REVIEW

The dynamics of Titan’s troposphere

BY TETSUYA TOKANO*

Institut für Geophysik und Meteorologie, Universität zu Köln, Albertus-Magnus-Platz, 50923 Köln, Germany

While the Voyager mission could essentially not reveal the dynamics of Titan’s troposphere, useful information was obtained by the Cassini spacecraft and, particularly, by the Huygens probe that landed on Titan’s surface; this information can be interpreted by means of numerical models of atmospheric circulation. The meridional circulation is likely to consist of a large Hadley circulation asymmetric about the equator, but is susceptible to disruption by turbulence in clouds. The zonal wind in the troposphere is comparable to or even weaker than that in the terrestrial troposphere and contains zones of easterlies, much in contrast to the super-rotating stratosphere. Unique to Titan is the transition from a geostrophic to cyclostrophic wind balance in the upper troposphere. While Earth-like storm systems associated with baroclinic instability are absent, Saturn’s gravitational tide introduces a planetary wave of wavenumber 2 and a periodical variation in the wind direction in the troposphere. Unlike on Earth, the wind over the equatorial surface is westerly. The seasonal reversal in the Hadley circulation sense and zonal wind direction is predicted to have a substantial influence on the formation of dunes as well as variation of Titan’s rotation rate and length of day.

Keywords: Titan; meteorology; atmospheric dynamics

1. Introduction

Dynamic meteorology is the study of those motions of the atmosphere that are associated with weather and climate (Holton 2004). Saturn’s largest moon, Titan, possesses an Earth-like nitrogen-dominated atmosphere with a surface pressure comparable to that of the Earth. In contrast to the stratospheric dynamics, the dynamics of Titan’s troposphere has attracted relatively little attention for many years. One obvious reason for this is the difficulty in accessing Titan’s troposphere with remote sensing and in situ exploration owing to the dense stratospheric haze layer.

However, the relevance of tropospheric dynamics for understanding Titan’s atmosphere is obvious. Titan’s troposphere contains approximately 90 per cent of the atmospheric mass. Even small variations in wind speeds and direction can...
appreciably change the total atmospheric angular momentum budget. The
troposphere is bound at the bottom by the (mainly) solid surface at which
energy, momentum and matter can be exchanged with the interior of Titan’s
body. Any exchange of momentum between the stratosphere and surface has to
pass the troposphere and depends on the atmospheric properties there.
Furthermore, the troposphere is the place where the methane hydrological
cycle takes place, presumably causing a diversity of meteorological phenomena
such as moist convection familiar to us from the Earth’s troposphere. Several
atmospheric waves such as gravity waves may have their origin near the surface.

This work focuses on the dynamics of the troposphere of Titan. Although
unusual for a review paper, we begin in §2 with an overview of the general
circulation pattern expected from the theory and predicted by various general
circulation models (GCMs) for Titan because, in the case of Titan’s troposphere
model, development of atmospheric dynamics preceded observations. In §3, these
model results are constrained and interpreted by direct and indirect
observational data obtained mainly by the Cassini–Huygens mission. The
influence of tropospheric wind on Titan’s geomorphology and geophysics is
discussed as well.

2. General circulation patterns predicted by models

(a) Meridional circulation

One major component of general circulation in the lower planetary atmosphere is
the thermally direct circulation in the meridional–vertical plane (Hadley
circulation), which results from a conversion of the available potential energy
supplied by the solar heating into kinetic energy. Theory of general circulation
(e.g. Held & Hou 1980; Schneider 2006) explains that on slowly rotating planets
the Hadley circulation extends to higher latitudes than on the Earth since the
smaller Coriolis parameter makes it more difficult for meridional temperature
gradients to exceed the threshold for baroclinic instability. Although the
temperature profile and atmospheric composition of Titan were unknown prior to
the Voyager mission, Leovy & Pollack (1973) had already estimated that Titan’s
Hadley circulation would readily extend from the equator to the poles and the
equator-to-pole temperature contrast would be tiny. This would also mean that
the thermally indirect circulation (e.g. Ferrel circulation at mid-latitudes of the
Earth’s troposphere), which derives its motion by converting the kinetic energy
of the motion into potential energy, is absent on Titan. Titan has an obliquity of
26.7°, so the Hadley circulation cannot be expected to be entirely symmetric
about the equator. If the location of maximum solar heating is off the equator, as
would be expected on planets with an obliquity except at equinox, the latitude of
the boundary between the summer and winter Hadley cell (i.e. the intertropical
convergence zone, ITCZ) has to be poleward of the latitude of maximum solar
heating in order to ensure the continuity of temperature and conservation of
energy across this boundary (Lindzen & Hou 1988). This was indeed numerically
shown by parametric GCM simulations by Williams (1988), who concluded that
on Titan, which is characterized by a slow rotation and medium obliquity, the
circulation should vary from the symmetric Hadley state at the equinox to the
solstitial–symmetric Hadley state with a single pole-to-pole cell at solstice.
These conclusions were drawn purely on theoretical grounds considering the astronomical and geophysical parameters of Titan. However, the meridional circulation pattern is also sensitive to the diabatic heating rate and the atmospheric response to it, which were unknown prior to the Voyager mission. Based on the atmospheric structure retrieved by the Voyager spacecraft, the radiative time constant in Titan’s troposphere was estimated to be longer than a Saturn (Titan) year (Flasar et al. 1981). If the absorption of sunlight by the tropospheric gases were the sole driver of the tropospheric circulation, seasonal variation in the Hadley circulation would be nearly absent owing to the long radiative time constant and there would be a pair of equator-to-pole cells converging at the equator considering the annual mean energy budget. A more careful analysis of the thermal structure near the equator showed that the troposphere is approximately in a radiative–convective balance (McKay et al. 1989). The heat budget of the troposphere is controlled by a balance between the solar heating and greenhouse effect by the tropospheric gases, but a small convective (sensible) heat flux from the surface is also required to account for the observed thermal structure in the lowest few kilometres. Approximately 10 per cent of sunlight arriving at the top of the atmosphere reaches the surface, and the small heat capacity of solid surface allows the surface temperature to vary by a few K almost in phase with the solar forcing (Tokano 2005). This would introduce some seasonal variation in the diabatic heating rate via sensible heat flux from the surface to the atmosphere despite the long radiative time constant of the atmosphere itself. Radiative flux measurements by the Cassini–Huygens mission confirm the analysis of McKay et al. (1989) and suggest that the solar heating rate at the Huygens site is significantly larger than the thermal cooling rate throughout the troposphere (Tomasko et al. 2008). Since this excess heat must be redistributed to other latitudes there is little doubt that a Hadley circulation must exist in Titan’s troposphere.

A more comprehensive picture of the possible circulation patterns of Titan’s troposphere became available with the advent of three-dimensional GCMs specifically devoted to Titan. The first Titan GCM with a detailed radiation model (McKay et al. 1989) was developed by Hourdin et al. (1995). In agreement with the theoretical expectation mentioned above, this GCM predicts the presence of a solstice-type Hadley cell during most of a Titan year, which quickly reverses after the equinox. This pattern is essentially common to the troposphere and stratosphere, but the tropospheric and stratospheric cells are loosely separated from each other. This basic pattern is also reproduced by those GCMs that use the same radiation model (Tokano et al. 1999; Richardson et al. 2007; Tokano 2007).

Given the presence of an Earth-like hydrology based on methane on Titan and the importance of the water cycle on the Earth’s climate, it is intuitive to expect a significant impact of methane hydrology on the general circulation of Titan’s troposphere because the solar drive is weak. GCMs, which include methane condensation (Tokano et al. 2001a; Mitchell et al. 2006; Rannou et al. 2006), have yielded conflicting interpretations as to the role of methane on the general circulation. Current sources of uncertainty in modelling include the necessary requirement for methane condensation under Titan’s condition, mechanism, location and timing of surface methane sources or mechanism of triggering moist convection. These unknowns are more critical than the radiative properties of methane cloud or rain particles.

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Tokano et al. (2001a) showed that the methane profile varies seasonally by condensation and meridional-vertical transport and that the meridional circulation pattern is sensitive to the methane profile since it affects the strength of the greenhouse effect and thus of the radiative heating rate. Nevertheless, the pole-to-pole extent of the Hadley cell outside the boundary layer was a common feature of the different model scenarios. A dramatic change in the meridional circulation pattern was predicted by Rannou et al. (2006), in which a tropospheric circulation model is coupled to a GCM, which also contains stratospheric photochemistry and a haze cycle. The appearance of clouds gives rise to a large equator-to-pole contrast of the near-surface temperature of 6 K, which is larger than in any other Titan GCM. A peculiar feature of this scenario is the coexistence of several meridional cells located side by side. Instead of a single pole-to-pole cell they found three oblique (tilted) cells on each hemisphere. This oblique cell structure is indicative of slantwise convective instability (moist symmetric instability), which arises from an imbalance among the pressure gradient and Coriolis and buoyancy forces in a baroclinic flow (Bennetts & Hoskins 1979). Mitchell et al. (2006) implemented a moist convection scheme in the GCM and found that moist convection confines the upwelling to a narrow region near the ITCZ, while all other regions experience slow downwelling. It is important to point out that both Mitchell et al. (2006) and Rannou et al. (2006) predicted optically thick clouds near the summer pole and sporadic clouds at mid-latitudes of the summer hemisphere, in agreement with the observations, but their predicted meridional circulations qualitatively differ from each other. The discrepancy may reflect differences in the treatment of dynamics, latent heat and radiative effects in the troposphere, all of which affect the latitudinal temperature profile.

A further forcing mechanism of atmospheric circulation was proposed by Tokano & Neubauer (2002). They proposed that the gravitational tide of Saturn on Titan caused by Titan’s elliptical orbit generates an eastward travelling planetary wave of wavenumber 2 superposed on the background circulation. The numerical simulation of Tokano & Neubauer (2002) predicts the periodical oscillation of the surface pressure by up to 1.5 hPa and of the zonal and meridional wind by an amplitude of up to a few m s\(^{-1}\). Given the generally small meridional wind speeds this means that the meridional wind reverses direction twice per Titan day.

Two-dimensional GCMs with parametrized barotropic waves (Luz et al. 2003; Rannou et al. 2004) predict strong wiggles near the equator within the Hadley circulation. They are visible down to the surface and have been interpreted as inertial instability caused by the strong winter jet or alternatively as an artefact of two-dimensional models (Luz et al. 2003).

Another possible mechanism to introduce longitudinal structure in the general circulation pattern in the troposphere is large-scale topography. Titan’s mountains have typical altitudes of a few hundred metres, with a maximum of approximately 2 km (Radebaugh et al. 2007), so they are modest by terrestrial standards. No global map of Titan’s surface topography is available yet, but numerical simulations by Tokano (2008) show that the Xanadu region can appreciably deflect the surface wind direction and modify the wind strength if one assumes large-scale topography there. He performed a sensitivity study by implementing a hypothetical bell-shaped mountain or basin of 1 km elevation at
Xanadu and found that a large mountain at Xanadu causes convergence, while a basin at the same place produces a divergent wind field and weakening of wind inside the basin. However, this simulation also shows that the zonal–mean zonal and meridional circulation barely changes by realistic topography. Figure 1 shows an example of the predicted surface wind, which includes the Hadley circulation, tidal wind and influence of topography.

Figure 1. Surface wind predicted by the GCM of Tokano (2008) under the assumption that the near-equatorial Xanadu area bounded by a contour is a 1000 m deep basin. (a) Instantaneous wind vector at the northern summer solstice, (b) diurnal mean wind vector in the same season and (c) annual mean wind vector. The instantaneous wind is multidirectional at high latitudes owing to Saturn’s gravitational tide. Diurnal averaging smoothes out much of the tidal wind, so the northward cross-equatorial wind of the Hadley circulation becomes evident. A hypothetical basin in Xanadu generates a divergent flow that persists even after annual averaging.

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(b) Zonal wind

By analogy with the super-rotating atmosphere of Venus, whose near-surface zonal wind is close to zero, the zonal wind in Titan’s troposphere has been assumed to be westerly down to the surface and to monotonically decrease towards zero near the surface (e.g. Flasar et al. 1997). Numerical models, however, so far have predicted an incredible diversity in the global pattern of the zonal wind. As a matter of fact, there is no consensus at all among the Titan GCMs concerning the mean direction, speed, spatial distribution and seasonal variability of the zonal wind in the troposphere. For instance, at the tropopause, some models predict almost zero wind, while others predict up to 40 m s$^{-1}$. Since many modellers focus on the development of the stratospheric super-rotation (or the lack thereof) in their own model, it is a difficult task to elucidate the mechanism that controls the zonal wind in the troposphere on the basis of the descriptions in the published literature only.

It is amazing that even the three most similar three-dimensional GCMs (Hourdin et al. 1995; Tokano et al. 1999; Richardson et al. 2007) predict completely different zonal wind speeds, while the Hadley circulation pattern in their models agree with each other. In these models, the treatment of large-scale hydrodynamics is essentially the same, the same radiation code (McKay et al. 1989) is used and haze and methane cycles are not treated. The reason for the large discrepancy is still unclear, yet subtle numerical differences in the hydrodynamical code, parametrization of subgrid-scale processes or computer accuracy might cause subtle differences that amplify after a long integration time.

The evolution of the zonal wind has to be analysed simultaneously with that of meridional circulation and temperature since they affect the angular momentum transport. There are basically two types of zonal wind profile predicted by the Titan GCMs. The most straightforward profile is a combination of either westerly (eastward) or easterly (westward) jets at mid-latitudes and the weak westerly or easterly equatorial wind (Tokano et al. 2001a; Grieger et al. 2004; Tokano & Neubauer 2005; Mitchell et al. 2006; Tokano 2007). Although the wind speed differs from model to model, this angular momentum-conserving wind profile can be readily understood as a result of poleward transport and accumulation of the angular momentum by the Hadley circulation, analogous to the low-latitude jet stream near the tropopause in the Earth’s atmosphere.

Another main type of zonal wind found in Titan GCMs is a monotonic increase of wind speeds with altitude and latitudinal uniformity, except in the boundary layer and in the polar region (Hourdin et al. 1995; Luz et al. 2003; Rannou et al. 2004; Richardson et al. 2007). This wind profile cannot be explained by the Hadley circulation alone since the angular momentum must not attain maximum at the equator in axisymmetric circulation (Hide 1969). As with the stratospheric super-rotation, up-gradient transport of angular momentum by barotropic eddies would be necessary to achieve such a latitudinal wind profile. However, barotropic instability is predicted to occur only in the upper stratosphere (Luz et al. 2003), so the question arises as to whether barotropic eddies could indeed be responsible for eastward zonal wind in the equatorial troposphere. Hourdin et al. (1995) pointed out that in their GCM equilibrium is reached when the upward transport of angular momentum by the Hadley circulation and downward transport of the same by the parametrized vertical turbulent mixing
are balanced. Furthermore, a comparison of different GCMs shows that the eastward zonal wind speed in the troposphere and stratosphere are positively correlated. This suggests that eastward equatorial wind in the troposphere may be a secondary result of downward diffusion of angular momentum from the super-rotating stratosphere. Similarly, the weakness of equatorial winds in some two- and three-dimensional GCMs may not be primarily a result of weak or absent barotropic eddies in the troposphere, but simply of too weak a stratospheric wind. Thus, wind predictions in GCMs may illustrate a chicken or egg problem, in that it is not very clear whether westerly tropospheric wind provides the angular momentum of the stratospheric super-rotation or vice versa.

Mingalev et al. (2006) presented the only non-hydrostatic three-dimensional GCM for Titan’s atmosphere so far, but in their model the temperature profile is prescribed and stationary rather than predicted. Therefore, the predicted wind merely represents the thermal wind in balance with the imposed temperature profile, which in the troposphere is barely constrained by observations, so it is not possible to interpret the results in terms of Hadley circulation or eddies. An important qualitative difference between the models can be discerned near the surface. Seasonal reversal in the wind direction is predicted by all those models in which the surface temperature varies with season (Hourdin et al. 1995; Tokano & Neubauer 2005; Richardson et al. 2007; Tokano 2007, 2008). In all other GCMs the zonal wind is nearly symmetric about the equator as with the near-surface temperature profile. The seasonal reversal of the zonal wind can be explained by the thermal wind balance under geostrophic conditions if the latitudinal temperature gradient changes sign across the equator (Tokano 2007), and is analogous to the seasonal reversal of the stratospheric zonal wind in the Earth’s atmosphere.

3. Observational data and their interpretation

(a) Cloud tracking

Detection of tropospheric clouds (Griffith et al. 1998; Brown et al. 2002) opened up the possibility of determining the wind profile by tracking cloud motions, which is a common method in planetary meteorology. During the early years of cloud detection, most clouds were found near the South Pole and were either motionless or moving eastward with at most a few m s$^{-1}$ (Bouchez & Brown 2005; Hirtzig et al. 2006; Schaller et al. 2006). Later, clouds were also detected at mid-southern latitudes, and many of them were elongated to several hundred to several thousand kilometres in the longitudinal direction, suggesting that the prevailing wind deforming these clouds is also zonally oriented, with a few exceptions (Roe et al. 2005). Systematic dependence of the wind speed on longitude or solar local time is not evident in the published data.

In addition to ground-based telescopes, two imaging instruments on board the Cassini spacecraft are suited for tracking cloud motion during Titan flybys. These are the imaging science subsystem (Porco et al. 2004) and the visual and infrared mapping spectrometer (VIMS; Brown et al. 2004). The majority of convective clouds near the South Pole were either motionless or slowly moving eastward at less than 10 m s$^{-1}$ (Porco et al. 2005; Brown et al. 2006), in agreement with the ground-based observations. However, there were also a few
distinct clouds that seemed to have performed a rapid eastward motion, with an exceptional eastward drift speed of $34 \pm 13 \text{ m s}^{-1}$ at $48^\circ \text{S}$. VIMS also enables the observation of the development of convective clouds by limb viewing. On 13 December 2004, VIMS observed the evolution of clouds residing between $41^\circ \text{S}$ and $61^\circ \text{S}$ (Griffith et al. 2005). The sequence of cloud images indicated vigorous updraughts of up to $10 \text{ m s}^{-1}$ in these clouds, as predicted by Hueso & Sánchez-Lavega (2006) or Barth & Rafkin (2007). After an initial vertical development, these clouds typically grew horizontally. The background wind speed was estimated as approximately $14 \text{ m s}^{-1}$ near the cloud top altitude (42 km). These observations also constrained the cloud altitudes essentially to between 20 and 42 km (Griffith et al. 2005).

These cloud tracking data give the impression that the prevailing wind in the troposphere is eastward. However, some caution is necessary in the interpretation of the cloud tracking data. First, optically thick, well-structured clouds suitable for cloud tracking are not ubiquitous in Titan’s troposphere. Second, the cloud altitude is not precisely known, so it is not viable to derive a latitudinal profile of zonal wind speed at a certain altitude from the cloud tracking data alone because they may have been acquired at different altitudes. While we have fairly good overall statistics for the zonal wind in the mid-troposphere of the summer hemisphere, the wind data are scarce or absent in the lower few kilometres and in the winter hemisphere. Therefore, we have to keep in mind that the cloud drift data provide incomplete wind statistics and probably overlook near-surface easterlies predicted by some GCMs. It is also unclear whether the apparent latitudinal wind profile reconstructed from the cloud drift data is angular momentum conserving or exhibits uniform angular velocity or absolute velocity.

(b) Wind profile measured by Huygens

The first in situ vertical profile of the wind in Titan’s troposphere was acquired by three instruments onboard the Huygens probe, which landed at $10^\circ \text{S}, 168^\circ \text{E}$ in January 2005. The wind profile measured by the Doppler wind experiment (DWE) in the troposphere (Bird et al. 2005; Folkner et al. 2006) is slightly westerly from the surface up to approximately 1 km, turns to easterly between 1 and 5 km and returns to zero by 5 km. The wind profile between 5 and 13 km is unknown, but is likely to be westerly and to increase to $3 \text{ m s}^{-1}$ at 13 km, above which the wind speed smoothly increases with altitude up to $20 \text{ m s}^{-1}$ (figure 2). The horizontal probe motion tracked by the descent imager/spectral radiometer is consistent with the zonal wind profile of DWE (Tomasko et al. 2005; Karkoschka et al. 2007). The surface wind was constrained to much less than $0.2 \text{ m s}^{-1}$ on the basis of the cooling behaviour of the Huygens probe after the landing (Lorenz 2006) as well as the thermal profile in the planetary boundary layer (PBL; Tokano et al. 2006b).

The three-dimensional descent trajectory reconstructed by the Descent Trajectory Working Group (Kazeminejad et al. 2007) can be used to derive the vertical profile of the meridional wind (figure 2b). According to Huygens, there is a northerly wind (approx. $0.3 \text{ m s}^{-1}$) in the lowest 500 m and a weak southerly wind between approximately 1 and 5 km. The meridional flow is less than $0.1 \text{ m s}^{-1}$ between 5 and 15 km, but there is another northerly flow of up to $0.8 \text{ m s}^{-1}$ between 15 km and the tropopause.
The vertical wind along the descent path of Huygens was retrieved from the in situ pressure profile measured by the Huygens atmospheric structure instrument (HASI; Mäkinen et al. 2006). Weak upwelling (approx. 0.05 m s\(^{-1}\)) was found throughout the troposphere, with some small superposed wiggles. In addition to this, the frequency content and statistical kurtosis of the tilt data of the Huygens probe during the descent in an altitude range of 20–30 km indicate excitation by turbulent air motions characteristic of freezing clouds (Lorenz et al. 2007). This corresponds to the altitude range in which evidence of a cloud layer made of solid methane is found in the humidity data measured by Huygens (Tokano et al. 2006a). Turbulence reduces towards the surface, and precise temperature and pressure measurements by HASI reveal the presence of only a weakly convective PBL in the lowest 300 m (Tokano et al. 2006b). The derived eddy diffusion coefficient is less than 10\(^{-2}\) m\(^2\) s\(^{-1}\), indicative of quite weak turbulence by terrestrial standards.

(c) Interpretation of the Huygens wind data

Although the Huygens data were acquired at a single site and time, they represent an important observational constraint on models and help to understand the mechanism behind this three-dimensional wind structure. The observed zonal wind in the troposphere is generally weaker than the Huygens...
engineering wind model (Flasar et al. 1997), but lies well within the large range of possible wind speeds predicted by various GCMs. While the super-rotating winds in the stratosphere are in approximate cyclostrophic wind balance, the slow wind in the lower troposphere satisfies the geostrophic wind balance (Tokano 2007). This is unlike other terrestrial planets in which the global-scale wind balance in the free atmosphere is either only geostrophic (Earth and Mars) or only cyclostrophic (Venus). Under geostrophy, the thermal wind relation couples the zonal wind direction and the sign of the latitudinal temperature gradient near the surface. The presence of easterlies at the Huygens site (10°S) can be explained by the thermal wind assuming that the near-surface temperature at the Huygens site increased from the equator towards the south (Tokano 2007). This confirms the zonal wind and near-surface temperature predictions in the lower troposphere by Hourdin et al. (1995), Tokano & Neubauer (2005), Richardson et al. (2007) and Tokano (2007). The twice wind reversals are not consistent with an Ekman spiral resulting from the variation with altitude of the zonal and meridional Coriolis force within the PBL (Tokano 2007). An intercomparison of model predictions with each other and with the Huygens data yields that, in the mid- and upper troposphere, the prediction by Hourdin et al. (1995), the oldest Titan GCM, comes closest to the observation. Models that are coupled to the haze cycle and photochemistry predict zonal wind speeds in the troposphere that are too fast.

The meridional wind speed of approximately 0.5 m s\(^{-1}\) measured by Huygens can be understood in terms of the Hadley circulation. The northerly wind near the surface and the southerly wind between 1 and 15 km are consistent with a cross-equatorial, asymmetric Hadley cell with ascending motion in the Southern Hemisphere (Tokano 2007). The enhanced meridional flow near the surface is a result of the horizontal pressure gradient between the winter and summer hemisphere. Since the Coriolis force is weak on Titan, particularly near the equator, the near-surface wind blows almost straight from high to low pressures, perpendicularly to the isobars that (on average) are aligned parallel to the latitudinal belts. With increasing distance from the surface the effect of sensible heat flux on the temperature diminishes and concomitantly the latitudinal temperature gradient, which translates into a smaller pressure gradient force and weaker meridional wind. On the other hand, the observed vertical profile of meridional wind rules out symmetric Hadley cells near the surface predicted by some GCMs. Models that include methane condensation generally predict a larger deviation of the meridional circulation pattern from the observed one.

These results give the impression that a supposed improvement of the GCM rather deteriorates the modelled tropospheric dynamics. This may indicate that either the haze and methane cycles in the troposphere are not satisfactorily understood or they are not relevant for the tropospheric circulation. The inclusion of gravitational tide has comparatively little impact on the mean circulation of the troposphere (Tokano 2007).

The persistence of upward vertical wind throughout the troposphere, except for small wiggles (Mäkinen et al. 2006), implies that the tropospheric cell mainly consists of a large Hadley cell with upwelling in the summer hemisphere and downwelling in the winter hemisphere (figure 3). This Hadley cell, however, may be disrupted in the mid-troposphere by cloud turbulence. Cloud turbulence may be a result of latent heat release as predicted by some GCMs and cloud
models. Additionally, occasional moist convection (Awal & Lunine 1994; Tokano et al. 2001b; Hueso & Sánchez-Lavega 2006; Barth & Rafkin 2007) with updraughts of up to 20 m s$^{-1}$ would also severely distort the mean meridional circulation, but may be a rather rare event. Since data from other latitudes are lacking, it is not possible to verify whether the cross-equatorial Hadley cell extends all the way to the poles or only up to mid-latitudes. However, it is clear from the data that the core of the Hadley cell must have been located at least north of the Huygens site ($10^8$S), which does not preclude that it may also have been located right at the equator.

Within the lower Hadley cell the zonal wind direction may be westerly in winter and easterly in summer quite similar to the Earth’s stratosphere, but there is considerable uncertainty at high latitudes (figure 3). In the upper Hadley cell the zonal wind direction is likely to be westerly at all latitudes, since the observed wind speed in this altitude region approaches a cyclostrophic balance, under which there is no tight relationship any more between the latitudinal temperature profile and zonal wind direction.

(d) Surface wind pattern evidenced by aeolian features

Information on the global surface wind pattern can be obtained from the type and orientation of the sand dunes observed by the Cassini radar at low latitudes on Titan (Lorenz et al. 2006). The vast majority of dunes are found to be longitudinal (linear) and oriented in the west–east direction, although there is substantial deflection in the vicinity of Xanadu, for instance. Longitudinal dunes require the presence of two major wind directions oblique to the dune orientation. GCM modelling (Tokano 2008) shows that such a bimodal wind pattern can naturally arise by the seasonal reversal of the Hadley circulation, further verifying the asymmetric solstice-type Hadley cell on Titan, which exists for many years.

The (near) equatorial surface westerlies evidenced by the dune orientation (Lorenz et al. 2006) are harder to understand than the presence of dunes on Titan. Despite the obvious large discrepancies among models, no existing Titan
GCM predicts persistent westerlies right at the equatorial surface. Angular momentum conservation indeed hampers the formation of westerlies there and global coverage of surface westerlies would certainly act to decelerate the overall super-rotation of the atmosphere. It is interesting to note that an analytic solution of the axisymmetric Hadley circulation under asymmetric heating profile and in the nearly inviscid limit yields equatorial westerlies (Lindzen & Hou 1988). This bias regularly disappears in numerical models by virtue of viscosity. This might imply that the tiny turbulence in Titan’s convective PBL (Tokano et al. 2006b) is somehow conducive to the formation of equatorial surface westerlies.

(e) Influence of the atmospheric circulation on Titan’s rotation rate

An important side effect of Titan’s atmospheric circulation is the torque exerted by the wind on the surface. Besides the aeolian features, such as dunes mentioned in §3d, the surface wind affects Titan’s surface by transferring angular momentum between the atmosphere and surface. Calculations by Tokano & Neubauer (2005) show that some $3 \times 10^{25}$ kg m$^2$ s$^{-1}$ relative angular momentum could be exchanged from the surface to the atmosphere and vice versa during one Titan year, and this exchange is caused by the seasonal reversal of the Hadley circulation. The surface exchange periodically accelerates and decelerates Titan’s rotation, so Titan’s length of day is predicted to vary by approximately 30 s during one Titan year if Titan’s interior is entirely rigid, and by approximately 400 s if there is an internal water ocean underneath the ice shell and if there is no internal gravitational coupling between the two solid layers. This length-of-day variation would then be four to five orders of magnitude larger than the Earth experiences.

Geodetic observations of Titan by the Cassini radar show first evidence of a variable rotational state of Titan (Lorenz et al. 2008). The deviation of the observed rotation period from synchronous spin of Titan was found to be consistent with the predictions by Tokano & Neubauer (2005), and may be interpreted as indirect evidence of seasonal exchange of angular momentum between the atmosphere and surface as well as of seasonal reversal of zonal winds near the surface.

4. Conclusions

Titan’s troposphere may be regarded as a unique laboratory of dynamic meteorology characterized by a slow planetary rotation, weak sunlight, influence of a hydrological cycle based on molecules other than water and vicinity to the giant planet Saturn. The dynamic regime in the troposphere is markedly different from that in the stratosphere. The observations by Huygens seem to indicate that the vertical structure of the general circulation is more complex than the horizontal structure. The general circulation pattern in the lower troposphere can be characterized by a cross-equatorial Hadley circulation, a pair of westerlies and easterlies and geostrophic wind balance, but could be disturbed by the methane hydrological cycle. Particularly, several lines of evidence based on the Huygens and Cassini data support the presence of a cross-equatorial, asymmetric Hadley cell near the surface. This can be best
understood by the thermal wind in balance with a warm summer hemisphere and a cold winter hemisphere. Even small seasonal temperature variations of at most a few K are predicted to change zonal and meridional wind direction and affect Titan's rotation rate and length of day with an amplitude much in excess of terrestrial counterparts.

The upper troposphere represents a transition zone between the geostrophic and cyclostrophic zone, and the wind profile is affected both by the weak winds in the troposphere and by the super-rotating stratosphere. GCMs, which are coupled to the tropospheric methane cycle so far, do not reproduce well the wind profile in the lower troposphere in comparison with simpler GCMs, probably indicating that either the methane cycle is not important for the tropospheric global dynamics or it is not yet satisfactorily understood. Similarly, while the inclusion of the haze cycle generally improves agreement of temperature and general circulation with the observational data in the stratosphere, it simultaneously tends to deteriorate the agreement of the predicted tropospheric dynamics with the few available data, and models without the haze cycle seem to do a better job in the troposphere. The equatorial surface westerlies represent another challenge in our understanding of Titan's atmospheric general circulation.

The scarcity of data from the troposphere in comparison with the stratosphere is the most serious obstacle in the understanding of the tropospheric dynamics as well as its modelling. Future observations including in situ measurements that last longer than the Huygens mission are highly desirable.

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