Available online at www.sciencedirect.com
SCIENCE DIRECT®
Advances in Space Research 36 (2005) 2194–2198
ADVANCES IN SPACE RESEARCH
(a COSPAR publication)
www.elsevier.com/locate/asr

Titan atmosphere database

P. Rannou [a,*], S. Lebonnois [b], F. Hourdin [b], D. Luz [c]

[a] Service d'Aéronomie/IPSL, BP3, Univ. Versailles-S^T-Quentin, 91371 Verriéres Le Buisson, France
[b] Laboratoire de Météorologie Dynamique/IPSL, Univ. Paris 6, 75252 Paris Cedex 05, France
[c] DESPA, Observatoire de Paris, 92195 Meudon Cedex, France

Received 13 July 2004; received in revised form 22 September 2005; accepted 28 September 2005

Abstract

We have developed in the last decade a two-dimensional version of the Titan global circulation model LMDZ. This model accounts for multiple coupling occuring on Titan between dynamics, haze, chemistry and radiative transfer. It was successful at explaining many observed features related to atmosphere state (wind, temperature), haze structure and chemical species distributions, recently, an important step in our knowledge about Titan has been done with Cassini and Huygens visits to Titan. In this context, we want to make the results of our model available for the scientific community which is involved in the study of Titan. Such a tool should be useful to give a global frame (spatial and time behaviour of physical quantities) for interpreting ground based telescope observations.

Keywords: Titan; Haze; Wind; Chemistry; Atmosphere; Database; Model

1. Coupled haze-chemistry-circulation model

Up to the middle of the last decade, Titan was investigated through its different systems separately; circulation, haze, chemistry, aeronomy and so on. However, it became obvious that all these components of Titan climate were interacting together, and so was the conclusions of many papers at this time (e.g, Hourdin et al., 1995; Hutzell et al., 1993; Rannou et al., 1997). The first serious attempt to couple circulation and haze is to be credited to Hutzell et al. (1996). However, no feedback due to haze distribution on circulation was accounted here.

Investigating reciprocal feedback of haze and dynamics was the first motivation for developing a coupled haze–dynamics general circulation model. The main idea was basically to couple the Hourdin et al. (1995) circulation model with the Cabane et al. (1993) microphysics model. Haze is transported by winds, and feedback due to haze is produced through radiative transfer and its effect on the heating rate. This model allowed to explain several features of haze distribution such as the detached haze, the polarhood and the hemispheric asymmetry. It also allowed to detail the strong radiative feedback produced by haze on winds (Rannou et al., 2002, 2004). In the same way, coupling between chemical composition and circulation was also studied by Lebonnois et al. (2001, 2003b). They give a comprehensive explanation for the distribution of some chemical species which was observed by IRIS/Voyager (Coustenis and Bézard, 1995). An explanation of the mechanism governing chemical distribution is given by Hourdin et al. (2005).

While our model is a two-dimensional circulation model, some three-dimensional features must be accounted for Hourdin et al. (1995) have shown that interaction between barotropic eddies and the mean circulation contributes to transport momentum (which contributes to maintain superrotation) and other physical quantities. Luz and Hourdin (2003a,b) have carefully studied transport by these eddies with a shallow water model and have proposed simple parametrizations for the two-dimensional version which significantly improves the results (Luz et al., 2003b; Rannou et al., 2004). Due to its two-dimensional

* Corresponding author. Tel.: +33 1 64 47 42 16; fax: +33 1 69 20 29 99.
E-mail address: pra@aero.jussieu.fr (P. Rannou).

0273-1177/$30 © 2005 COSPAR. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.asr.2005.09.041

nature, our model does not include diurnal cycle and gravitational tide effects although they clould affect the three-dimensional structure of the atmosphere (Tokano and Neubauer, 2002).

Characteristics of the GCM configuration used here for the building of the current version of the database are as follows. The model grid is based on 49 latitude points regularly spread from north pole to south pole (3.75° intervals), with 55 vertical layers (Table 1), of which the last three serve as a sponge layer to dump down the wind and prevent spurious reflexion of waves. Level 52 is approximately 480 km above the surface. The vertical resolution is about 3 km in the troposphere, 5 km at the tropopause and 10–15 km in the stratosphere, which correspond to one half to one third of a scale height. The surface pressure is set to 1.429 bar. The dynamical equations are integrated with a time step of 3 min. Physical parameterizations (radiative transfer, haze microphysics) are computed 10 times per Titan day. Gaseous infrared cooling rates are still computed from prescribed uniform descriptions of CH_4, H_2, C_2H_2 and C_2H_6 as described in Hourdin et al. (1995). Coupling with computed composition will be added in future versions of the database. Haze is also not yet coupled with the photochemistry (source function of haze, condensation), and is treated as described in Rannou et al. (2004). Chemistry includes 44 species with 343 reactions, and is computed once per Titan day, with diurnal mean used for photodissociation rates. Hydrogen recombination at the surface of haze particles (Lebonnois et al., 2003a) is taken into account. Haze production parameterization (Lebonnois et al., 2002) is not yet included, but should be considered in the next version of the database. At the upper boundary, the exchange flux between the upper atmosphere and the upper layer of the GCM is fixed for chemical species. These fluxes are calculated using a one-dimensional model of Titan's atmosphere in equatorial conditions (Lebonnois et al., 2002, 2003a). As a first approximation, these fluxes are fixed, both in time and as a function of latitude. At the lower boundary, methane mole fraction is fixed at the surface and at the tropopause.

Table 1
Sigma (pressure/surface pressure) and approximate altitude levels (km)

1	1.000	0.057
2	9.886×10^{-1}	0.284
3	9.665×10^{-1}	0.727
4	9.303×10^{-1}	1.471
5	8.785×10^{-1}	2.577
6	8.121×10^{-1}	4.077
7	7.341×10^{-1}	5.979
8	6.489×10^{-1}	8.269
9	5.613×10^{-1}	10.908
10	4.759×10^{-1}	13.845
11	3.961×10^{-1}	17.025
12	3.243×10^{-1}	20.393
13	2.617×10^{-1}	23.906
14	2.086×10^{-1}	27.537
15	1.645×10^{-1}	31.272
16	1.285×10^{-1}	35.095
17	9.962×10^{-2}	38.995
18	7.673×10^{-2}	42.998
19	5.879×10^{-2}	47.118
20	4.484×10^{-2}	51.360
21	3.407×10^{-2}	55.827
22	2.581×10^{-2}	60.830
23	1.950×10^{-2}	66.805
24	1.471×10^{-2}	73.875
25	1.107×10^{-2}	81.881
26	8.326×10^{-3}	90.677
27	6.253×10^{-3}	100.162
28	4.692×10^{-3}	110.284
29	3.518×10^{-3}	120.968
30	2.636×10^{-3}	132.149
31	1.975×10^{-3}	143.760
32	1.479×10^{-3}	155.712
33	1.107×10^{-3}	167.940
34	8.286×10^{-4}	180.391
35	6.201×10^{-4}	193.077
36	4.641×10^{-4}	205.912
37	3.472×10^{-4}	218.888
38	2.598×10^{-4}	232.082
39	1.944×10^{-4}	245.366
40	1.454×10^{-4}	258.856
41	1.088×10^{-4}	272.420
42	8.145×10^{-5}	286.002
43	6.096×10^{-5}	299.541
44	4.563×10^{-5}	312.880
45	3.410×10^{-5}	325.937
46	2.557×10^{-5}	338.567
47	1.913×10^{-5}	350.661
48	1.426×10^{-5}	362.193
49	1.067×10^{-5}	373.081
50	7.951×10^{-6}	383.502
51	5.874×10^{-6}	393.495
52	4.155×10^{-6}	403.864
53	2.722×10^{-6}	415.523
54	1.361×10^{-6}	439.416
55	2.865×10^{-7}	512.468

2. Presentation of the database

2.1. Motivation for a database

The model was fixed to match several important results derived from observations, as temperature meridional profiles at 1 and 0.4 mbar retrieved from IRIS observation (Flasar and Conrath, 1990; Coustenis and Bézard, 1995), temperature vertical profile (Lellouch et al., 1989), zonal winds at 0.25 mbar (Hubbard et al., 1993), haze distribution at Voyager time (Smith et al., 1981, 1982; Rages and Pollack, 1983), related photometry (Sromovsky et al., 1981; Neff et al., 1984; Courtin et al., 1991), and meridional distribution of chemical species (Coustenis and Bézard, 1995). Once these "landmarks" are set, we suppose our model to work correctly, and then we can use it to predict the state of Titan at other places and at other times than those observed. As well, we are able to produce fields of quantities which are not (or hardly) observables like, for instance, aerosol distribution. Finally, we also use the model to understand the mechanism of the atmosphere (as the haze feedback, and the effect of the variation in chemical composition on circulation).

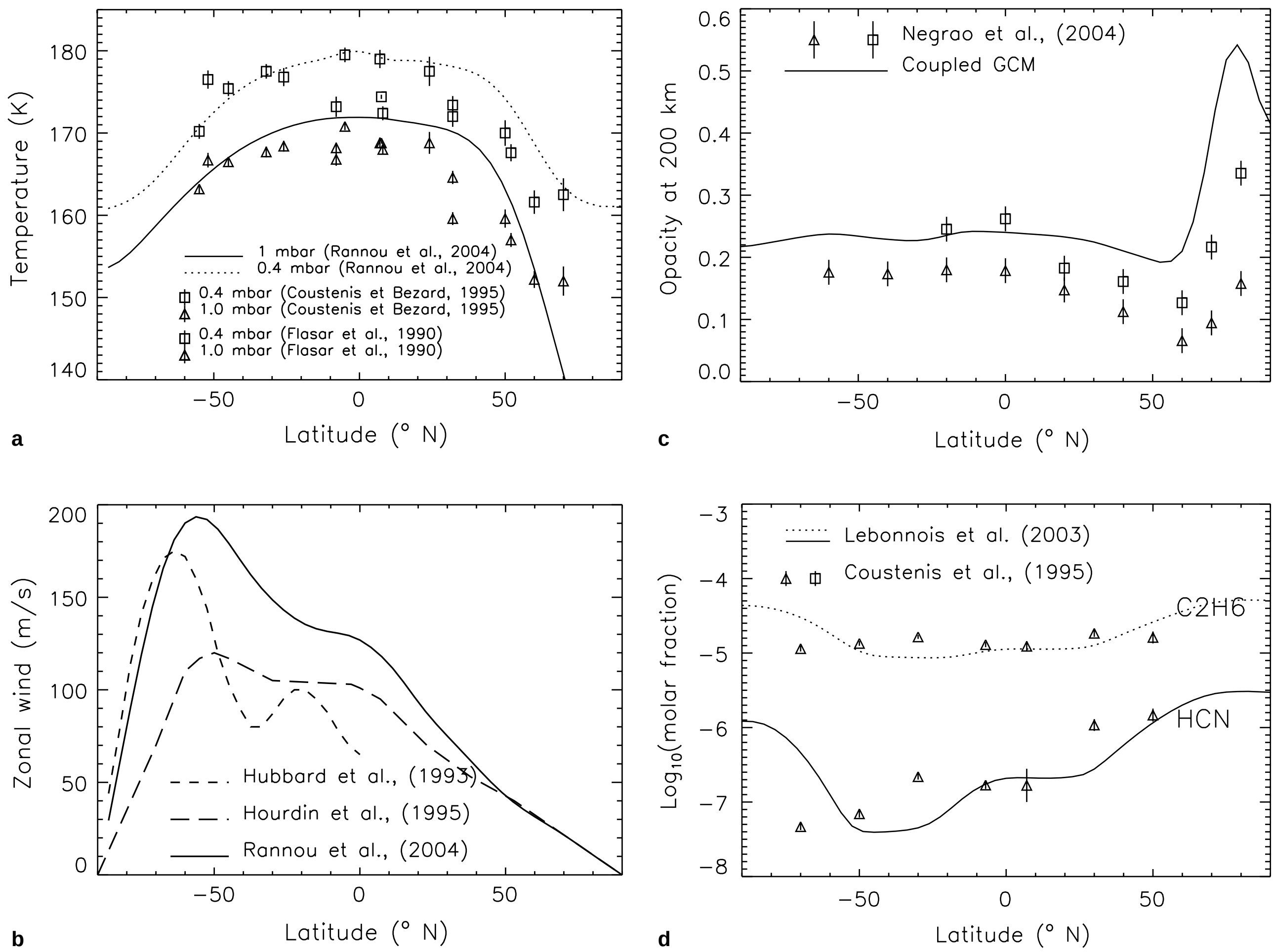

Fig. 1. Sketch of comparisons between the model and selected physical quantities retrieved from observations. The results of the model are compared with latitude profiles of: (a) temperature, deduced from Voyager/IRIS observations at 1 and 0.4 mbar ($L_s = 9°$); (b) zonal wind retrieved from the start 28-Sgr occultation in 1989 (at 0.25 mbar, $L_s = 128°$); (c) haze opacity at 200 km retrieved from high phase angle photometry and at last; (d) C_2H_6 (2 mbar) and HCN (9 mbar) mixing ratios, retrieved from Voyager/IRIS observations.

To illustrate the results of this model, we first show comparisons between several fields of our model with well known values derived from observations (Fig. 1). These comparisons are published elsewhere (Lebonnois et al., 2001; Rannou et al., 2004; Negrão et al., 2005; Hourdin et al., 2005) and are gathered here to show how the model is validated. Fig. 2 shows the temperature field, the zonal wind and the haze extinction at the time of Huygens arrival given by the model, as the present database is able to provide these values.

2.2. Short technical description

This database – as the circulation model – has two-dimensions of space; latitude and pressure level. The third dimension is time. A given field of the database, for instance temperature, wind or any physical quantity of interest, is described by $49 \times 55 \times 32$ values. As mentioned previously, 49×55 is the GCM grid. One Titan year of simulation is evenly divided in 32 time periods, and mean values of each variable are stored for each period. Any value of a given field is determined by three components (latitude θ, pressure P, and time t).

Values in the database can be requested using several modes. A single interpolated value, a one-dimensional array or a two-dimensional array of values can be returned, when providing three, two or one input components. For arrays, values are interpolated along the components which are explicitly given (N component among three), and the dimension of the arrays are deduced from the missing component (that is $3 - N$). Returned values are given, in the $3 - N$ dimensions, at the same coordinates than those of the database.

The fields available concerning the state of the atmosphere are: the geopotential, the temperature and the three wind components. Concerning haze, we give the concentration of aerosols in the 10 bins of the distribution (from 1.5 nm to 7 μm). Then, any optical properties (extinction, phase function) can be retrieved with the appropriate routine of scattering. Only extinction and opacity at 575 nm are included directly in the database. No cut-off is applied to the distribution given by the database. Haze increases

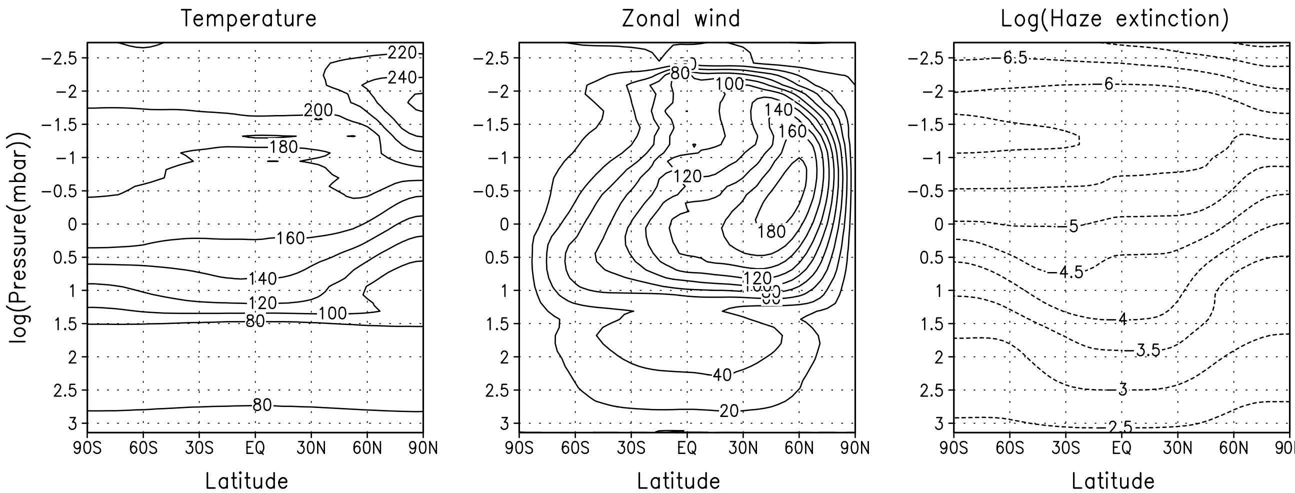

Fig. 2. Prediction given by the model for temperature, zonal wind and haze extinction at about the time of Huygens descent ($L_s = 292°$).

continuously down to the ground, and then cut-off may have to be applied if one wants to reproduce specific observations as geometric albedo or temperature profile. At last, we give mixing ratios for 13 chemical species: H_2, CH_4, C_2H_2, C_2H_4, C_2H_6, CH_3C_2H, C_3H_8, C_4H_2, C_6H_6 (benzene), HCN, HC_3N, CH_3CN and C_2N_2. In the present version, the database is set up with 31 fields.

3. The database on the web

We have chosen to write the codes of the database in Fortran 77. However, in principle, C routines are able to call Fortran 77 routine with minor adaptations. The "database" is composed of an ASCII file containing $49 \times 55 \times 32$ values for each of the 31 fields. This database file is roughly 27 MB. Series of codes which read and make interpolations inside the database is also available. Finally two codes (interfaces) show how to call the database and display its results. A first code is a simple example to call the database in different modes. The second code is especially oriented toward haze application; it shows how to get aerosol distributions and how to compute haze properties (extinction, average phase function). To do so, routines which return fractal aggregates optical properties (cross sections, phase function) (Rannou et al., 1999) are also included. The URL location for this database is http://www.lmd.jussieu.fr/titanDbase/index.hml.

References

Cabane, M., Rannou, P., Chassefière, E., Israel, G. Fractal aggregates in Titan's atmosphere. Planet. Space Sci. 41, 257–267, 1993.

Courtin, R., Wagener, R., McKay, C.P., Caldwell, J., Fricke, K.-H., Raulin, F., Bruston, P. UV spectroscopy of Titan's atmosphere, planetary organic chemistry and prebiological synthesis. II. Interpretation of new IUE observations in the 220–335 nm range. Icarus 90, 43–56, 1991.

Coustenis, A., Bézard, B. Titan's atmosphere from Voyager infrared observations: IV. Latitudinal variations of temperature and composition. Icarus 115, 126–140, 1995.

Flasar, F.M., Conrath, B.J. Titan's stratospheric temperature: a case for dynamical inertia? Icarus 85, 346–354, 1990.

Hourdin, F., Talagrand, O., Sadourny, R., Courtin, R., Gautier, D., McKay, C.P. Numerical simulation of the general circulation of the Titan. Icarus 117, 358–374, 1995.

Hourdin, F., Lebonnois, S., Luz, D., Rannou, P. Titan's stratospheric composition driven by condensation and dynamics. J. Geophys. Res. 109, E12, 2005, E12005.

Hubbard, W.B., Sicardy, B., Miles, R., Hollis, A.J., Forrest, R.W., Nicholson, I.K.M., Appleby, G., Beisker, W., Bittner, C., Bode, H.-J., Bruns, M., Denzau, H., Nezel, M., Rieder, E., Strucmann, H., Arlot, J.E., Roques, R., Sevre, F., Thuillot, W., Hoffmann, M., Geyer, E.H., Buil, C., Colas, F., Lecacheux, J., Klotz, A., Thouvenot, E., Vidal, J.L., Carreira, E., Rossi, F., Blanco, S., Cristaldi, S., Nevo, Y., Reitsema, H.J., Brosch, N., Cernis, K., Zdanavicius, K., Wasserman, L.H., Hunten, D.M., Gautier, D., Lellouch, E., Yelle, R.V., Riszk, B., Flasar, P.M., Porco, C.C., Toublanc, D., Coregedu, G. The occupation of 28 Sgr by Titan. Astron. Astrophys. 269, 541–563, 1993.

Hutzell, W.T., McKay, C.P., Toon, O.B. Effects of time-varying haze production on Titan's geometric albedo. Icarus 105, 162–174, 1993.

Hutzell, W.T., McKay, C.P., Toon, O.B., Hourdin, P. Simulations of Titan's brightness by a two dimensional haze model. Icarus 119, 112–129, 1996.

Lebonnois, S., Toublanc, D., Hourdin, F., Rannou, P. Seasonal variations of Titan's atmospheric composition. Icarus 152, 384–406, 2001.

Lebonnois, S., Bakes, E., McKay, C.P. Transition from gaseous compounds to aerosols in Titan's atmosphere. Icarus 159, 505–517, 2002.

Lebonnois, S., Bakes, E., McKay, C.P. Atomic and molecular hydrogen budget in Titan's atmosphere. Icarus 161, 474–485, 2003a.

Lebonnois, S., Hourdin, F., Rannou, P., Luz, D., Toublanc, D. Impact of the seasonal variations of composition on the temperature field of Titan's stratosphere. Icarus 163, 164–174, 2003b.

Lellouch, E., Coustenis, A., Gautier, D., Raulin, F., Dubouloz, N., Frere, C. Titan's atmosphere and hypothesized ocean: a reanalysis of Voyager 1 radio-occultation and IRIS 7.7 μm data. Icarus 79, 328–349, 1989.

Luz, D., Hourdin, F. Latitudinal transport by barotropic waves in Titan's stratosphere: i. general properties from a horizontal shallow-water model. Icarus 166, 328–342, 2003a.

Luz, D., Hourdin, F., Rannou, P., Lebonnois, S. Latitudinal transport by barotropic waves in Titan's stratosphere: ii. results from a coupled dynamics-microphysics-photochemistry GCM. Icarus 166, 343–358, 2003b.

Neff, J.S., Humm, D.C., Bergstrahl, J.T., Cochran, A.L., Cochran, W.D., Barker, E.S., Tull, R.G. Absolute spectrophotometry of Titan, Uranus and Neptune: 3500–10500 A. Icarus 60, 221–235, 1984.

Negrão, A., Roos-Serote, M., Rannou, P., Rages, K., Lourengo, B. On the latitudinal distribution of Titan's haze at the Voyager epoch. Planet. Space Sci. 53, 526–534, 2005.

Rages, K., Pollack, J.B. Vertical distribution of scattering haze in Titan's upper atmosphere. Icarus 55, 50–62, 1983.

Rannou, P., Cabane, M., Botet, R., Chassefière, E. A new interpretation of scattered light measurements at Titan's limb. J. Geophys. Res. 102, 10997–11013, 1997.

Rannou, P., McKay, C.P., Botet, R., Cabane, M. Semi-empirical model of absorption and scattering by isotropic fractal aggregates of spheres. Planet. Space Sci. 47, 385–396, 1999.

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

Rannou, P., Hourdin, F., McKay, C.P., Luz, D. A coupled dynamics-microphysics model of Titan's atmosphere. Icarus 170, 443–462, 2004.

Smith, B.A., Soderblom, R., Beebe, R., et al. Encounter with Saturn: Voyager 1 imaging science results. Science 212, 163–190, 1981.

Smith, B.A., Soderblom, L., Batson, R., et al. A new look at the Saturn system: the Voyager 2 images. Science 215, 504–537, 1982.

Sromovsky, L.A., Suomi, V.E., Pollack, J.B., Kraus, R.J., Limaye, S.S., Owen, T., Revercomb, H.E., Sagan, C. Implication of Titan's north-south brightness asymmetry. Nature 292, 698–702, 1981.

Tokano, T., Neubauer, F. Tidal winds on Titan caused by Saturn. Icarus 158, 499–515, 2002.