotation on Venus has remained a mystery, and the previously proposed hypotheses are mutually inconsistent. This

lack of resolution of the superrotation issue on Venus has also caused further confusion and debate concerning equatorial superrotation in Titan's stratosphere (e.g., Refs. 13–15). Titan is also a slowly rotating planetary body, which, similar to Venus' cloud layer, has a haze layer that absorbs a significant portion of its incident solar radiation.

Recently, I solved the problem of equatorial superrotation in a planetary atmosphere by specifying the 2-D zonal winds in an analytical form that resembles a jet stream.¹ As a result, each of the 10 terms in Eq. 2 can be analyzed systematically, first by scale analysis, then through analytical formulations and numerical evaluations, and finally by comparison with well-known planetary atmospheres. Key parameters of the analytical formulations are consistent with fundamental physical concepts and agree with observational constraints. Furthermore, this theory has been developed from the general perspective of equatorial superrotation for any given planetary atmosphere. The analytical forms of the approach explicitly show how an equatorial superrotation depends on various external and internal parameters. This general theory has been applied to the atmospheres of Venus, Titan, and Earth.

For the atmospheres of these three bodies, which have or could have equatorial superrotation, the terms that make the major contributions to the momentum budget in Eq. 2 are III, VI, and VIII. Dynamically, $III = -(\rho w'u')_z$ represents the convergence of the vertical eddy momentum flux caused by tidal wave pumping, i.e., the dynamical effect of waves on mean flow through the nonlinear interaction between the two. The physical mechanism is shown schematically in Fig. 2a. When an oscillatory heating source caused by the absorption of solar radiation moves in a direction opposite to the zonal flow, the phase surfaces (tilted lines) and air parcel trajectories (arrows) of the excited tidal waves slant differently above and below the heating layer. As a result, a vertical momentum flux convergence arises across the heating layer, which produces an acceleration of the mean zonal flow. Leovy¹² also noted that the momentum flux convergence can be rewritten as

$$-(\rho w'u')_z = \rho w'\xi', \quad (3)$$

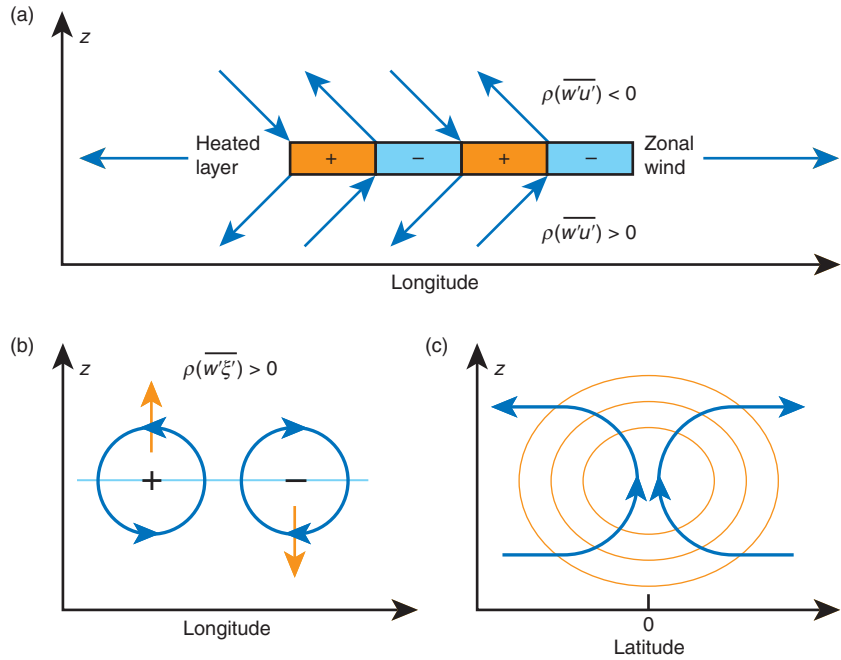


Figure 2. (a) Oscillating heating (+) and cooling (-) centers move opposite to the direction of the zonal wind. The phase surfaces (tilted lines) and air parcel trajectories (arrows) of the excited tidal waves cause a negative mean momentum flux *above* the heating layer and a positive one *below* the heating layer. Vertical momentum flux convergence across the heating layer produces an acceleration of the mean zonal flow. (b) Momentum flux convergence within the heating layer can also be represented as the vorticity flux. A positive correlation between w' and ξ' also leads to the acceleration of the mean zonal flow. (c) The incoming branches of the Hadley circulation cell cause the convergence of the momentum-depleted air mass from the outside into the region of the superrotational jet, whereas the outgoing branches cause the divergence of the momentum surplus air mass from the jet center to the region outside. The Hadley circulation is a zonally averaged thermal circulation that consists of warm air rising at the equator, moving poleward, then descending at the high latitudes and moving equatorward at the lower altitudes.

where $\xi' = -u'_z + w'_x$ is the horizontal vorticity (along the y direction) of the perturbation field that corresponds to tides in this study. Equation 3 shows that the momentum flux convergence within the heating layer can also be represented as a vorticity flux. Figure 2b illustrates how a positive correlation between w' and ξ' leads to an acceleration of the mean zonal flow at the center as the vortex parcels move in an organized way. Though the schematic depictions of III shown in Figs. 2a and 2b are apparently different, they are actually identical in terms of mathematics and physics.

Since the momentum source III produces prograde acceleration of the equatorial superrotational winds, terms VI and VIII produce retrograde acceleration to balance III. The momentum sink $VI = -\alpha_R \rho \bar{u}$ due to parameterized Rayleigh friction represents the effect of small-scale eddies. These eddies cascade the kinetic energy of the flow from large-scale motions to smaller ones until completely dissipated by the molecular viscosity. The momentum sink $VIII = -\rho \bar{v}(a \cos \phi)^{-1} (\bar{u} \cos \phi)_\phi$ represents the advection of horizontal wind shear by the horizontal branches of the Hadley circulation cell. The dynamical mechanism of momentum sink VIII

decelerates the wind at the jet center as shown schematically in Fig. 2c. The incoming branches of the Hadley circulation cause the convergence of the momentum-depleted air mass into the region of the superrotational jet, whereas the outgoing branches cause the divergence of the momentum surplus air mass from the jet center to the outside region.

As a result of wave/mean-flow interaction, the functional dependence of the wave pumping III on the zonal wind at the jet center \bar{u}_0 is highly nonlinear, as shown schematically in Fig. 3 by the red curve (see Box 2, “Stability Analysis”), which vanishes when \bar{u}_0 gets too small or too large. However, both VI and VIII are linearly proportional to \bar{u}_0 , so the sum of the two is a straight line passing through the origin. A steady and stable solution exists where the momentum sink line intersects the momentum source curve (Fig. 3). The peak value of the red curve and slope of the straight lines in Fig. 3 depend on the strength of the solar heating rate Q , since both the amplitude of the tidal waves (u', v', w') and the strength of the Hadley circulation (\bar{v}, \bar{w}) are linearly proportional to Q . However, III depends quadratically on the wave amplitude, whereas VIII depends linearly on \bar{v} . Hence, the relative strength of the momentum sink VIII is inversely proportional to Q . Note that VI is independent of Q . Thus, the slope of the straight lines in Fig. 3, which measures the relative strength of the total momentum sinks, increases with increasing d_{sp} , since less solar energy is received when a planet gets farther away from the Sun.

I show in Table 2 an example of equatorial superrotation corresponding to the steady and stable solutions illustrated in Fig. 3, typically at the intersection of the red curve and the solid blue line (Box 2). Here, u_s is the surface angular velocity at the equator for the solid planet, \bar{u}_0 is the zonal wind at the atmospheric jet center located at altitude z_0 with a pressure p_0 , and \bar{u}_{0c} is the critical zonal wind below which there is no superrotation (Box 2). In the analytic model, the jet center is characterized by a layer where the solar radiation is strongly absorbed: a cloud layer for Venus, a haze layer for Titan, and a dust cloud layer for Earth. For Venus, the modeled atmospheric angular velocity at the cloud-top level is 65 times greater than its solid body rotation.

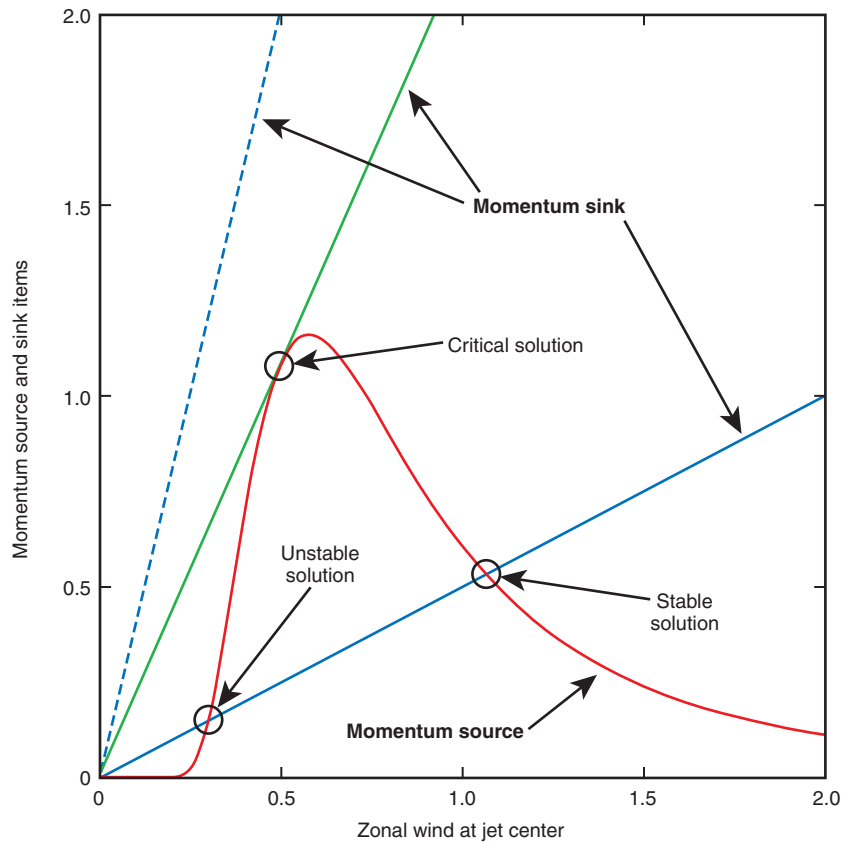


Figure 3. Dimensionless relationship between the wave pumping and momentum sinks as a function of the magnitude of the zonal wind at the superrotational jet center. The red curve represents the momentum source caused by wave pumping. Three straight lines represent relative momentum sinks under different parameter settings. A steady and stable superrotational solution is possible when two intersections exist between the source curve and a sink line.

The modeled Venus \bar{u}_0 (118 m s^{-1}) is very close to the measured zonal wind of $\approx 115 \text{ m s}^{-1}$ at the 65-km cloud-top level.¹⁶

For Titan’s stratosphere, limited measurements¹⁷ and numerical simulations by a 3-D model¹³ suggest superrotational winds of $\approx 100 \text{ m s}^{-1}$ centered at the 1.0-mbar (100-Pa) pressure level. My analytic model shows that no solution is possible for equatorial superrotation at this level, corresponding to the case of nonintersection between the blue dashed line and the red curve in Fig. 3. Titan is far from the Sun and only intercepts a small portion of the Sun’s energy. However, if the main solar radiation absorption layer in Titan’s stratosphere is lifted from 1.0 mbar ($\approx 185 \text{ km}$) to 0.1 mbar ($\approx 288 \text{ km}$), which increases the solar heating rate per unit volume by a factor 10 because of decreasing air density, an equatorial superrotation of 106 m s^{-1} could be maintained at the 0.1-mbar (10-Pa) level (Table 2). It is hoped that ongoing observation by the Cassini-Huygens mission will provide suitable data to validate this model prediction.

The last three rows in Table 2 show the relative contributions to the momentum budget from three terms in Eq. 2. Negative values indicate momentum sinks. The

BOX 2: STABILITY ANALYSIS OF A BALANCED SUPERROTATIONAL JET AT THE EQUATOR

The source of zonal momentum is wave pumping, which is the dynamical effect of the nonlinear wave/mean flow interaction. It is a nonlinear function of the zonal wind as shown by the red curve in Fig. 2. However, the momentum sink can be expressed as a linear function of the strength of the jet. The strength of the momentum sink relative to the momentum source is measured by the slope of the straight lines in Fig. 2. The jet center acceleration can be described by the difference between the wave pumping and the relative momentum sink,

$$\varepsilon \frac{\partial \eta}{\partial t} = \eta^{-3} e^{-1/2 \eta^2} - \alpha \eta, \tag{1}$$

where η is the dimensionless wind at the jet center and the two positive coefficients ε and α denote the relative strengths of the acceleration and momentum sink, respectively. When the wave pumping is exactly balanced by the momentum sink, zonal wind acceleration vanishes:

$$\varepsilon \frac{\partial \eta_0}{\partial t} = \eta_0^{-3} e^{-1/2 \eta_0^2} - \alpha \eta_0 = 0. \tag{2}$$

To see whether such a balance leads to a stable or unstable solution η_0 , I introduce a small perturbation η' that is superimposed on η_0 to examine how η' will change with time. By

substituting $\eta = \eta_0 + \eta'$ into Eq. 1, using Eq. 2, and keeping only the linear terms on η' since it is a small perturbation, I obtain the following linearized equation governing the evolution of η' :

$$\varepsilon \frac{\partial \eta'}{\partial t} = -\alpha(4 - \eta_0^{-2})\eta'. \tag{3}$$

When $\eta_0 = \eta_{0c} \equiv 1/2$, the right-hand side of Eq. 3 vanishes. Corresponding to the tangent point of the blue and red lines in Fig. 3, η_{0c} is the critical zonal wind below which there is no solution for a steady and stable equatorial superrotation. The dimensional values of critical zonal velocity \bar{u}_{0c} for three planets are listed in Table 2.

The solution of Eq. 3 can be written as

$$\eta' = \eta'_{t=0} \exp[-\varepsilon^{-1} \alpha(4 - \eta_0^{-2})t], \tag{4}$$

where $\eta'_{t=0}$ denotes the initial perturbation. Equation 4 indicates that when two solutions exist, say, $\eta_{01} < \eta_{0c}$ and $\eta_{02} > \eta_{0c}$, from Eq. 2, as shown in Fig. 3, the smaller η_{01} corresponds to an unstable solution because an initial perturbation $\eta'_{t=0}$ will grow exponentially, whereas the larger η_{02} leads to a stable solution because of its exponential suppression of an initial perturbation.

Table 2. Equatorial superrotation and momentum budgets for the atmospheres of three bodies.

	Bodies		
	Venus	Titan	Earth
Rotation rate, Ω (s^{-1})	3.001×10^{-7}	4.573×10^{-6}	7.292×10^{-5}
Radius, a (m)	6.052×10^6	2.575×10^6	6.371×10^6
Surface angular velocity, u_s ($m s^{-1}$)	1.82	11.8	465.0
Zonal wind at jet center, \bar{u}_0 ($m s^{-1}$)	118	106	120
Critical zonal wind, \bar{u}_{0c} ($m s^{-1}$)	14.5	86.3	55.7
Altitude, z_0 (km)	65	288	17
Pressure, p_0 (mbar)	100	0.1	100
Momentum source, III	100%	100%	100%
Momentum sink, VI	-31.5%	-81.9%	-69.5%
Momentum sink, VIII	-67.2%	-17.7%	-29.8%

momentum source driving equatorial superrotation is wave pumping (III) due to the strong absorption of solar radiation in an absorbing layer within the atmosphere. Wind shear advection by the horizontal branches of the Hadley circulation (VIII) is a major momentum sink for Venus. For the atmospheres of Titan and Earth, frictional drag (VI) mainly balances the momentum source.

EQUATORIAL SUPERROTATION IN EARTH'S LOWER STRATOSPHERE AND IMPLICATIONS FOR THE EXTINCTION OF THE DINOSAURS

There is no steady equatorial superrotation in the Earth's atmosphere because it is almost transparent to

visible solar radiation. The majority of the solar energy is either absorbed at Earth's surface or reflected back to space by clouds. Superrotational winds in the Earth's atmosphere (Table 2) could, however, exist if a layer of suspending dust were injected into the stratosphere by huge meteorite impacts or by massive volcanic eruptions, which would lead to the strong absorption of solar radiation by the resulting dust cloud.

Huge meteorite impacts and massive volcanic eruptions have emerged as the dominant theories to explain paleo-extinction events, specifically the extinction of dinosaurs (e.g., Ref. 18) at the Cretaceous/Tertiary (K/T) boundary, about 65 million years ago. Alvarez et al.¹⁹ proposed that a 10-km-dia. asteroid struck Earth in the Yucatan Peninsula in Mexico and injected a layer of debris clouds into the lower stratosphere, blocking sunlight and causing a rapid cooling that wiped out about 50% of the biota, including nearly all of the dinosaurs. If the extinctions near the K/T boundary were gradual or stepwise, a volcanic explanation for the extinctions would be more consistent (e.g., Ref. 18). However, in either theory, an environment favorable to the survival of dinosaurs was disrupted locally and quickly spread across the entire planet, resulting in global mass extinction. Numerical simulations by an aerosol model show that the environmental consequences of the impact-generated dust cloud are sensitive to the horizontal transport time, since the effect on dinosaur extinction requires the dust cloud to remain in the stratosphere for a long enough period to have a global impact.²⁰

Based on my analytic model,¹ it is found that an optically thick dust cloud in the Earth's lower stratosphere centered at the 100-mbar level, such as one created by an asteroid impact, could produce an equatorial superrotation of $\approx 120 \text{ m s}^{-1}$ (Table 2). Such a strong equatorial superrotational jet would greatly enhance the meridional transport of the dust cloud. Two processes associated with equatorial superrotation can cause this enhanced transport. First, enhanced heating of the dust cloud increases the strength of the radiatively driven Hadley circulation and reduces the meridional transport time. Second, global-scale waves are expected to be generated from the jet stream, possibly as a result of instability, which can also effectively transport the dust cloud poleward. The large meridional spreading of organized cloud features shown by the dark horizontal Y-shaped 4-day waves apparent near Venus' cloud top (Fig. 1) can be considered an example of the presence of global-scale waves in a strongly superrotational atmosphere.⁸

In the Earth's current atmosphere (with no strong equatorial superrotational winds), large-scale waves excited in the equatorial lower atmosphere are usually confined within a narrow band about 15° north and south of the equator. These equatorially trapped waves play a major role in driving equatorial circulation in the stratosphere through wave/mean-flow interaction, but

have little direct effect on mid-latitude atmospheric circulation.²¹ Since the zonal mean winds are driven by equatorially trapped waves, their effects are also mainly confined to lower latitudes. From the viewpoint of tracer transport in the Earth's lower stratosphere, the tropics can be considered isolated from the mid-latitudes.

Measurements and model simulations suggest that the transport time from the equator to high latitudes is 1 to 2 years in the lower stratosphere.^{22,23} On the other hand, because of the presence of superrotational wind and the associated global-scale wave modes near Venus' cloud-top level, it only takes a few days to transport cloud features from low- to high-latitude regions on the planet. One would expect similar modes of unstable global-scale waves to appear on Earth if the meridional variations of strong superrotational wind in the lower stratosphere were large enough to cancel out the curvature effect that traps large-scale equatorial waves. Therefore, more efficient meridional transport of a dust cloud would be expected to accelerate the globalization of a substantial meteoritic dust cloud, rapidly spreading an environment unfavorable to the survival of the dinosaurs on a scale of a few days rather than over a few years as in the Earth's present atmosphere.

CONCLUDING REMARKS

The comparative approach to studying planetary science has received increasing attention and has become fruitful as more data from different planets have become available.^{24–26} Because of the extensive diversity of planetary bodies, in-depth studies of comparative planetary atmospheres are often conducted on a one-to-one comparison basis. In this article, atmospheric equatorial superrotation is investigated for Venus, Titan, and Earth. By a brief and hierarchical overview of various modeling methods, I have demonstrated the feasibility and usefulness of the comparative approach of studying planetary atmospheres using a common set of physical laws. The main results are summarized in Table 2, which shows that under appropriate conditions all three bodies could maintain stable equatorial superrotational winds greater than 100 m s^{-1} . The single momentum source that maintains the superrotation is thermal pumping by tidal waves, balanced by the two momentum sinks of frictional drag and the advection of the horizontal shear by the Hadley circulation. Furthermore, since I have solved the problem analytically, the general parameter dependence of equatorial superrotation on various external and internal parameters becomes apparent. The detailed derivations and explicit expressions for the solution are given in a comprehensive paper.¹ The analytic model includes the following important parameters:

- Sun–planet distance
- Radius of the planet
- Rotation rate

- Inclination of the equatorial plane
- Gravity
- Atmospheric scale height
- Atmospheric buoyancy frequency
- Rayleigh friction coefficient
- Albedo
- Pressure level at which the absorption of the solar radiation occurs

Studies of the atmospheres of other planets also benefit our understanding of the Earth's atmosphere. I have already pointed out one example: the understanding of the Antarctic "ozone hole" associated with the catalytic destruction of ozone by chlorine and other halogen-containing components benefited in part from theoretical studies of the photochemistry of HCl in the atmosphere of Venus.² One important by-product of investigating the equatorial superrotation of a slowly rotating planetary atmosphere, such as Venus or Titan, is the realization that Earth's atmosphere could also have had equatorial superrotation 65 million years ago. Since atmospheric equatorial superrotation was first observed on Venus, it has always been associated with a slow planetary rotation rate. Therefore, the possibility of superrotation and its consequences on the faster-rotating Earth have never been considered before in a similar perspective as that of Venus or Titan. My analytic solution to the problem, i.e., evaluating all of the momentum terms in Eq. 2, suggests that the magnitude of the planetary rotation rate is *not* critical for the existence of equatorial superrotation on a slowly rotating planet. The dominant cause of equatorial superrotation is layered solar heating, the rate of which is inversely proportional to the air density and increases exponentially with altitude. As a result, I am also able to examine the possibility of superrotation and its consequences on Earth. This leads to my conclusion that equatorial superrotation in the Earth's lower stratosphere following an asteroid impact could have accelerated the globalization of an environment unfavorable to the survival of the dinosaurs.

Planetary atmospheric research is a multidisciplinary field. Among the three major disciplines—dynamics, radiation, and photochemistry—I have focused on atmospheric dynamics in this article and discussed radiative energy balance very briefly. The APL Space Department has a unique science team whose members are actively engaged in all three disciplines. Understanding planetary atmospheres is important both for its own scientific merits and for gaining insight into the Earth's biosphere. Looking at atmospheric processes on Earth from the perspective of the entire solar system will transform our view of atmospheric science. The possibility of equatorial superrotation in the Earth's lower stratosphere and its implications for the extinction of dinosaurs discussed in this article is one such example.

I recently encountered the following paragraph that describes the possible GCM (general circulation model) simulation of equatorial superrotation in the Martian atmosphere.

The grid point dynamic model is based on the LMD terrestrial model described by *Sadoury and Laval* [1984]. The discretization scheme conserves both potential enstrophy for barotropic nondivergent flows [Sadoury, 1975] and total angular momentum for constant surface pressure axisymmetric flow. The latter property was not included in the original terrestrial version but was found to be very important for simulating the Martian atmosphere in order to avoid spurious prograde zonal winds in equatorial regions [Hourdin, 1992b].²⁷

Because the Martian atmosphere is known to have suspended dust that absorbs solar radiation and produces strong tides, the originally simulated prograde equatorial zonal winds in the LMD (Laboratoire de Météorologie Dynamique) Martian model may not be entirely due to the model's spurious momentum source.

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REFERENCES

- ¹Zhu, X., *Maintenance of Equatorial Superrotation in a Planetary Atmosphere: Analytic Evaluation of the Zonal Momentum Budgets for the Stratospheres of Venus, Titan and Earth*, SRA-2005-01, JHU/APL, Laurel, MD (2005). (PDF file available upon request from the author.)
- ²Lewis, J. S., and Prinn, R. G., *Planets and Their Atmospheres: Origin and Evolution*, Academic Press (1984).
- ³Holton, J. R., *An Introduction to Dynamic Meteorology*, 4th Ed., Elsevier Academic Press (2004).
- ⁴Houghton, J. T., *The Physics of Atmospheres*, 3rd Ed., Cambridge Univ. Press, New York (2002).
- ⁵Tryka, K. A., Brown, R. H., Cruikshank, D. P., Owen, T. C., Geballe, T. R., and DeBergh, C., "Temperature of Nitrogen Ice on Pluto and Its Implications to Flux Measurements," *Icarus* **112**, 513–527 (1994).
- ⁶Zhu, X., "Radiative Transfer in the Middle Atmosphere and Planetary Atmospheres, in *Observation, Theory and Modeling of Atmospheric Variability*, X. Zhu et al. (eds.), World Scientific, Singapore, pp. 359–396 (2004).
- ⁷Yung, Y. L., and DeMore, W. B., *Photochemistry of Planetary Atmospheres*, Oxford Univ. Press (1999).
- ⁸Schubert, G., "General Circulation and Dynamical State of the Venus Atmosphere," in *Venus*, D. M. Hunten et al. (eds.), Univ. of Arizona Press, Tucson, pp. 681–765 (1983).
- ⁹Gierasch, P., "Meridional Circulation and the Maintenance of the Venus Atmospheric Rotation," *J. Atmos. Sci.* **32**, 1038–1044 (1975).
- ¹⁰Rosow, W. B., and Williams, G. P., "Large-scale Motion in the Venus Stratosphere," *J. Atmos. Sci.* **36**, 377–389 (1979).
- ¹¹Fels, S. B., and Lindzen, R. S., "The Interaction of Thermally Excited Gravity Waves with Mean Flows," *Geophys. Fluid Dyn.* **6**, 149–191 (1974).
- ¹²Leovy, C. B., "Zonal Winds Near Venus' Cloud Top Level: An Analytic Model of the Equatorial Wind Speed," *Icarus* **69**, 193–201 (1987).
- ¹³Hourdin, F., Talagrand, O., Sadoury, R., Courtin, R., Gautier, D., and McKay, C. P., "Numerical Simulation of the General Circulation of the Atmosphere of Titan," *Icarus* **117**, 358–374 (1995).

- ¹⁴Tokano, T., Neubauer, F. M., Laube, M., and McKay, C. P., "Seasonal Variation of Titan's Atmospheric Structure Simulated by a General Circulation Model," *Planet. Space Sci.* **47**, 493–520 (1999).
- ¹⁵Zhu, X., and Strobel, D. F., "On the Maintenance of Thermal Wind Balance and Equatorial Superrotation in Titan's Stratosphere," *Icarus* **176**, 331–350 (2005).
- ¹⁶Gierasch, P. J., Goody, R. M., Young, R. E., Crisp, D., Edwards, C., et al., "The General Circulation of the Venus Atmosphere: An Assessment," in *Venus II: Geology, Geophysics, Atmosphere, and Solar Wind Environment*, J. W. Bucher, D. M. Hunten, and R. J. Philips (eds.), Arizona Univ. Press, Tucson, pp. 459–500 (1997).
- ¹⁷Kostiuk, T., Fast, K. E., Livengood, T. A., Hewagama, T., Goldstein, J. J., Espenak, F., and Buhl, D., "Direct Measurement of Winds on Titan," *Geophys. Res. Lett.* **28**, 2361–2364 (2001).
- ¹⁸Oard, M. J., "The Extinction of the Dinosaurs," *CEN Tech. J.* **11**, 137–154 (1997).
- ¹⁹Alvarez, L. W., Alvarez, W., Asaro, F., and Michel, H. V., "Extraterrestrial Cause for the Cretaceous–Tertiary Extinction," *Science* **208**, 1095–1108 (1980).
- ²⁰Pollack, J. B., Toon, O. B., Ackerman, T. P., McKay, C. P., and Turco, R. P., "Environmental Effects of an Impact-generated Dust Cloud: Implications for the Cretaceous–Tertiary Extinctions," *Science* **219**, 287–289 (1983).
- ²¹Andrews, D. G., Holton, J. R., and Leovy, C. B., *Middle Atmosphere Dynamics*, Academic Press, New York (1987).
- ²²Hall, T. M., Waugh, D. W., Boering, K. A., and Plumb, R. A., "Evaluation of Transport in Stratospheric Models," *J. Geophys. Res.* **104**(D15), 18,815–18,839 (1999).
- ²³Zhu, X., Yee, J.-H., and Strobel, D. F., "Middle Atmosphere Age of Air in a Globally Balanced Two-dimensional Model," *J. Geophys. Res.* **105**(D12), 15,201–15,212 (2000).
- ²⁴Luhmann, J. G., Tatrallyay, M., and Pepin, R. O. (eds.), *Venus and Mars: Atmospheres, Ionospheres, and Solar Wind Interactions*, AGU, Washington, DC (1992).
- ²⁵Mendillo, M., Nagy, A., and Waite, J. H. (eds.), *Atmospheres in the Solar System: Comparative Aeronomy*, AGU, Washington, DC (2002).
- ²⁶Irwin, P. G. J., *Giant Planets of Our Solar System: Atmospheres, Composition and Structure*, Springer-Verlag, New York (2003).
- ²⁷Forget, F., Hourdin, F., Fournier, R., Hourdin, O., Talagrand, O., et al., "Improved General Circulation Models of the Martian Atmosphere from the Surface to Above 80 km," *J. Geophys. Res.* **104**(E10), 24,155–24,175 (1999).

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