The structure and dynamics of Titan’s middle atmosphere

By F. M. Flasar¹,* and R. K. Achterberg²

¹NASA Goddard Space Flight Center, Code 693, Greenbelt, MD 20771, USA
²Department of Astronomy, University of Maryland, College Park, MD 20742, USA

Titan’s middle atmosphere is characterized by cyclostrophic winds and strong seasonal modulation. Cassini CIRS observations, obtained in northern winter, indicate that the stratosphere near 1 mbar is warmest at low latitudes, with the South Pole a few degrees colder and the North Pole approximately 20 K colder. Associated with the cold northern temperatures are strong circumpolar winds with speeds as high as 190 m s⁻¹. Within this vortex, the mixing ratios of several organic gases are enhanced relative to those at low latitudes. Comparison with Voyager thermal infrared measurements, obtained 25 years ago in northern spring, suggests that the enhancement currently observed will increase as the winter progresses. The stratopause height increases from 0.1 mbar near the equator to 0.01 mbar near the North Pole, where it is the warmest part of the atmosphere, greater than 200 K. This implies subsidence at the pole, which is consistent with the enhanced organics observed. Condensate features, several still not identified, are also apparent in the infrared spectra at high northern latitudes. In many ways, the winter vortex observed on Titan, with cyclostrophic winds, resembles the polar winter vortices on the Earth, where the mean winds are geostrophic.

Keywords: Titan; middle atmosphere; dynamics; temperatures

1. Introduction

Planetary atmospheres are nonlinear dynamical systems that defy simple explanation or prediction. Little wonder that the student of extraterrestrial atmospheres has traditionally drawn on the much more extensive body of observations and theory that has been developed for the Earth, in order to make some headway in understanding these other worlds. Even here, one is continually aware of the importance of comparing the behaviour of different atmospheres. These are the large-scale natural laboratories available to the researcher, and the hope and expectation are that trying to make sense of the dynamical response of

* Author for correspondence (f.m.flasar@nasa.gov).

One contribution of 14 to a Discussion Meeting Issue ‘Progress in understanding Titan’s atmosphere and space environment’.
an atmosphere to differing ‘external’ factors (e.g. solar forcing, heat flux from the planetary interior, rotation rate of the solid surface) can provide a deeper conceptual insight into the behaviour of all these atmospheres, including the Earth’s.

One of the most intriguing atmospheres belongs to Saturn’s giant moon, Titan. Its base pressure is approximately 50 per cent larger than the Earth’s, but its temperatures are much lower. N₂ is its main constituent, but CH₄, not O₂, is the next most abundant species. The photo- and electron-impact dissociation of N₂ and CH₄ leads to the irreversible production of higher order organic molecules, hydrocarbons and nitriles, which either condense and slowly precipitate or form the more complex photochemical smog than enshrouds Titan. Unlike the Earth, Titan is a slow rotator, its day to a high approximation being equal to its orbital period about Saturn, 15.95 days. In this sense, it is more similar to Venus, and the characteristic winds in its stratosphere, even at low and mid-latitudes, are much larger than the equatorial rotation speed of its surface (table 1). The global wind systems on Titan and Venus are therefore cyclostrophic, and have a specific angular momentum (angular momentum per unit mass) that exceeds that of the underlying solid bodies. This is in contrast to the Earth, where the specific angular momentum of the atmosphere is dominated by the component associated with the rotation of the Earth itself. How slowly rotating planets produce atmospheres with such large angular momentum excesses remains puzzling. Titan and Venus have one key difference that may help: Venus’s rotation axis is nearly perpendicular to its orbit about the Sun, and there is little seasonal modulation of its circulation. Temporal changes in the zonal-mean circulation are driven by internal dynamical processes. Titan’s seasonal behaviour, however, is dictated by Saturn’s obliquity, 27°, comparable to the Earth’s (23°). Its radiative time scales are short enough that its stratospheric winds experience a strong seasonal variation. Observing the way Titan’s stratospheric winds and temperatures change over a full annual cycle (29.5 years) may go a long way towards deciphering how cyclostrophic systems work.

This paper reviews the dynamic meteorology of Titan’s middle atmosphere, i.e. of its stratosphere and mesosphere (figure 1), in the light of the Cassini–Huygens data acquired in the last 3 years. The plan of the paper is as follows: §2 discusses the temperature and zonal wind fields in Titan’s middle atmosphere. The available data imply the existence of a strong circumpolar vortex during winter and early spring. The meridional circulation is inferred more indirectly, and §3 discusses how the temperature field and the spatial distribution of minor gaseous species provide markers for this motion, much as they do in the Earth’s atmosphere. Section 4 discusses the spatial distribution of condensates that have been inferred from infrared spectra of the winter polar region. Section 5 briefly discusses the use of general circulation models (GCMs).

Table 1. Geostrophic and cyclostrophic systems.

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<th></th>
<th>Earth</th>
<th>Venus</th>
<th>Titan</th>
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<td>mean zonal wind (m s⁻¹)</td>
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to simulate Titan’s zonal winds and the distribution of hazes and organic gases. Finally, §6 concludes with a discussion of the remarkably analogous behaviour that seems to exist between the winter polar vortices on Titan and those on the Earth. An earlier review of the dynamics of Titan’s middle atmosphere, written prior to Cassini–Huygens data acquisition, can be found in Flasar (1998a,b).

2. Temperatures and zonal winds

Spatially resolved mapping of Titan’s atmosphere really began with the Voyager flyby observations in late 1980, a few months after Titan’s northern spring equinox. Two instruments retrieved temperatures in the middle and lower atmospheres. The first was the radio occultation experiment, which detected refraction of monochromatic radio waves transmitted from the spacecraft.
through the atmosphere to a Deep Space Network station on the Earth. The Doppler shift in the frequency of the received signal and knowledge of the relative positions and motions of the Earth, the spacecraft and the occulting atmosphere (Titan’s) allows one to determine the refraction bending angle as a function of altitude in the atmosphere, and invert this to obtain profiles of pressure and temperature (Lindal et al. 1983). The second was IRIS, a Fourier transform spectrometer in the thermal infrared. It was primarily able to map atmospheric temperatures in the stratosphere near 1 mbar (note: 1 mbar=100 Pa), using the emission in the ν4-band of CH4 near 1300 cm$^{-1}$ (7.7 μm) as a thermometer (Flasar et al. 1981). (Brightness temperatures near 200 cm$^{-1}$ were also used to infer the small meridional variation at the tropopause level (approx. 100 mbar) and near 530 cm$^{-1}$, where the atmosphere is relatively transparent, to infer variations in surface temperature.) With Cassini–Huygens, the orbiter-based CIRS is the thermal infrared descendent of IRIS (Flasar et al. 2004), and there is also a three-frequency radio occultation experiment (Kliore et al. 2004). In addition, the Huygens probe had an atmospheric structure experiment (HASI), which obtained temperature and pressure soundings (approx. 10° S) during the descent phase (altitudes less than 170 km); use of deceleration data enabled one to extend these profiles to higher altitudes (Fulchignoni et al. 2005).

The vertical structure of Titan’s atmospheric temperature, at least at low latitudes, is remarkably similar to the Earth’s. It was known from the Voyager radio occultations that there is a well-defined troposphere and stratosphere (figure 1). Both CIRS and HASI also detected the maximum in temperature defining the top of the stratosphere (the stratopause) and the mesosphere, where temperature decreases with altitude, at higher levels. Titan’s temperatures are lower than the Earth’s—e.g. a surface temperature near 94 K instead of 280 K—and the pressure scale height in the lower and middle atmosphere is much larger—15–50 km compared with 5–8 km on the Earth—primarily owing to Titan’s much smaller gravitational acceleration.

The CIRS and HASI profiles exhibit some notable differences, despite being close in latitude. Near 1 mbar, the HASI temperature profile is approximately 10 K warmer than the CIRS profile. The stratopause is approximately 250 km in the HASI profile, but 60 km higher in the one from CIRS. Furthermore, the CIRS temperatures are approximately 2 K warmer at the tropopause, where the temperature profiles have a minimum. The latter could result from errors in the ab initio calculations of pressure-induced absorption by N$_2$–N$_2$ and N$_2$–CH$_4$ pairs (Borysow & Frommhold 1986; Borysow & Tang 1993) used in the CIRS retrievals, as well as the possible unknown contribution of hazes to the far-infrared opacity, which was not accounted for in the profile shown. However, the spectroscopic parameters of the ν4-band of CH4 are well established, and it is unlikely that this is a major source of error for the temperatures near 1 mbar. Synthetic spectra based on the HASI temperature profile yield radiances in the ν4-band that are much too large (Constenis et al. 2005; Ferri et al. 2006). CIRS nadir mapping (see below) indicates that zonal and meridional variations in temperature near 1 mbar are much smaller than the HASI–CIRS difference. The cause of the discrepancy is not understood.

The horizontal coverage and resolution of temperatures by the Voyager experiments was limited. Both the two soundings associated with the single radio occultation were in the equatorial region. IRIS did obtain fairly good latitude
coverage, but the spectra had to be averaged in large latitude bins (often 15° or greater; e.g. Flasar et al. 1981). Moreover, coverage in longitude was limited to the strips on the day and night sides, nearly 180° apart. Cassini observations have changed this, primarily from CIRS observations in the mid-infrared (analysis of the radio occultation data has not yet been completed). Figure 2a depicts the temperature cross section in the middle atmosphere from CIRS limb- and nadir-viewing observations. The region of validity of the retrievals extends from approximately 5 mbar to 3 mbar, except at high northern latitudes, where the temperatures at the 1 mbar level become quite cold. At these latitudes, the deep pressure limit is closer to 2 mbar. The relatively cold temperatures near 1 mbar are consistent with the long polar night. What is initially surprising is that the temperatures at the stratopause in the North Polar region are the warmest in the atmosphere, greater than 200 K. Furthermore, the height of the stratopause varies markedly with latitude. Near the North Pole, it is near the 10 mbar level, but decreases equatorward to the approximately 70 mbar level (figure 1).

The zonal winds are coupled to the temperatures in figure 1a by the (diagnostic) thermal wind equation,

\[ \frac{\partial}{\partial z_{||}} \left( 2\Omega u + \frac{u^2}{r \cos A} \right) = - \frac{g}{T} \frac{1}{r} \left( \frac{\partial T}{\partial A} \right)_p, \tag{2.1} \]

where \( \Omega \) is the rotation rate of Titan; \( A \) is the latitude; \( g \) is the gravitational acceleration; \( p \) is the pressure; \( T \) is the temperature; and \( z_{||} \) is a coordinate perpendicular to the equatorial plane. The ‘vertical’ derivative must be taken along cylinders parallel to the rotation axis because the vertical scale of Titan’s atmosphere (figure 1) is not small compared with its 2575 km radius (e.g. Flasar et al. 2005). (With thin atmospheres, one can recover the more familiar case in which one can use a vertical derivative \( \partial/\partial z \) with the substitution \( dz = dz_{||} \sin A_0 \), where \( A_0 \) remains constant over the vertical integration.) Figure 2b depicts the winds from (2.1), assuming that the winds at 10 mbar correspond to four times the surface rotation rate as a lower boundary condition. The large gradient in temperatures at the levels of the cold North Pole implies strong circumpolar winds, up to 190 m s\(^{-1}\). The vortex is quite broad, with the winds being strongest between 30° and 55° N, centred approximately at 0.1–0.2 mbar. In the Southern Hemisphere, the winds are much slower, consistent with the weaker meridional temperature gradients there.

Some comments are in order. (i) The integration of (2.1) along the cylinders follows quasi-parabolic curves, such as those depicted in figure 2b. With the bottom boundary condition, winds can be calculated at any pressure and latitude that lies on a curve intersecting the 10 mbar level. The middle curve depicted, which is tangent to the 10 mbar level, is the equatorial boundary within which we cannot use (2.1) with the specified boundary condition. In figure 2, winds within the equatorial region were linearly interpolated along the isobars. (ii) Although the bottom boundary condition is arbitrary, it is consistent with the winds derived from the Doppler tracking of the Huygens probe descent (Bird et al. 2005; Folkner et al. 2006). However, in most of the Northern Hemisphere, the winds are fairly insensitive to the boundary condition at 10 mbar, and the existence of the strong vortex surrounding the winter pole and its approximate strength remain valid. This is because the zonal winds increase markedly with
altitude, and the $u^2$ term in (2.1) dominates the left-hand side. At mid- and high latitudes in the Southern Hemisphere, the winds are much weaker, and they are more sensitive to the bottom boundary condition.

The temperatures and zonal winds vary seasonally. The radiative relaxation time in the upper stratosphere is much shorter than the seasonal cycle, approximately 1 (terrestrial) year at 1 mbar (Flasar et al. 1981), except in the colder regions near the winter pole. In addition to the Voyager IRIS and Cassini CIRS temperature data, the central flashes observed at the Earth during occultations of stars by Titan have provided information on the shape of the isopycnal (i.e. constant density) surfaces near the 0.25 mbar level (Hubbard et al. 1993; Bouchez 2003; Sicardy et al. 2006). Without too large an error, one can

Figure 2. (a) Meridional cross section of temperature (K) from CIRS limb and nadir spectra in the mid-infrared. (b) Zonal winds (m s$^{-1}$) computed from the thermal wind equation (2.1) with the winds at 10 mbar fixed at four times Titan’s rotation rate. The parabolic curves correspond to surfaces parallel to Titan’s rotation axis. Adapted from Achterberg et al. (2008).
take these surfaces to be isobars (see Hubbard et al. 1993) and apply the gradient wind equation that relates the zonal winds themselves to the meridional gradient in the height of isobaric surfaces (e.g. Andrews et al. 1987). (The thermal wind equation (2.1) is derived by combining the gradient wind balance with the barometric law.) Comparison of the zonal winds inferred from the temperature and stellar occultation datasets indicates a seasonal variation with the strongest winds in the winter hemisphere, which decay as the summer approaches.

3. Meridional motions

The zonal-mean meridional circulation transports angular momentum, heat and constituents. Although eddy transports can be important, use of the transformed Eulerian-mean velocities incorporates many of the eddy fluxes into the mean circulation when motions are quasi-adiabatic and steady (Andrews et al. 1987). In the Earth’s middle atmosphere, the transformed Eulerian-mean circulation is equivalent to the Lagrangian circulation—which follows the motions of conserved quantities—to a good approximation (Dunkerton 1978).

One of the most striking features in figure 2 is the warm stratopause at the North Pole. It is possible that this may partially have a radiative origin. The altitude at 10 μbar, approximately 400 km, is above the height (307 km) at which Titan’s surface blocks the Sun at winter solstice, and there are thick condensate hazes over the winter pole. The properties of these hazes are not well determined, and a detailed estimate of solar heating has not been made. However, the adiabatic heating from subsidence could also contribute to the warm stratopause. The lowest order balance in the heat equation (Flasar et al. 1981; Achterberg et al. 2008) is between this heating and radiative relaxation,

\[ w \left( \frac{\partial T}{\partial z} + \frac{g}{C_p} \right) = - \frac{T - T_{eq}}{\tau_r}. \tag{3.1} \]

In (3.1) \( w \) is the transformed Eulerian-mean vertical velocity; \( T \) is the temperature; \( C_p \) is the specific heat; \( T_{eq} \) is the radiative equilibrium temperature; and \( \tau_r \) is the radiative relaxation time; temperatures and velocity are zonal averages. A rough estimate of \( T - T_{eq} \approx 25 \) K at 10 μbar can be reasonably estimated from the contrast between the North Pole and lower latitudes. At a given temperature, the relaxation time \( \tau_r \) should fall off slowly with altitude, because the decrease in mass per scale height with altitude is to some degree offset by the reduced emissivity of CH₄, C₂H₂ and C₂H₆, the principal infrared gaseous coolants (Flasar et al. 1981). Using the earlier estimate of \( 3 \times 10^7 \) s (at 170 K) yields \( w \sim -1 \) mm s⁻¹ (Achterberg et al. 2008). At 200 K \( \tau_r \) is somewhat smaller, implying a larger \( |w| \).

The meridional distribution of organic gases provides further evidence of subsidence at high northern latitudes. Figure 3 depicts the variation of several organic molecules, retrieved from Cassini and Voyager thermal infrared spectra (Coustenis & Bézard 1995; Teanby et al. 2005; Coustenis et al. 2007). All the nitriles (HCN, HC₃N and C₂N₂) and several hydrocarbons (C₃H₄, C₄H₂, C₆H₆, C₂H₄ in the spring) exhibit enhanced concentrations at high northern latitudes. Most of the formation of these species, following the breakup of N₂ and CH₄, occurs higher up in
the atmosphere. One expects the concentration to increase with altitude, towards the source region. Limb sounding at mid-infrared wavelengths with Cassini CIRS (figure 4; Teanby et al. 2007; Vinatier et al. 2007) indicates that this typically is the case. Subsidence at high northern latitudes could naturally lead to an enhanced concentration of these species at the 1–10 mbar level. Polar enhancement of the more abundant organics, e.g. C$_2$H$_6$ and C$_2$H$_2$, is less, because the vertical gradients of their concentration are smaller (figure 4).

Comparison of Titan’s meridional distribution of organic molecules in winter (Cassini) with spring (Voyager) (figure 3) indicates that the enhancements increase from winter into early spring, possibly the result of a persistent subsidence over the poles. Simulations of Titan’s general circulation (e.g. Hourdin et al. 2004) also predict subsidence over the winter pole into spring.

4. Winter condensates

Titan’s poles have an extended layer of haze and probably condensates during their respective winter seasons into early spring (e.g. Smith et al. 1981, 1982; Lorenz et al. 2001; Porco et al. 2005). Recently, Cassini near-infrared

Figure 3. Meridional profiles of organic gases and CO$_2$ from nadir-viewing observations in the mid-infrared in northern spring (Coustenis & Bézard 1995) and in northern winter (Coustenis et al. 2007). The spectral emission features used to retrieve the profiles typically have maxima in their contribution functions at a level of several mbar, with a spread of several scale heights. The values of C$_2$H$_6$ shown in the figure should be multiplied by 0.7, owing to a recently improved determination of its spectroscopic constants (Vander Auwera et al. 2007). (a) Cassini CIRS (2004–2005): northern winter and (b) Voyager IRIS (1980): early northern spring. Note that the abundances of HC$_3$N and C$_2$N$_2$ in (b) have been offset by a factor of 10 for clarity.
observations have detected a bright feature extending poleward of approximately 50°N (Griffith et al. 2006), which is consistent with the presence of a dense C$_2$H$_6$ cloud situated somewhere between 30 and 50 km altitude. Broad spectral features, believed to be indicative of condensates, have been seen in both Voyager IRIS and Cassini CIRS spectra at mid- and far-infrared wavelengths. They have been seen at high northern latitudes only in winter or early spring. Some of these ice features have been identified, at least tentatively (C$_4$N$_2$, HC$_3$N, HCN and C$_2$H$_2$), but others remain unknown (Samuelson et al. 1997, 2007; Coustenis et al. 1999; Khanna 2005b). Recently, a broad prominent feature centred at 221 cm$^{-1}$ (figure 5) has been the subject of close attention.

Figure 4. Vertical profiles of several organic gases at a (a(i)–(iii)) low (Tb (15°S)) and (b(i)–(iii)) North Polar latitude (T3 (80°N)), retrieved from CIRS mid-infrared limb spectra. Except for CH$_3$C$_2$H, solid portions of the curves correspond to levels where the spectra provide information. Adapted from Vinatier et al. (2007).
The feature was first seen in IRIS spectra, and laboratory work suggested that it was crystalline propionitrile (CH$_3$CH$_2$C≡N) ice (Khanna 2005), which has a strong torsion or bending mode centred at 225 cm$^{-1}$ (Dello Russo & Khanna 1996). Crystalline propionitrile has another strong spectral feature centred at 110 cm$^{-1}$, this one associated with resonant lattice vibrations. The long wavelength (low wavenumber) limit of IRIS was only 180 cm$^{-1}$, but CIRS extends down to 10 cm$^{-1}$. Synthetic limb spectra of Titan using the laboratory data predict a strong emission feature between approximately 80 and 150 cm$^{-1}$, while the CIRS spectra do not display this behaviour (de Kok et al. 2007; Samuelson et al. 2007). One issue is whether propionitrile on Titan is liquid or amorphous ice; in either case, the lattice mode would be suppressed. The CIRS limb spectra (figure 5) in the North Polar region are centred at approximately 125 km, where the average temperature is approximately 115 K. This is well below the freezing point of propionitrile, but high enough so that the amorphous ice changes to the crystalline phase in a relatively short time. Hence, the identity of the broad 221 cm$^{-1}$ feature that is so prominent remains elusive, and it may represent a mixture of several kinds of organic ice.

Although one cannot yet identify the condensate (call it ‘X’), the CIRS spectra allow one to map it fairly well. Figure 5 indicates that the feature is very prominent at 55° and poleward. But the boundary is quite abrupt. At 50° the feature has almost disappeared, and the spectra qualitatively look similar to those at low and at southern latitudes, where it is summer.

**Figure 5.** CIRS far-infrared limb spectra with the limb tangent point in the lower stratosphere (125–135 km) at several latitudes. The broad emission feature between 190 and 240 cm$^{-1}$ is probably associated with a condensate. The sharp features, e.g. CH$_4$, C$_4$H$_2$, C$_2$N$_2$, C$_3$H$_4$, are emissions from gases. Red curve, T$_4$ (85° N) 135 km; violet curve, T$_{10}$ (55° N) 125 km; blue curve, T$_{14}$ (50° N) 125 km; green curve, T$_{6}$ (55° S) 130 km.

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*Phil. Trans. R. Soc. A (2009)*
5. General circulation model studies

An important aspect of understanding Titan’s middle atmosphere has been the attempts of GCMs to simulate the observed variables. This has entailed (i) the establishment and maintenance of global super-rotation, in other words, excess angular momentum; and (ii) the seasonally varying distribution of organic molecules, aerosols and condensates. The history of terrestrial GCMs suggests that their predictive ability is limited, given the nonlinearity and complexity of the system they simulate. Much of their value lies rather in elucidating the physical mechanisms that play an important role in dynamical transports, which comes through an iterative comparison of the model predictions with observed atmospheric variables. This is particularly true for Titan, where constraining observations have been limited.

Many of the explanations of global super-rotation on Titan have entailed a mechanism proposed by Gierasch (1975; see also Rossow & Williams 1979) to account for Venus’s super-rotating atmosphere. In this model, the thermally direct Hadley circulation is a critical component for maintaining a super-rotating atmosphere. In the context of Venus, solar heating gives rise to ascent at low latitudes, where the specific axial angular momentum is large, owing to the large distance to the rotation axis. The air mass aloft moves poleward conserving angular momentum, spinning up and producing strong zonal jets at high latitudes. These are barotropically unstable and the eddies generated act to transport angular momentum back to the equator. This last step is necessary not only to produce steady flow (the Hadley circulation is removing angular momentum from the equator), but also to generate global super-rotation. There is a fundamental limitation—known as Hide’s theorem—on zonally symmetric circulations by themselves or with diffusion of specific angular momentum that is downgradient (Hide 1969; Held & Hou 1980). The maximum specific angular momentum achievable in these circumstances is that of the equatorial surface. The barotropic instabilities mentioned above transport angular momentum upgradient and avoid the restrictions of Hide’s theorem. Del Genio et al. (1993) used a terrestrial GCM stripped of seasonal and diurnal cycles, topography and hydrology, and applied to a 16-day rotator with the Earth’s radius and surface pressure. Varying the stratification in the troposphere with clouds that could reduce surface heating, they concluded that the Gierasch mechanism would work, provided the coupling of the surface to the atmosphere aloft was weak. Surface–atmosphere coupling is crucial for transferring angular momentum from the solid body to the atmosphere, but it cannot be too large: strong surface heating generates deep convection that acts to drag the atmosphere towards co-rotation with the surface. Inasmuch as only 10 per cent of globally averaged incident sunlight reaches Titan’s surface (McKay et al. 1989), the net heating aloft can plausibly stabilize the atmosphere and reduce the coupling to the surface.

Hourdin et al. (1995) adapted the terrestrial GCM at the Laboratoire de Météorologie Dynamique (LMD) to Titan conditions, including the use of a realistic radiative transfer code. Their simulations produced 100 ms$^{-1}$ zonal winds at low latitudes, and they attributed this to the Gierasch mechanism. Subsequent developments of the model incorporated hazes, clouds and organic gases: their distribution with altitude and latitude; their transport by meridional

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cirkulations; and their effects on the radiation field (e.g. Hourdin et al. 2004; Lebonnois et al. 2009). The models also included the microphysics of photochemical hazes. Owing to computational limitations, however, these detailed models are axisymmetric, i.e. two dimensional. The effects of mixing by barotropic and any other eddies are parametrized. The models indicate that, owing to the strong forcing driven by the seasonal variation of surface temperatures, the dominant meridional cell during most of the annual cycle is a cross-equatorial circulation that extends into the middle atmosphere with ascent at high latitudes in the summer hemisphere. A relatively small portion of Titan’s year is spent with ascent at low latitudes and sinking motion at high latitudes in both hemispheres. This is a little puzzling, because, if the Gierasch mechanism is maintaining the global super-rotation, it is only most effective over a small portion of Titan’s year.

Other three-dimensional GCMs have not succeeded in achieving zonal velocities as large as those in the LMD simulations. Simulations by Tokano et al. (1999) and Richardson et al. (2007) achieved equatorial winds of approximately 10–20 m s\(^{-1}\). The reason for the dispersion in results is not obvious.

Most of the comparisons of the observed distributions of hazes and organic gases have been with the LMD simulations. Using a two-dimensional circulation with eddy parametrization and a haze microphysical model, Rannou et al. (2002, 2004) were able to reproduce the winter polar hood and the detached haze layer at lower latitudes. The latter resulted from the combination of meridional transport, coagulation and sedimentation of the haze particles. The enhanced infrared cooling from the thicker haze at the winter pole increased the subsidence and adiabatic warming there.

Attempts to compare the LMD simulations with observations of organic gas distributions (Lebonnois et al. 2001, 2003; Hourdin et al. 2004; Crespin et al. 2008) have been partially successful. In part, this is a consequence of the very limited dataset available until recently—primarily Voyager IRIS observations in northern spring. The simulations appear to be more successful in reproducing the spatial distribution at low latitudes, which is more characteristic of the global average, than at the winter pole, although the enhancement of several species, resulting from subsidence there, is reproduced. However, the magnitude of the enhancements is not always in agreement. Discrepancies are greatest for higher order organics, e.g. C\(_4\)H\(_2\), CH\(_3\)C\(_2\)H. This may not be completely attributable to the dynamical modelling, as the photochemical pathways and rate constants have uncertainties.

6. Conclusion: winter polar vortices on the Earth and Titan

Winter polar vortices are not unique to the Earth. They have also been observed on Mars (e.g. Smith et al. 2001) and Titan. This is of interest, because the Earth and Mars are rapid rotators and their zonally averaged circulations are geostrophic. Titan, on the other hand, has a cyclostrophic zonal-mean circulation. The vortices on Titan and the Earth share several common characteristics (table 2). Both have cold winter poles in the stratosphere, owing to radiative cooling during the long polar night. The thermal wind equation implies that these cold cores are surrounded by strong circumpolar winds, i.e. the vortices. There is a decoupling of the polar atmosphere within the vortex from the atmosphere outside, evidenced by the sharp
contrast between various constituents within the vortex and those outside. This is better understood in the Earth’s atmosphere. Shuttle-based observations of both the winter Arctic and Antarctic circumpolar vortex regions on the Earth with the ATMOS infrared spectrometer have yielded vertical profiles of the concentrations of CH₄, N₂O and HF. Compared with the ‘ambient’ atmosphere outside the vortices, the stratospheric concentrations at 20–30 km are more typical of the ambient mesosphere at 50 km, and this has been interpreted as evidence of undiluted descent (Abrams et al. 1996a, b). The strong circumpolar vortex inhibits mixing by planetary waves across it (Schoeberl & Hartmann 1991). There is an inertia in the system (from Ertel’s theorem): any perturbation on an axisymmetric vortex about the pole will tend to induce waves that propagate around the pole, instead of across it. Only as spring progresses and the vortex weakens can wave perturbations induce nonlinear amplitudes that break up the vortex and mix low- and high-latitude air masses. Until that occurs, the only transport across the polar vortex is from the relatively weak mean meridional circulation with subsidence in the polar region.

Titan appears to differ from the Earth in at least two ways. First, the vortex on Titan is much broader, approximately 30–40°, extending down to subtropical latitudes during winter (figure 2). Second, the subsidence contributes to the heating of the winter stratopause itself and increases its altitude by almost two scale heights. On the Earth, the stratopause varies by less than a scale height with latitude, and it is the winter mesopause, rather than the stratopause, that is markedly warmed by subsidence. Perhaps this is attributable to the different chemistry and radiative heating profiles in the two atmospheres. Titan has a production factory of organic molecules occurring at higher altitudes.

The heterogeneous chemistry occurring on terrestrial polar stratospheric cloud particles of nitric acid trihydrate (HONO₂·3H₂O) is critical for denitrifying the atmosphere of the reservoirs of active Cl, e.g. ClONO₂, releasing Cl₂ (Schoeberl & Hartmann 1991). The appearance of the Sun over the horizon in spring leads to the dissociation of Cl₂ producing atomic Cl, which feeds on O₃ and produces the

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\text{HONO}_2 \cdot 3\text{H}_2\text{O} \rightarrow \text{HONO}_2 + 3\text{H}_2\text{O} \rightarrow \text{H}_2\text{O} + \text{N}_2 + \text{H}_2
\]

Table 2. Winter polar vortices.

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<th>Earth (ozone hole)</th>
<th>Titan</th>
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<tr>
<td>seasonal variation: forms in winter, disappears in late spring</td>
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<tr>
<td>cold polar temperatures (( p &gt; 0.1 ) mbar)</td>
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<td>strong circumpolar winds, inhibiting mixing between low and high latitudes</td>
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<td>warm polar atmosphere (( p &lt; 0.1 ) mbar), consistent with subsidence</td>
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<td>anomalous composition within vortex</td>
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<tr>
<td>low (high) abundance of CH₄, N₂O, (HF) (evidence of rapid descent from mesosphere)</td>
<td>enhanced organics: nitriles (HCN, HC₃N and C₂N₂)</td>
</tr>
<tr>
<td>active nitrogen compounds that bind Cl (e.g. ClONO₂)</td>
<td>more reactive hydrocarbons (e.g. C₃H₄, C₄H₂)</td>
</tr>
<tr>
<td>polar stratospheric clouds: HONO₂·3H₂O</td>
<td>C₄N₂, HCN, HC₃N, X</td>
</tr>
<tr>
<td>disruption by planetary waves forced by flow over topography</td>
<td>???</td>
</tr>
</tbody>
</table>

Phil. Trans. R. Soc. A (2009)
ozone hole. Whether heterogeneous chemistry occurs on Titan’s organic-rich atmosphere is not known. However, the question should not be what proof does one have, but why should it not occur and be as complex as on the Earth?

The breakup of the terrestrial winter polar vortex in spring is from the planetary waves that were kept at bay earlier, On Titan, it is not clear which waves are important and whether planetary, or Rossby, waves play an important role. Part of the problem is that, given Titan’s slow rotation, the Rossby deformation radius is larger than Titan’s radius (Leovy & Pollack 1973; Hunten et al. 1984). The study of waves in Titan’s atmosphere is still at an early stage. However, observations of the pole as spring progresses, e.g. of the temperature field, showing how the vortex decays, whether with a nonlinear disruptive collapse as on the Earth or with a whimper, still need to be made.

References


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