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Simulating Titan's tropospheric circulation with the Portable University Model of the Atmosphere

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Abstract

The Portable University Model of the Atmosphere (PUMA) is a general circulation model of intermediate complexity. In the model setup used herein, the dynamics is driven by restoration to a prescribed temperature field. Given an observed three-dimensional field of restoration temperatures, the feedback of aerosol distribution to the radiation scheme and hence to the dynamics is excluded from calculations. PUMA is adapted to Titan conditions and used to carry out a series of experiments with temperature fields based on radio occultation and infrared spectroscopy measurements taken by Voyager 1 in 1980. The resultant winds are prograde with maximum wind speeds of about 14 m/s in the troposphere. This simulation demonstrates capabilities of a restricted complexity model and provides a contribution to the prediction of the descent trajectory of the Huygens lander in January 2005.

Keywords: Titan; Titan's troposphere; Model of the atmosphere

1. Introduction

Saturn's satellite Titan is the only moon in the solar system with a considerable atmosphere (Taylor and Coustenis, 1998). The surface pressure is 1.5 times that of the Earth. Titan's rotation period of barely 16 days is synchronous with its orbit. Thus, like Venus, Titan is a slowly rotating body with a dense atmosphere. Under such conditions, the circulation of the atmosphere is not close to geostrophic balance like Earth's or Mars', where pressure gradients are balanced by coriolis forces, creating large gyres. Instead, pressure gradients are balanced by the centrifugal forces of an almost latitudinal circulation, i.e. the atmosphere is in cyclostrophic balance (Flasar, 1998).

Until recently, only data allowing indirect estimations of wind velocities on Titan were available, e.g. the observation of the occultation of 28 Sgr by Titan in 1989 (Hubbard et al., 1993). Measurements during this occultation indicate a deviation of the atmosphere from spherical symmetry which can be explained by strong zonal winds (70–170 m/s) in the upper stratosphere (250 km altitude). The Titan zonal wind model (Flasar et al., 1997) which was used for planning the Huygens mission design is primarily based on temperature measurements by Voyager 1's infrared spectroscopy experiment (IRIS, Lellouch et al., 1989). From meridional temperature gradients, zonal winds are estimated by the *thermal wind relation* (Flasar, 1998). This relation does not completely capture the atmospheric dynamics:

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Two solutions are possible, one with prograde and one with retrograde winds. Recent ground based spectroscopy of Doppler-shifted ethane provides the first direct wind measurements and points towards a much higher probability for a prograde circulation (Kostiuk et al., 2001).

Titan's atmosphere has been subject to several studies with general circulations models (GCMs). However, the results obtained with different GCMs differ considerably (Hourdin et al., 1995; Tokano et al., 1999). This may be due to the fact that the scattering and absorption properties of the aerosols and their distribution have to be prescribed, and these are not very well constrained. The aerosols have a great impact on the radiative heating in the GCM. In turn, the aerosol distribution may also be influenced by the atmospheric circulation, as indicated by the observed hemispherical asymmetry and also by recent coupled model simulations (Rannou et al., 2002).

Herein, we present first results from the application of an intermediate complexity GCM on Titan. This is on one hand more comprehensive than using only the thermal wind relation. The GCM computes not only the zonal wind velocity component (with unknown sign), but the complete circulation. On the other hand, our approach is simpler than a full scale GCM, thus avoiding problems due to uncertainties in the aerosol-circulation interaction. Providing self-consistent scenarios for Titan's atmospheric circulation is not only of great interest for the physics of slowly rotating dense atmospheres. It is also important to assess the drift of the Huygens probe during its decent in January 2005. A recently discovered design flaw of the Huygens receiver onboard the Cassini orbiter led to a significantly different mission geometry (Huygens Recovery Task Force, 2001). As a consequence, the gain of the probe antenna would decrease steeply with eastward drift during the descent (Kazeminejad et al., 2002), and accurate prediction of the tropospheric winds could be critical for mission success.

2. The Portable University Model of the Atmosphere

The temporal evolution of the temperature T in a GCM is governed by the differential equation

$$\rho C_\rho \frac{\partial T}{\partial t} = -\mathrm{div}\,\mathbf{F} + Q + \cdots, \tag{1}$$

where ρ and C_ρ are density and heat capacity, respectively, $\mathbf{F}$ are advective and diffusive heat transports, Q is radiative heating, and the ellipsis indicates any additional processes that have to be parameterized, e.g. heat release due to cloud formation. From T, horizontal and vertical winds (which determine $\mathbf{F}$) are calculated by the dynamical core of the GCM, and Q is obtained by radiative transfer computations. The latter requires knowledge of the transmissivity of the atmosphere in dependence on altitude. Usually, two wavelength bands are considered, one shortwave for the optical insolation by the sun and one longwave for thermal radiation from the ground and from the atmosphere itself. The model dynamics is driven by solar insolation (cf. e.g., Lorenz et al., 1996). If aerosols are present, they may contribute considerably to the radiative heating or cooling. Thus the distribution and the absorption properties of the aerosols have to be provided as boundary conditions. The aerosols in Titan's atmosphere have been simulated with one-dimensional (altitude dependent) microphysical models (e.g., Cabane et al., 1992; Lemmon, 1994; McKay et al., 2001; Rodin, 2003; Grieger et al., 2003). The interaction of aerosols and atmospheric dynamics has recently been investigated with a two-dimensional (altitude–latitude dependent) coupled model (Rannou et al., 2002).

The approach utilized herein avoids the necessity of prescribing the properties of Titan's aerosols, but requires providing temperatures. We make use of the portable university model of the atmosphere (PUMA, Fraedrich et al., 1998) in a model setup where radiative and any other heating processes are implicitly described by relaxation to a prescribed restoration temperature T_R:

$$\frac{\partial T}{\partial t} = -\frac{\mathrm{div}\,\mathbf{F}}{\rho C_\rho} + \frac{1}{\tau}(T_\mathrm{R} - T). \tag{2}$$

Here τ is the relaxation time constant which is set to 30 Titan days. In fact, the radiative time constants in Titan's lower atmosphere are much longer (Flasar, 1998). But because an observed temperature field is taken as restoration temperature, the relaxation time constant is small in order to keep the modeled temperature close to the observed one. A realistic time constant could only be used if the true radiative equilibrium temperature was provided.

The restoration temperature field T_R is prescribed according to Voyager 1 observations. The mean vertical profile is adopted from estimates based on radio occultation measurements (Lellouch et al., 1989). It is illustrated in Fig. 1. In the off-the-shelf geometry used for the simulations presented herein, the model is restricted to the troposphere. The latitudinal temperature gradients are prescribed according to Voyager 1 IRIS measurements (Lellouch et al., 1989; Courtin and Kim, 2002) by setting the equator to pole temperature difference to 3 K. The values for the parameters of the restoration temperature field are listed in Table 1. To simulate different seasons, a North pole to South pole temperature difference varying between 0 and 2 K is imposed on the restoration temperature for different model runs.

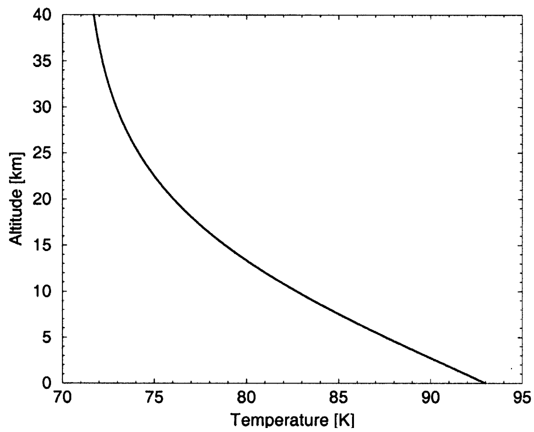

Fig. 1. Global mean temperature profile used for restoration in the PUMA runs.

Table 1
Parameters of the restoration temperature field

Ground temperature	93 K
Average lapse rate	1.1 K/km
Tropopause temperature	71 K
Equator to pole temp. diff.	3 K
North pole to South pole temp. diff.	0, 1, 2 K

3. Results

All model runs are started from an atmosphere at rest with random white noise added to the surface pressure. After a few hundred Titan days, the model state does not change significantly any more. To ensure that equilibrium with the restoration temperature is reached, the runs are integrated over 3600 Titan days. As the restoration temperature field is constant in time, the runs presented herein do not comprise an annual cycle.

The tropospheric circulation from three runs with different North pole to South pole temperature differences is illustrated in Fig. 2. The color coding shows the zonal mean zonal wind speed, with positive values corresponding to eastward (prograde) wind. Additionally, isolines of the zonally integrated meridional stream function are shown. White and black lines indicate clockwise and counterclockwise circulation, respectively. The isoline spacing is given above each panel.

The Voyager 1 observations were made close to Titan's vernal equinox. While the IRIS measurements (Lellouch et al., 1989; Courtin and Kim, 2002) indicate a symmetric temperature pattern in the Northern and Southern hemisphere near the surface, the stratospheric temperature exhibits a pronounced assymmetry. This is not in agreement with the current understanding of the radiative time constants in Titan's atmosphere (Flasar, 1998). Because of the small time constant in the stratosphere, the temperature there should be in equilibrium with the insolation, and thus symmetric at the time of

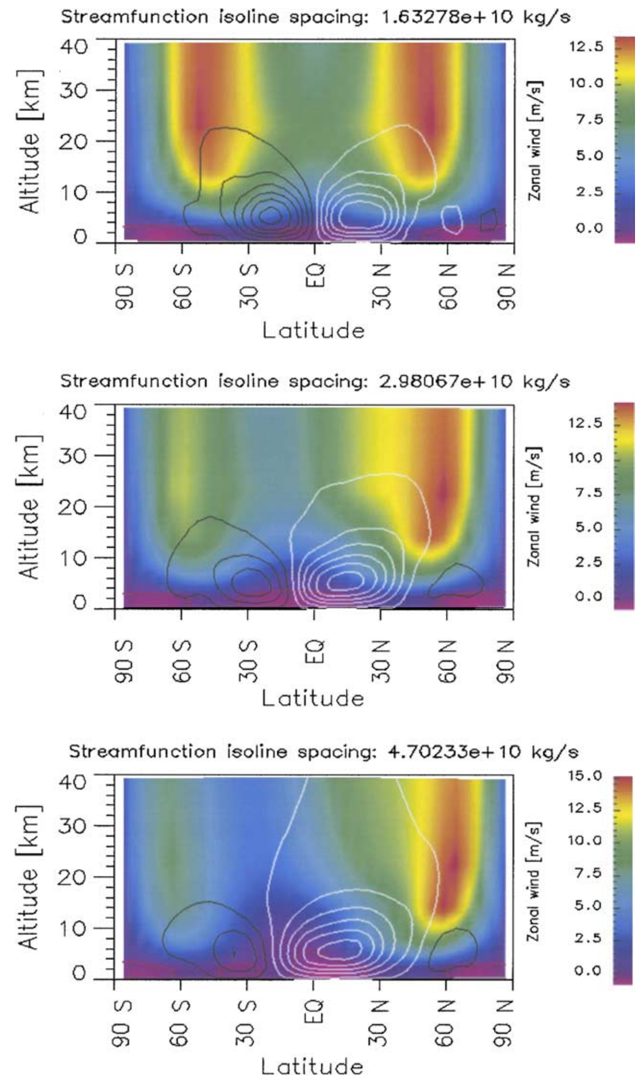

Fig. 2. Zonal wind velocity (colored) and meridional stream function (isolines) for varying North pole to South pole temperature difference: 0 K (top), 1 K (center), and 2 K (bottom). White isolines indicate clockwise, black isolines counterclockwise circulation. Note the different contour intervals.

the equinox. In contrast, the long time constant in the lower atmosphere should preserve the North–South assymmetry from the winter season beyond the vernal equinox.

Considering these uncertainties about the annual cycle of the horizontal temperature distribution, the model run with symmetric restoration temperature in the Northern and the Southern hemisphere can be interpreted as to represent some season between vernal equinox and summer solstice. The resultant circulation is presented in Fig. 2, top. As to be expected, the circulation is almost symmetric around the equator. Small deviations are due to temporal variability (Titan "weather"); the shown circulation represent a 30 Titan days average. The zonal circulation is prograde with two jets of up to 13 m/s wind speed at 50° latitude.

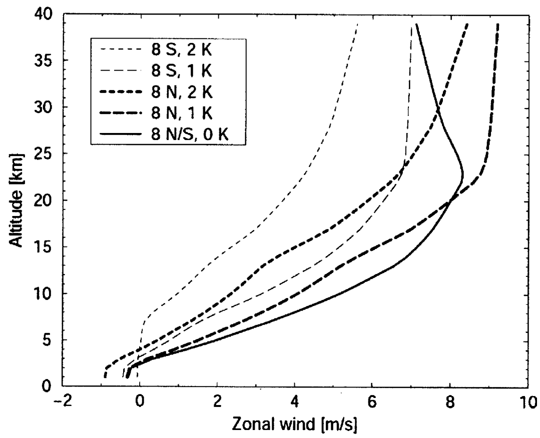

Fig. 3. Zonal wind at two possible latitudes (8°N, bold lines, and 8°S, thin lines) for Huygens' landing. Results from three model runs with different North pole to South pole temperature differences (0 K, solid line, 1 K, long-dashed and 2 K, short-dashed) are shown.

The meridional circulation can be described by a Headley cell extending northward and southward to the latitudes of the zonal jets. The eastward jets can be comprehended as driven by the transport of angular momentum from the equator by the meridional circulation.

A season of particular interest is shortly after Titan's winter solstice, when the descent of the Huygens probe in January 2005 will take place. Coupled simulations of circulation and aerosol distribution with a two-dimensional model (Rannou et al., 2002) indicate a North pole to South pole temperature difference of about 1 K at that season (P. Rannou, private communication). The circulations resultant from model runs with North pole to South pole temperature differences of 1–2 K are presented in Fig. 2, center and bottom, respectively. With increasing temperature difference, the upward branch of the Headley cell is shifted towards the summer hemisphere (i.e. to the South, in this case). The meridional circulation in the winter hemisphere increases while it decreases in the summer hemisphere. Consequently, the Northern hemisphere eastward jet is stronger while it is weaker in the Southern hemisphere.

Two landing sites are under consideration for the Huygens probe, one at 8°N and one at 8°S (Huygens Recovery Task Force, 2001). The zonal wind speeds in dependence on altitude for both latitudes as they result from the three presented model simulations are shown in Fig. 3.

4. Conclusion and outlook

Our results fall in the range spanned by other simulations (Hourdin et al., 1995; Tokano et al., 1999), and also within the limits given by the Titan zonal wind model (Flasar et al., 1997) that was used to design the Huygens mission. Beyond the confirmation of the Titan zonal wind model, some robust features have been found in all model runs. These additional constraints on the winds in Titan's troposphere are in particular the presence of considerable prograde wind in equatorial latitudes, although the zonal circulation retains features typical for the case of a global-scale, cross-equatorial Hadley cell: The zonal winds are mainly confined in two jets at high latitudes, with stronger jet in the winter hemisphere and considerably lower wind speeds at low latitudes. The Headley cell is always extending to high latitudes but not to the poles. The. simulated circulation will be used as input for a microphysical model (Rodin, 2002, 2003) to estimate the aerosol distribution throughout the atmosphere.

To optimize the communication link between the Huygens lander and the Cassini orbiter in the new high-fly-by scenario (Huygens Recovery Task Force, 2001), the eastward drift of the lander should be as small as possible (Kazeminejad et al., 2002). Considering this, the results give a first indication that the southern landing site at 8°S is preferable. A shortcoming of the simulations carried out so far is that the current model version is constrained to the troposphere. To assess possible high speed superrotational winds in the upper stratosphere indicated by observations (Hubbard et al., 1993), the model will be extended to the stratosphere and further model experiments with varying parameters will be carried out.

An interesting perspective of the PUMA GCM driven by restoration temperatures is the possibility of "on the fly" simulations during the Cassini/Huygens mission. Before the release of the Huygens probe scheduled for Christmas 2004, Cassini will perform two Titan fly-bys on October 26 and December 13 with observations and measurements. Temperature data acquired at these fly-bys could be used to simulate the corresponding winds and predict the descent trajectory of the probe.

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References

Cabane, M., Chasseféire, E., Israel, G. Formation and growth of photochemical aerosols in Titan's atmosphere. Icarus 96, 176–189, 1992.

Courtin, R., Kim, S.J. Mapping of Titan's tropopause and surface temperature from Voyager IRIS spectra. Planet. Space Sci. 50, 309–321, 2002.

Flasar, F.M. The dynamic meteorology of Titan. Planet. Space Sci. 46, 1125–1147, 1998.

Flasar, F.M., Allison, M.D., Lunine, J.I. Titan zonal wind model, in: Wilson, A., (Ed.), Huygens – Science, Payload and Mission. vol. SP-1177, ESA Publications Division, ESTEC, Noordwijk, The Netherlands, pp. 287–298, 1997.

Fraedrich, K., Kirk, E., Lunkeit, F. PUMA: portable university model of the atmosphere, DKRZ Technical Report 16, DKRZ-Hamburg, 1998. Available at: <http://puma.dkrz.de/puma>.

Grieger, B., Rodin, A.V., Salinas, S.V., et al. Simultaneous retrieval of optical depths and scattering phase functions in Titan's atmosphere from Huygens/DISR data. Planet. Space Sci. 51, 991–1001, 2003.

Hourdin, F., Talagrand, O., Sadourny, R., et al. Numerical simulation of the general circulation of the atmosphere of Titan. Icarus 117, 358–374, 1995.

Hubbard, W.B., Sicardy, B., Miles, R., et al. The occupation of 28 Sgr by Titan. Astron. Astrophys. 269, 541–563, 1993.

Huygens Recovery Task Force, HRTF final report. Tech. Rep. HUY-RP-12241, ESA/NASA, 2001.

Kazeminejad, B., Lebreton, J.-P., Bird, M.K., et al. Earth-like planets and moons. In: Foing, B.H., Battrick, B. (Eds.), Proceedings of the 36th ESLAB Symposium, 3–8 June, 2002. European Space Agency, Noordwijk, Netherlands, pp. 191–199, 2002.

Kostiuk, T., Fast, K.E., Livengood, T.A., et al. Direct measurements of winds on Titan. Geophys. Res. Lett. 28, 2361–2364, 2001.

Lellouch, E., Coustenis, A., Gautier, D., et al. Titan's atmosphere and hypothesized ocean: a reanalysis of the Voyager 1 radio-occultation and IRIS 7.7/ion data. Icarus 79, 328–349, 1989.

Lemmon, M.T. Properties of Titan's haze and surface, Ph.D. thesis, University of Arizona, 1994.

Lorenz, S., Grieger, B., Helbig, P., et al. Investigating the sensitivity of the atmospheric general circulation model ECHAM 3 to paleoclimatic boundary conditions. Geologische Rdsch. 85, 513–524, 1996.

McKay, C.P., Coustenis, A., Samuelson, R.E., et al. Physical properties of the organic aerosols and clouds on Titan. Planet. Space Sci. 49, 79–99, 2001.

Rannou, P., Hourdin, F., McKay, C.P. A wind origin for Titan's haze structure. Nature 418, 853–856, 2002.

Rodin, A.V. On the moment method for the modeling of cloud microphysics in rarefied turbulent atmospheres: I condensation and mixing. Solar System Res. 36 (2), 97–106, 2002.

Rodin, A.V. On the moment method for the modeling of cloud microphysics in rarefied turbulent atmospheres: II stochastic coagulation. Solar System Res. 37 (2), 101–111, 2003.

Taylor, F.W., Coustenis, A. Titan in the solar system. Planet. Space Sci. 46, 1085–1097, 1998.

Tokano, T., Neubauer, F.M., Laube, M., et al. Seasonal variation of Titan's atmospheric structure simulated by a general circulation model. Planet. Space Sci. 47, 493–520, 1999.