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Dynamics of Titan's thermosphere

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Abstract

We estimate the wind speeds in Titan's thermosphere by considering the various terms of the wind equation, without actually solving it, with a view to anticipating what might be observed by the Cassini spacecraft in 2004. The winds, which are driven by horizontal pressure gradients produced by solar heating, are controlled in the Earth's thermosphere by ion-drag and coriolis force, but in Titan's thermosphere they are mainly controlled by the nonlinear advection and curvature forces. Assuming a day–night temperature difference of 20 K, we find that Titan's thermospheric wind speed is typically 60 m s^{-1}. In contrast, the Earth's thermospheric winds, of order 50 m s^{-1}, do not equalize day and night temperatures. We speculate on other factors, such as the electrodynamics of Titan's thermosphere and the tides due to Saturn. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

Titan's atmosphere is comparable in density to the Earth's, though much colder. Both atmospheres have an upper region called the thermosphere, situated at heights above about 600 km in Titan's atmosphere and 80 km in the Earth's, in which the temperature increases upwards because of the absorption of solar extreme ultraviolet and X-rays (XUV). The XUV radiation, possibly augmented in Titan's case by fluxes of energetic electrons and neutral atoms from Saturn, heats the neutral air and sets up gradients of temperature and pressure that drive global wind systems. Energy inputs from the mesosphere and the magnetosphere may also play a part in the dynamics. Titan also experiences strong gravitational tides because of the proximity of Saturn. In this paper we apply current ideas about the Earth's thermosphere and ionosphere to discuss the thermospheric dynamics of Titan, a topic not treated in detail by current models. We start by listing some features of the Earth's thermosphere above about 150 km:

1. large day–night temperature differences exist, of order 300 K, mainly due to the absorption of solar XUV;
2. winds blow, with speeds of order 50 m s^{-1} (i.e., nearly 1 Earth radius per day), both meridionally (summer–winter) and zonally (day–night);
3. the winds do not equalize day and night temperatures;
4. the wind speeds are largely controlled by ion-drag because of the high concentration of ions, which are constrained in their motion by the geomagnetic field;
5. vertical wind shears are limited by molecular viscosity, so that wind speeds are almost height-independent.

None of these apply to the Earth's middle and lower atmosphere, where the day–night temperature differences are very much smaller, ion-drag does not exist, and the wind patterns are coriolis-controlled. We shall show that conditions are different again in Titan's thermosphere, mainly because of the slow rotation and the much weaker solar radiation.

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Titan is 10 AU from the Sun. Its radius (r) is 2575 km and its rotational and orbital period is about 16 Earth days. The acceleration due to gravity (g) is 1.35 m s^{-2} at the surface, but falls off to 0.63 m s^{-2} at the height (h) of 1100 km for which our calculations are made. The atmosphere has a surface pressure $p = 1.4 \times 10^5$ Pa = 1.4 bar = 1.4 Earth atmospheres, and is mostly composed of molecular nitrogen N_2 with minor constituents such as CH_4. The mesopause is at about 600 km, with temperature $T = 135$ K and pressure $p = 0.01$ Pa = 1×10^{-7} bar. At 1100 km, with $T = 185$ K, the atmospheric scale height is given by $H = kT/mg = RT/Mg = 86$ km, where k is Boltzmann's constant and R the universal gas constant, and the mean molecular mass is m in kg or M in atomic mass units; we take $M = 27$ for N_2 with a small proportion of CH_4.

Theoretical steady-state models of Titan's ionosphere have been constructed by Yung et al. (1984), Ip (1990), Yelle (1991), Keller et al. (1992) and Fox and Yelle (1997). In the upper ionosphere, at heights above about 1500 km, the main source of ionization is the impact of electrons (roughly 10–100 eV) from Saturn's magnetosphere. Lower down, the main daytime source is photoionization by solar XUV, peaking at the level of unit optical depth at 1000–1200 km, corresponding to the Earth's daytime E and F1 layers at 100–180 km. According to Fox and Yelle (1997), the peak electron density N_e at solar zenith angle 60° is 7.5×10^9 m^{-3} at height 1030 km. Ip's (1990) model has a higher peak at around 1300 km, due to electron impact ionization, but other models lack this feature. These models are based on data acquired at the Voyager fly-bys in 1980–1981 and thus represent high solar activity. From ground-based observations of an occultation of a star by Titan, Hubbard et al. (1993) deduced that at heights of 250–450 km Titan's atmosphere is oblate, and inferred wind speeds of order 100 m s^{-1}, but information on thermospheric winds is lacking.

Titan has no counterpart to the Earth's ionospheric F2-peak at 250–350 km, where the relatively abundant oxygen atoms give rise to long-lived O^+ ions and the electron distribution is controlled both by photochemistry and dynamics. Instead, Titan's ionosphere has a complex photochemical regime, in which the principal ions are hydrocarbons $C_xH_y^+$ and, in some models, H_2CN^+. With dissociative recombination coefficients $\boldsymbol{\alpha} \sim 5 \times 10^{-13}$ m^3 s^{-1} for these ions, the mean lifetime of the ionization is given by $1/(2\boldsymbol{\alpha} N_e) \sim 130$ s. This time is so short that, by day, the ionization must be close to chemical equilibrium, and by night, the ionosphere's survival must depend on other sources such as Saturn's magnetospheric electrons.

In Section 2 we consider the various terms in the equation of motion for the neutral air in the thermosphere, and see what we can deduce about Titan's thermospheric winds without actually solving the full equation. First we have to estimate the horizontal pressure differences that drive the winds (Section 3). In Sections 4–6 we estimate the relative strengths of the processes that control and limit the wind speeds, namely curvature, coriolis force, ion-drag and viscosity, and discuss the form the wind system might take. This "scaling analysis" requires some knowledge of the results, and we cannot comment on whether the wind pattern is stable against small-scale circulations (of size$\ll r$) and instabilities. We can at least hope to show that our results are appropriate to global-scale circulations and self-consistent within our assumptions. Other factors, such as electrodynamic effects and the gravitational tides due to Saturn, may well be important but we cannot at present evaluate their effects (Sections 7 and 8). We sum up in Section 9, with a view to anticipating what might be observed by the Cassini spacecraft in 2004.

2. The thermospheric equation of motion

For both Earth and Titan, the air is constrained to move on a spherical surface in a rotating coordinate system rotating at angular velocity $\boldsymbol{\Omega}$ (7.3×10^{-5} rad s^{-1} for Earth, 4.5×10^{-6} rad s^{-1} for Titan). The equation for the horizontal wind velocity $\mathbf{U}$ in the thermosphere takes the form

$$\mathrm{d}\mathbf{U}/\mathrm{d}t = \mathbf{F} - 2\boldsymbol{\Omega} \times \mathbf{U} + \mathbf{U} \times (\mathbf{U} \times \mathbf{a})/a^2 - \nu_{ni}(\mathbf{U} - \mathbf{V}_i) + (\mu/\boldsymbol{\rho})\nabla^2\mathbf{U} - \nabla\boldsymbol{\Psi} + \mathbf{D} \quad (1)$$

where

$$\mathrm{d}\mathbf{U}/\mathrm{d}t = \partial\mathbf{U}/\partial t + (\mathbf{U} \cdot \nabla)\mathbf{U} \quad (2)$$

Here $\mathbf{F}$ denotes the horizontal component of the force per unit mass due to the pressure gradient, given by $-(1/\boldsymbol{\rho})\nabla p$, μ is the coefficient of molecular viscosity, and $\boldsymbol{\rho}$ is the air density. The neutral-ion collision frequency $\mathbf{v}_{ni}$ is given by the product of the neutral-ion collision parameter K_{ni} and the ion concentration N_i, summed over all ions present. The ion-drag term is only effective if the ion velocity $\mathbf{V}_i$ differs from the neutral-air wind $\mathbf{U}$, which requires a magnetic field (Section 6). $\boldsymbol{\Psi}$ is a tidal potential, which could be absorbed into $\mathbf{F}$ though we display it separately, and $\mathbf{D}$ represents the drag due to momentum transferred from the lower atmosphere, for example by gravity waves.

As gravity is omitted, the "wind equation", Eq. (1) applies only to the horizontal components of $\mathbf{U}$. If gravity is included, the vertical component of this equation is dominated by gravity and the vertical pressure gradient force, and effectively reduces to the hydrostatic equation $-\partial p/\partial h = g$ (Rishbeth et al., 1969). We make no attempt to discuss vertical winds in this paper. The coriolis term $-2\boldsymbol{\Omega} \times \mathbf{U}$ gives rise to the "geostrophic wind" that is dominant in the Earth's lower atmosphere, but is less important in the thermosphere. The term $\mathbf{U} \times (\mathbf{U} \times \mathbf{a})/a^2$ represents the centripetal acceleration of the air which, to meet the constraint imposed by the spherical geometry, is forced to flow in a curved path (curvature **a**); this term represents a "cyclostrophic" wind, and we call it the "curvature" term. The nonlinear term $(\mathbf{U}\cdot\nabla)\ \mathbf{U}$ in Eq. (2) represents advection of momentum.

If the circulation is global in scale, as in the situation discussed in this paper, the vector **a** is comparable in magnitude to the planetary radius r. The "curvature" term is thus of order U^2/a, where U is the wind speed, and its components contain cross-products of the meridional and zonal wind (Holton (1979), his Eqs. (2.19) and (2.20)). At latitude ϕ, the horizontal advection, curvature and coriolis terms in Eqs. (1) and (2) are as follows:

Advection:	zonal: $u\ \partial u/\partial x + v\ \partial u/\partial y$
	meridional: $u\ \partial v/\partial x + v\ \partial v/\partial y$
Curvature:	zonal: $-(uv/a)\tan\phi$
	meridional: $+(u^2/a)\tan\phi$
Coriolis:	zonal: $+2\boldsymbol{\Omega}v\sin\phi$
	meridional: $-2\boldsymbol{\Omega}u\sin\phi$

Here x and u denote distance and speed in the zonal direction (positive eastward) and y and v denote distance and speed in the meridional direction (positive northward). Thus, for global scale motions, the advection and curvature terms are of the same order of magnitude, and our scale analysis cannot distinguish between them.

3. Estimates of Titan's thermospheric temperatures and pressure gradients

Winds blow if there is a driving force **F** produced by horizontal variations of temperature and pressure. On the Earth, the day-night temperature difference produces the well-known "diurnal thermospheric bulge" with strong horizontal pressure gradients. The resulting horizontal transport plays an important part in thermospheric behaviour. We need to consider how the day–night temperature and pressure gradients on Titan might compare with those of Earth, though in Titan's case the Saturn tides will cause a further distortion of the thermosphere (Section 8). In principle, winds may also be driven by other forces represented in Eq. (1), such as tides, momentum transfer from below, or (if the ions are driven by electric fields) through the ion-drag term.

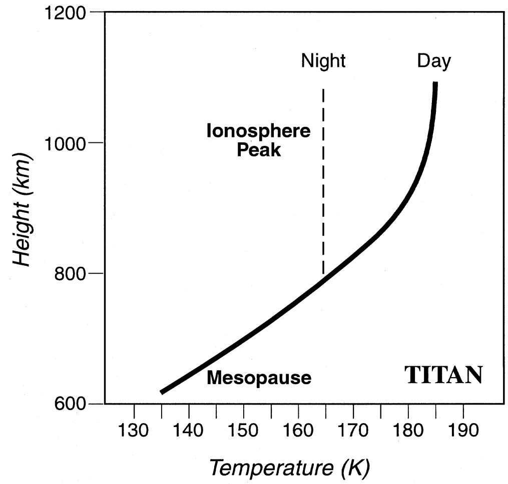

Fig. 1. Idealized sketches of temperature profiles in Titan's thermosphere, starting from the mesopause at 600 km height. Full curve: day. Dashed curve: night, assuming that the thermosphere cools to its daytime temperature at 800 km.

The dominance of radiative processes renders Titan's thermosphere unique among planetary bodies. Radiative processes in a one-dimensional model of Titan's thermosphere have been examined by Yelle (1991). His calculations show that the thermosphere above 800 km is in radiative balance, in that the heating by solar XUV is virtually equal to the radiative cooling, which is mainly due to HCN. Thermal conduction, though important in the Earth's thermosphere, is not important at these heights on Titan. The estimated time constant for radiative cooling of Titan's thermosphere at 800 km is 1×10^6 s, which is about 0.8 Titan days, so both latitudinal and local-time temperature variations are possible; our numerical estimates apply equally well to both.

The temperature profile $T(h)$, determined by solar input and radiation, increases monotonically upwards from the mesopause to the limiting exospheric temperature T_∞, for which the calculations of Yelle (1991) were the first to give the observed value at the terminator of 185 ± 20 K. Neglecting fine details, the temperature profile resembles the "day" profile (full curve) sketched in Fig. 1. For the calculations, we choose a height of 1100 km, near the peak of the ionosphere.

To estimate the pressure gradient force F (i.e., the horizontal component of $-(1/\rho)\nabla p$), we first need to estimate the day–night pressure difference Δp. As a starting point, we assume that the thermosphere from 800 km upwards becomes isothermal at night, and cools down to the daytime temperature of about 165 K, as sketched by the dashed profile in Fig. 1. The day–night temperature difference ΔT is then 20 K. Taking the pressure $p = 2.8 \times 10^{-4}$ Pa at 800 km, and

Table 1
Parameters at the peak of the daytime midlatitude ionosphere for Earth and Titan

Parameter	Earth (solar min)	Earth (solar max)	Titan (solar max)
Height h (km)	230	300	1100
Radial distance $a = r + h$ (km)	6600	6670	3675
Temperature T (K)	1000	1500	185
Gravity g (m s^{-2})	9.1	8.9	0.66
Mean molar mass (amu)	19	19	27
Scale height H (km)	48	74	86
Pressure p (Pa)	2.9×10^{-5}	3.0×10^{-5}	4.8×10^{-6}
Mass density $\boldsymbol{\rho}$ (kg m^{-3})	6.7×10^{-11}	4.5×10^{-11}	8.5×10^{-11}
Neutral concentration n (m^{-3})	2.1×10^{15}	1.4×10^{15}	1.9×10^{15}
Ion concentration N_i (m^{-3})	4.0×10^{11}	9.0×10^{11}	7.0×10^{9}
Rotation period (s)	8.64×10^{5}	8.64×10^{5}	1.45×10^{6}
Ion-neutral collision parameter K_{ni} (m^3 s^{-1})	9×10^{-16}	1.1×10^{-15}	5×10^{-16}
Molecular viscosity μ (kg m^{-1} s^{-1})	4.5×10^{-5}	6.0×10^{-5}	1.3×10^{-5}
Kinematic viscosity $\mu/\boldsymbol{\rho}$ (m^2 s^{-1})	6.7×10^{5}	1.3×10^{6}	1.5×10^{5}
Viscosity parameter $\mu/\boldsymbol{\rho}H^2$ (s^{-1})	2.9×10^{-4}	2.5×10^{-4}	2.1×10^{-5}
Coriolis parameter $f = 2\boldsymbol{\Omega} \sin 45°$(s^{-1})	1.0×10^{-4}	1.0×10^{-4}	6.4×10^{-6}
Neutral-ion collision frequency $\mathbf{v}_{ni}$ (s^{-1})	3.6×10^{-4}	1.0×10^{-3}	3.5×10^{-6}
Ion-neutral collision frequency $\mathbf{v}_{in}$ (s^{-1})	1.9	1.6	1
Ion gyrofrequency $\boldsymbol{\omega}_i$ (s^{-1})	200	200	(A) .06 (B) 2

using the appropriate values of scale height for $T = 165$ K, a straightforward calculation based on the hydrostatic equation gives the night time pressure at 1100 km as 3.9×10^{-6} Pa, as compared to the day time value of 4.8×10^{-6} Pa deduced from the model of Fox and Yelle (1997). Thus we estimate that $\Delta p = 0.9 \times 10^{-6}$ Pa. If the pressure maximum and minimum are on opposite sides of Titan, and are thus separated by a horizontal distance of $\pi(r + h) = 11500$ km, we find that:

$$F = \Delta p/(\boldsymbol{\rho}\pi(r + h)) = 0.0010 \text{ m s}^{-2} \tag{3}$$

where $\boldsymbol{\rho} = 8.1 \times 10^{-11}$ kg m^{-3}, the mean of the day and night densities at 1100 km. This arbitrary procedure is not as hazardous as might appear, because F varies only linearly with height, not exponentially. If, as is possible, the winds are more effective in equalizing day and night temperatures than our assumed night time profile implies, then ΔT would be smaller; we return to that point in Section 5. Although the temperature maximum and minimum may not be exactly on opposite sides of Titan, our simple analysis does not depend on just where they are situated. There may, however, be other sources of heating at night such as energetic particles.

4. Values of parameters that determine thermospheric winds

We now consider the other terms in Eqs. (1) and (2) that control the wind velocity. We need to discuss whether the winds are geostrophic (coriolis-controlled), cyclostrophic (curvature-controlled), or limited by advection or by friction due to ion-drag or molecular viscosity.

The relative importance of molecular viscosity, coriolis force and ion-drag may be judged from the parameters $\mu/\boldsymbol{\rho}H^2$, f and ν_{ni} listed in Table 1. The numerical values for Earth are based on those given for 300 km by Rishbeth (1972), adjusted to typical

Table 2
Quantities in the equation of motion

Parameter (unit mm s^{-2}, except U)	Earth (solar min)	Earth (solar max)	Titan (solar max)
Pressure gradient force (F)	18	20	1.0
Acceleration ($\partial U/\partial t$)$\sim 2\pi\boldsymbol{\Omega}U$	3.6	1.5	0.4
Advection/curvature ($U^2/(r+h)$)	0.4	0.03	1.0
Coriolis (fU)	5	2	0.4
Ion-drag ($\mathbf{v}_{ni}U$)	17	20	0.2
Viscosity ($\mu U/\boldsymbol{\rho}H^2$)	15	5	1.3
Steady-state wind U (m s^{-1})	50	20	60
Controlled by:	Ion-drag/coriolis	Ion-drag	Curvature/advection

heights of the F2 peak at latitude 45°; they are quoted for both solar minimum and solar maximum, represented by solar 10.7 cm radio flux values of 70 and 200 units. The values are model-dependent, and the solar cycle variations may not be very accurate.

For Titan, the estimates are for 1100 km height at solar maximum only. They are based on the concentrations shown by Fox and Yelle (1997) (their fig. 1), and on the assumed day and night temperatures. The values of coefficients are adapted from those of the Earth's ionosphere. The parameters v_{in} and ω_i are used in Section 6 to establish whether ion-drag actually operates in Titan's thermosphere, using two radically different assumptions about Titan's magnetic field. In general we make our calculations to two significant figures.

Table 2 shows which forces dominate in each case. Once the dominant force has been determined, the steady-state wind speeds are computed from Eq. (4) (ion-drag and coriolis control) for the Earth, and Eq. (5) (nonlinear control) for Titan, to give the values shown in Table 2:

$$U = F/\sqrt{(f^2 + \mathbf{v}_{ni}^2)} \tag{4}$$

$$U^2 = F(r + h) \tag{5}$$

From Eq. (3) we can substitute for F in Eq. (5) to give a relation independent of the planet's radius:

$$U^2 = \Delta p/\rho\pi \sim \Delta T \tag{6}$$

(the proportionality to ΔT is inexact, because Δp depends on both $\Delta\rho$ and ΔT). Titan's thermospheric wind system is clearly very different from the Earth's, in which the winds are largely controlled by ion-drag, at least by day, and the wind vector $\mathbf{U}$ is nearly aligned with the pressure gradient force $\mathbf{F}$; the nonlinear advection term, which depends on the horizontal gradients of $\mathbf{U}$, is generally unimportant, though it has some effect near the terminator (Rüster and Dudeney, 1972). In the case of Titan, the winds are controlled by the advection and curvature terms, which in general are similar in magnitude, though not necessarily at the same time and place.

Without fully solving the three-dimensional wind equation, together with the continuity equation for the air, we cannot determine the precise role of each term. We can expect the pressure distribution continually to adjust itself, in such a way that continuity of air flow is maintained everywhere — rather like the way in which the voltage distribution in an electric circuit adjusts itself to ensure that the current satisfies the requirement of continuity.

5. Titan's nonlinear winds

To improve our order of magnitude estimate (Section 3), we would have to compute the vertical wind speed from the continuity equation, and then estimate the adiabatic and convective transport terms in the thermodynamic equation, which would involve full three-dimensional modelling. We therefore confine our discussion to a qualitative description of the circulation.

Table 2 shows that pressure gradients are primarily balanced by the advection and curvature terms for a wind speed of 60 m s^{-1}. This has interesting implications for the nature of the circulation. The dynamical time constant associated with a wind speed of u m s^{-1} is roughly $a/u = 6 \times 10^4$ s, which is an order of magnitude shorter than the radiative cooling time and a factor of about 20 shorter than a Titan day. This suggests that the zonal winds on Titan could significantly reduce the local time temperature gradient. A diminished day–night temperature gradient does not imply weaker forcing of the zonal winds. Indeed, if curvature terms dominate, the meridional temperature gradient forces zonal winds. From the discussion in Section 2, we see that the meridional pressure gradient is balanced by the meridional component of the centripetal acceleration associated with the zonal wind, $-1/\rho\ \partial p/\partial y = u^2\ (\tan\boldsymbol{\phi})/a$. Although the interpretation is slightly different, wind speed estimates based on this equation give the same results as Eq. (6). In other words, assuming cyclostrophic balance and an equator–pole temperature difference of 20 K also implies zonal wind speeds of order 60 m s^{-1}.

The situation described above is similar to that believed to exist in Titan's stratosphere. As previously mentioned, Hubbard et al. (1993) inferred a zonal wind speed of 100 m s^{-1} in the upper stratosphere from the shape of the atmosphere measured in a stellar occultation experiment. Hourdin et al. (1995) succeeded in reproducing stratospheric winds of this order with a general circulation model and argue that the strong winds are produced by meridional transport of angular momentum, as first proposed for Venus by Gierasch (1975). The equator–pole temperature difference that drives Titan's stratospheric circulation is also approximately 20 K (Flasar et al., 1981; Flasar and Conrath, 1990). The same processes should be operating in Titan's thermosphere and moreover these strong zonal winds at the lower boundary of the thermosphere should greatly reduce the day–night temperature gradient. This will lead to the establishment of the cyclostrophic circulation pattern mentioned above, with a low pressure region at the poles balanced by inertial forces from strong zonal winds.

The magnitude of the meridional winds is more difficult to estimate, because they depend on the smaller terms in the momentum balance equations; the coriolis term, the viscous term, the advection term, and whatever day–night pressure gradient remains. All that we can really say is that as long as a strong zonal circulation reduces the day–night temperature difference the meridional circulation should be weaker than the zonal circulation. We note that if ΔT is reduced by a factor of 4, to 5 K, our estimated wind zonal speed is reduced to 30 m s^{-1}. In this case the winds are still limited by nonlinear terms, though viscosity and coriolis forces have some effect. Within the assumptions we have made, our conclusion that Titan's thermospheric winds are controlled by the nonlinear terms seems robust.

The circulation pattern suggested here for Titan's thermosphere differs from that of the terrestrial thermosphere. The reason for this difference is that dynamical time constants are shorter than one day on Titan but longer than one day on the Earth. In addition, strong meridional winds in the Earth's thermosphere are forced by auroral activity. Although the possibility exists for magnetospheric forcing of winds in Titan's thermosphere, we have too little information on the interaction of Titan and Saturn's magnetosphere to investigate this question.

6. The effects of viscosity and ion-drag in Titan's thermosphere

The parameter $\mu/\rho H^2$ is a measure of the extent to which molecular viscosity smooths out the height variation of wind velocity (Rishbeth, 1972). It increases exponentially upwards, because of the exponential decrease of ρ. At great heights, in order for the viscosity term in Eq. (1) to remain in balance with the other terms, the velocity profile $\mathbf{U}(h)$ has to adjust itself so that $\nabla^2\mathbf{U}$ becomes small. Unless there exists some strong force not included in Eq. (1), acting horizontally at great heights (which seems most improbable), this requires the velocity $\mathbf{U}$ to become height-independent.

Table 2 shows that $\mu U/\rho H^2$, which represents the order of magnitude of the viscosity term in the wind equation, is similar to the other major terms at 1100 km. This implies that viscosity becomes important here, and that the wind speed U tends to a limiting value above this height (Rishbeth, 1972). This is the reason for choosing a height around 1100 km for our calculations. At lower heights, in the region where viscosity is unimportant, the calculations would be valid but the result would not necessarily give a good idea of the limiting wind speed. At higher heights, where $\mu/\rho H^2$ is large, we would be unable to carry out our numerical analysis without evaluating $\nabla^2\mathbf{U}$ (which would entail solving Eq. (1)).

Whether ion-drag operates at all depends on whether there is a magnetic field. If not, the ions are free to move with the neutral air, in which case $\mathbf{U} = \mathbf{V}_i$ and the ion-drag term vanishes. Even if there is a magnetic field, it needs to be strong enough for the ion motions to be magnetically controlled. This requires $\omega_i \geq \nu_{in}$ where ω_i is the ion gyrofrequency and ν_{in} is the ion-neutral collision frequency (which greatly exceeds the neutral-ion collision frequency ν_{ni}, approximately in the ratio of the neutral and ion concentrations). This condition is well satisfied at 300 km in the Earth's thermosphere.

For Titan, we use two alternative hypotheses: (A) a field of about 25 nT, as suggested for the ramside ionosphere by Keller and Cravens (1994); (B) a field of 750 nT, as discovered in Ganymede's magnetosphere (Kivelson et al., 1996). Then, for $C_xH_y^+$ ions of mass 40 (i.e., with $x = 3$, $y = 4$) we obtain values of the gyrofrequency ω_i as given in Table 1. They show that magnetic control of the ions is very weak ($\omega_i \ll \nu_{in}$) in case (A), so ion-drag does not operate at all. In case (B), our postulated Ganymede-type magnetic field is strong enough to influence the ions at heights above 1100 km, though the winds are not controlled by ion-drag because the ion-drag term $\nu_{ni}U$ is smaller than other terms in Eq. (1); see Table 2. Ion-drag may have some influence on the direction of the wind direction, depending on the (unknown) orientation of the magnetic field.

7. Electric fields and currents

With an assumed magnetic field of 750 nT, the "Ganymede case" of Section 6, Titan's ionosphere has appreciable electrical conductivity σ. Let ω_e and ω_i denote the electron and ion gyrofrequencies, and ν_{en} and ν_{in} the electron-neutral and ion-neutral collision frequencies. The conducting region extends from the level where $\omega_e = \nu_{en}$, estimated to be at about 600 km, up to the level where $\omega_i \approx \nu_{in}$, which is near 1000 km (see Table 1). There is little ionization at heights below 900 km, so the conducting layer is roughly 150 km thick (i.e., approximately from 900 to 1050 km), with an average electron density of about 5×10^9 m^{-3}. Using the standard theory (Chapman, 1956; Rishbeth and Garriott, 1969), a rough estimate gives the height-integrated conductivity (Pedersen and Hall components) as $\int \sigma \mathrm{d}h \sim 1$ mho, similar to that of the Earth's ionosphere. With winds of order 60 m s^{-1}, the total current might approach that in the Earth's ionosphere, with a possible component due to the Saturn tide (Section 8).

If the magnetic field is weaker (stronger) than Ganymede's value of 750 nT, say by a factor of X, the conducting layer is shifted upwards (downwards) by ln X scale heights. For the "weak magnetic field case" assumed earlier, 25 nT, the conducting layer extends roughly over the height range 900–1300 km, with an integrated conductivity larger than in the case of the "Ganymede-type" magnetic field.

We may further speculate that an electric field is induced by Titan's motion through Saturn's magnetosphere. In principle this could give rise to convective ion drifts, as in the Earth's polar ionosphere. With an orbital speed of 5.5 km s^{-1} and an assumed ambient field of say 25 nT, this field would be about 0.15 mV m^{-1}. If it extends over Titan's ionospheric diameter of 7000 km, the voltage developed is then 1 kV, far less than the 100 kV generated by the solar wind interaction with the Earth's magnetosphere.

Titan's thermospheric wind patterns may be modified if there are localized regions of particle precipitation, as in the Earth's auroral thermosphere. Even with a weak magnetic field of 25 nT, as in case (A) of Section 6, the gyroradius of kilovolt electrons is only a few kilometres, so the particle precipitation is constrained, perhaps into well-defined "auroral zones". Thus particle heating might create significant high-latitude driving forces for the wind system, as in the Earth's thermosphere. Energetic ions, having gyroradii comparable to the radius of Titan's orbit, are much less constrained than electrons, and there may be interesting "ion pick-up" phenomena in Titan's outer magnetic field. The flux of energetic neutral particles is unaffected by any magnetic field, and it is possible that influx of meteoric ions and neutral particles may lead to the formation of layers in Titan's ionosphere, rather like terrestrial sporadic E.

8. Tides

The proximity of Saturn forces large gravitational tides in Titan's thermosphere. Since Titan always presents the same face to Saturn, these tides are presumably almost stationary. We may compare them with lunar tides in the Earth's thermosphere, of which the observable effects are minor perturbations of the equatorial ionosphere. The lunar tides are much weaker than the thermally excited solar tides, but in the case of Titan we can probably ignore solar tides.

Let G be the gravitational constant, M be mass, r be radius and D be planet–moon distance, with subscripts E, M, S, T as appropriate. First, for Titan, we compare Saturn's gravitational tide on Titan, $\mathbf{\Phi}_{\mathrm{ST}} \approx GM_{\mathrm{S}}r_{\mathrm{T}}/D_{\mathrm{ST}}^3$, with Titan's own surface gravity, $g_{\mathrm{T}} = GM_{\mathrm{T}}/r_{\mathrm{T}}^2$; and similarly compare the Moon's gravitational tide, $\mathbf{\Phi}_{\mathrm{ME}} \approx GM_{\mathrm{M}}r_{\mathrm{E}}/D_{\mathrm{ME}}^3$, with the Earth's surface gravity, $g_{\mathrm{E}} = GM_{\mathrm{E}}/r_{\mathrm{E}}^2$. We find

$$g_{\mathrm{T}}/\mathbf{\Phi}_{\mathrm{ST}} \approx 2.5 \times 10^4, \quad g_{\mathrm{E}}/\mathbf{\Phi}_{\mathrm{ME}} \approx 1.8 \times 10^7, \quad \mathbf{\Phi}_{\mathrm{ST}}/\mathbf{\Phi}_{\mathrm{ME}} \approx 360 \tag{7}$$

Hence Saturn's gravitational tide in Titan's atmosphere is 360 times stronger than the Moon's gravitational tide in the Earth's atmosphere. Nevertheless, it is only (1/25000) of Titan's own gravity.

Although the Saturn tide is stationary with respect to Titan, it is not constant in size, because the 3% eccentricity of Titan's orbit causes a 9% variation in tidal amplitude in the course of Titan's 16-day orbital period. Quite strong winds must accompany the periodic redistribution of air implied by this variation of amplitude. The superimposition of the Saturn tide on the day–night temperature difference discussed in Section 3 must give rise to a complicated pattern of winds, controlled by Titan's orbital phase around Saturn as well as by solar local time.

9. Conclusion

Our calculations based on the wind Eqs. (1) and (2) indicate that Titan's thermospheric winds are controlled by the nonlinear advection and curvature (cyclostrophic) terms. They are very different from the Earth's thermospheric winds, which are controlled by ion-drag and coriolis force, and for which the nonlinear terms have little importance. Because of the nonlinearity of the equations, the complicating effects of coriolis force and possibly ion-drag (depending on the magnetic field, as yet hypothetical), the strong tides due to Saturn (Section 8), and the seasonal changes of insolation due to Titan's equatorial inclination of about 27°, Titan's wind field may well be as complex as the Earth's. In order to estimate the wind speed, we had to make reasonable estimates of the terms in the equation, and then find self-consistent values that satisfy the equation. To make more progress, we need a better way of estimating the day–night temperature difference and the associated horizontal pressure gradient force, particularly if particle heating is appreciable in Titan's thermosphere, as it is in the Earth's.

The Voyager fly-bys were at solar maximum, but Cassini arrives at Titan at solar minimum. Although the solar cycle probably affects Titan's thermosphere much less than the Earth's, we may expect the temperature difference ΔT to be smaller at solar minimum than at maximum. The ion density N_{i} is also expected to be smaller, but probably only by a factor of two because of the nonlinear loss processes.

Our basic conclusions can be verified and investigated in more detail with numerical simulations of Titan's thermospheric circulation. However, many important input parameters, such as magnetospheric energy deposition, momentum and energy sources from the mesosphere, and the possibility of a magnetic field, require direct measurements for their determination. These will be carried out as part of the investigations on board the NASA/ESA Cassini mission to the Saturn system. The Cassini orbiter, which carries instrumentation designed to measure temperature and the ion and neutral composition, will pass through the thermosphere of Titan 30–50 times during the primary mission (Waite et al., 1999). Winds will not be measured directly, but can be calculated from measurements of temperature and density provided that sufficient latitude and local time coverage is obtained. Wind velocities can also be determined from chemically active species that serve as tracers of the atmospheric flow. Magnetospheric energy input to the atmosphere will be directly measured and solar energy input can be inferred from UV observations. With this host of measurements the dynamics of Titan's thermosphere will be well investigated and we should gain a good understanding of its similarities and differences to the Earth's thermosphere.

Although the solar radiation at Titan's thermosphere is 100 times weaker than at the Earth we predict that wind speeds are comparable or greater. This conclusion is based on the fact that radiative time constants on Titan are small and this allows temperature gradients to develop. Furthermore the smaller size of Titan, plus the weaker ion-drag, results in larger winds in Titan's thermosphere than in the Earth's for a comparable day-night pressure difference. Based on these considerations we anticipate wind speeds of 60 m s^{-1}, though we are unable to investigate the stability of the circulation.

These 60 m s^{-1} winds, as estimated from Eq. (5) of Section 4, circle Titan's thermosphere in about 100 h, a small fraction of Titan's rotation period. This suggests that the winds may be very effective in reducing the day–night temperature difference ΔT. In contrast, the winds in the Earth's thermosphere move the air through only 1000 km in the course of a day, and do not remove the day–night temperature difference of about 300 K.

Titan may be expected to have an active system of winds and waves in its middle atmosphere. Strong zonal winds at the mesopause, such as the 100 m s^{-1} winds inferred by Hubbard et al. (1993), will give rise to a drag term $\mathbf{D}$ in Eq. (1), which presumably transmits zonal momentum into the thermosphere and so gives rise to zonal winds.

Another area of speculation is the electrodynamics of Titan's ionosphere, touched upon in Section 7. This again requires a hypothesis about Titan's magnetic field, but we may expect the ionosphere to have a conductivity comparable to that of the Earth's. Interesting electrodynamic phenomena may be expected, especially in the hypothetical case of a magnetic field comparable to Ganymede's. Many puzzles await Cassini's exploration of the Titan thermosphere in 2004.

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