Insolation in Titan’s troposphere

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1. Introduction

Circulation models for the troposphere of Titan mainly focus on meridional motion as the primary driver for the climate, typically invoking the upwelling branch of a circulation cell as the source of convective cloud formation. Two sets of models suggest that all cloud activity is explained with a simple seasonally-wandering Hadley-type cell that creates a seasonal sinusoidal pattern of upwelling cloud activity is explained with a simple seasonally-wandering Hadley-type cell that creates a seasonal sinusoidal pattern of upwelling.

2. Insolation

Titan’s hazy atmosphere efficiently absorbs and scatters solar radiation. Due to the nonzero optical depth of the atmosphere, the magnitude of insolation versus latitude varies at different levels in the atmosphere. At latitude φ and optical depth τ, the daily-average direct insolation is given by

where S0 is the solar constant at Titan, h is the hour angle of the Sun and δ is the solar declination. h0 denotes the hour angle of sunrise/sunset; the Sun does not set around solstice at the summer pole, thus h0 is simply π. The factor E = 1 + cos(θ − π) is due to Saturn’s orbital eccentricity e, where θ is approximately the angle of the orbit (θ = 0 at vernal equinox) and π is Saturn’s longitude of perihelion. As described by Aharonson et al. (2009), this effect causes the summer solstice solar flux at the top of the atmosphere to differ by about 1.5 W m−2 between southern and northern poles.

At the top of the atmosphere, τ = 0 and only curvature affects the latitudinal distribution of insolation, for a given δ. In the atmosphere, where τ is nonzero, the airmass encountered by the solar beam also depends on latitude so that attenuation is greater at the poles than at low latitudes. Thus, the insolation distribution at the surface is qualitatively different from that at the top of the atmosphere for any nonzero value of τ. Tomasko et al. (2008) measured the net solar flux as a fraction of incident solar flux at multiple levels in the atmosphere with the DISR instrument aboard the Huygens probe. From these measurements and Eq. (1), we can calculate “effective” extinction optical
depths for shortwave radiation and, using these optical depths again in Eq. (1), approximate the daily-average solar flux at all latitudes (see Fig. 1). This approach yields an extinction optical depth $\tau = 0.87$ at the surface. A key feature of these results is that the maximum in surface insolation does not reach the pole during summer solstice.

Scattering in Titan’s atmosphere causes diffuse radiation to be a significant component of the solar flux; thus, the above approximation is not entirely valid. However, Tomasko et al. (2008) computed solar heating rates as a function of altitude for different latitudes at different seasons, including a scattering model, and also found that the maximum (below about 50 km) reached only mid-latitudes around solstice. That is, in the troposphere, the insolation distribution is qualitatively different from that at the top of the atmosphere, and is better described by Eq. (1) than by a distribution that ignores the longer path and greater attenuation that sunlight encounters at higher latitudes. This distribution with latitude can be approximated with an adjusted extinction optical depth in Eq. (1), normalized to match the DISR measurements of solar flux (Fig. 2). The resulting insolation distribution for the surface, throughout a Titan year, is shown in the bottom panel of Fig. 1.

**Fig. 1.** Daily-averaged insolation versus time. Top: The insolation at the top of Titan’s atmosphere, where $\tau = 0$. Here, the maximum average insolation occurs at the poles during solstices. Bottom: The insolation with $\tau = 0.4$, which closely matches the heating distribution near the surface.

**Fig. 2.** Calculations of the solar energy at the surface around solstice using Eq. (1). The $\tau = 0.0, 0.4$ curves are adjusted to match the DISR measurements at around 10°S latitude. Note that the vertical axis for the heating rates from Tomasko et al. (2008) (solid curve) is on the right. The best match to these heating rates is the adjusted $\tau = 0.4$ curve; the worst match is $\tau = 0$. 
3. Implications for surface temperatures and circulation

We can examine the basic response of the surface and troposphere to the insolation distributions discussed in Section 2. In particular, we consider the differences between the top-of-atmosphere (zero-opacity) distribution, with flux values scaled for the lower atmosphere and surface, and the nonzero-opacity distribution (Fig. 1) with \( \tau = 0.40 \) at the surface.

3.1. Methods

We implement a simple grey atmosphere box model of Titan's troposphere as an order-of-magnitude study of the implications of these insolation distributions. The model consists of twelve "boxes," six upper and six lower, which represent Titan's troposphere (with an additional six boxes for the surface), in which temperature, \( T \), is solved via the thermodynamic equation:

\[
\frac{\partial \theta}{\partial t} = A (S - F_{\text{out}} + F_{\text{in}}) + \frac{Q \partial T}{\partial t} + SH
\]  

where

\[
\theta = T \left( \frac{P_0}{P} \right)^{\frac{\kappa}{C}}
\]

\[
Q = k \Delta T_{\text{bottom}}
\]

\[
SH = \frac{C}{P_{\text{an}}} f (T_{\text{air}} - T_{\text{surf}})
\]

\( SH \) is the sensible heat term (heat exchange between surface and bottom atmospheric boxes), and \( Q \) parameterizes advection. All other model parameters are listed in Table 1. The temperature evolution of the surface follows a similar function to Eq. (2), but without the advection term.

To compute solar heating rates for each box, the insolation distributions are averaged over the appropriate latitudes (i.e. 90°S to 60°S for the southern polar box). In the case of the nonzero distribution, \( \tau = 0.32, 0.35, \) and 0.40 for the top, bottom, and surface boxes, respectively. Each box also emits thermally according to \( F_{\text{IR}} = \epsilon T^4 \), with constant emisivities.

Advection is parameterized assuming only a thermally direct circulation. In each group of four adjacent atmospheric boxes, the direction of flow is governed by the direction in which the warmest air ascends; the magnitude is determined by the temperature difference \( \Delta T_{\text{bottom}} \) between the two bottom boxes, as a proxy for buoyancy. The total advection in each box is the sum of the advection in both adjacent cells (except the polar boxes, which only take part in one cell).

It should be noted that the box model only considers thermally driven advection, which assumes a significant seasonal response to  heating. Because of Titan's slow rotation, the mean meridional circulation is expected to extend to the poles (Mitchell et al., 2006); thus, we ignore the effects of dynamics on the latitudinal extent of upwelling and downwelling. Mitchell et al. (2006) also showed that latent heat release could limit the poleward extent of upwelling; here, we do not consider methane thermodynamics and concentrate exclusively on the response due to solar heating.

3.2. Results

Under the zero-opacity insolation distribution, the calculated surface temperature maximum reaches the polar region during solstice, making the summer pole warmer than the equatorial surface by nearly 3 K, and creating a pole-to-pole temperature gradient. The resulting circulation has upwelling and downwelling in the summer and winter hemispheres, respectively (Fig. 3a). Around equinox, the temperature maximum occurs at the equator (Fig. 4), and the circulation's upwelling branch shifts hemispheres, following the pole-to-pole sinusoidal pattern of the insolation.

When forced with the nonzero-opacity insolation distribution, the surface temperature maximum oscillates between northern and southern mid-latitude boxes. The surface temperature difference between equator and pole remains positive year-round (Fig. 4), and is approximately 1 K and up to 5 K in the summer and winter hemispheres, respectively, in agreement with observations (Jennings et al., 2009). Additionally, the surface temperature at the pole is about 1 K warmer in southern summer than northern summer. Upwelling in the model remains at low- and mid-latitude boxes throughout the year, reaching the mid-latitude boxes during summer, with little movement in the polar box (Fig. 3b). The strongest upwelling remains at equatorial latitudes year-round. Summer upwelling at southern equatorial and mid-latitude boxes is stronger than that in the north, due to the effect of the orbital eccentricity on the insolation.

4. Discussion and conclusions

Observations of clouds on Titan suggest an active and important tropospheric circulation, with significant activity at the summer pole (Brown et al., 2002, 2010; Porco et al., 2005; Rodriguez et al., 2009; Turtle et al., 2009, 2011a). A realistic treatment of the attenuation of sunlight in the lower atmosphere, however, indicates that the maximum insolation does not occur over the pole during solstice, posing an obstacle to previous explanations of polar clouds.

Our simple model results highlight the implications of this insolation distribution: Assuming a completely homogeneous surface, the highest surface temperatures would oscillate between mid-latitudes, not the poles, with season, following the maximum insolation. This is in agreement with CIRS measurements of temperature during mid to late southern summer, where the equator was warmer than the summer pole by about 2 K (Jennings et al., 2009). The upwelling arm of a circulation cell (assumed here to be a proxy for possible cloud formation) following this pattern of heating would thus be confined to the mid- and low-latitudes instead of wandering between poles. Still substantial heating of the summer pole, which might be relatively humid due to surface liquids, could still produce convective cloud formation, but in a region of otherwise little vertical motion. Considerable upwelling around the equator during equinox would be consistent with the most recent cloud observations (Turtle et al., 2011a,b), as well as previous models (Mitchell et al., 2006, 2009; Tokano, 2009).

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**Table 1**

List of parameters and constants.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Units</th>
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</thead>
<tbody>
<tr>
<td>( V )</td>
<td>Volume of box</td>
<td>m(^3)</td>
</tr>
<tr>
<td>( T )</td>
<td>Temperature</td>
<td>K</td>
</tr>
<tr>
<td>( \theta )</td>
<td>Potential temperature</td>
<td>K</td>
</tr>
<tr>
<td>( \rho )</td>
<td>Air density</td>
<td>kg m(^{-3})</td>
</tr>
<tr>
<td>( A )</td>
<td>Area of box side</td>
<td>m(^2)</td>
</tr>
<tr>
<td>( S )</td>
<td>Absorbed shortwave radiation</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>( P_{\text{IR}} )</td>
<td>Infrared radiation flux</td>
<td>W m(^{-2})</td>
</tr>
<tr>
<td>( P )</td>
<td>Pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>( k )</td>
<td>Advection parameter</td>
<td>m(^2) s(^{-1}) K(^{-1})</td>
</tr>
<tr>
<td>( u_s )</td>
<td>Surface wind term</td>
<td>m s(^{-1})</td>
</tr>
<tr>
<td>( \epsilon )</td>
<td>Emissivity</td>
<td>Dimensionless</td>
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<table>
<thead>
<tr>
<th>Constant</th>
<th>Description</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>( c_p )</td>
<td>Heat capacity</td>
<td>( 10^7 ) J kg(^{-1}) K(^{-1}) (air)</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>Stefan–Boltzmann constant</td>
<td>( 5.67 \times 10^{-8} ) W m(^{-2}) K(^{-4})</td>
</tr>
<tr>
<td>( P_{\text{ref}} )</td>
<td>Reference pressure</td>
<td>1450 hPa</td>
</tr>
<tr>
<td>( \kappa )</td>
<td>Poisson constant</td>
<td>0.3</td>
</tr>
<tr>
<td>( f )</td>
<td>Drag coefficient</td>
<td>0.002</td>
</tr>
</tbody>
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\( a \) From Flasar (1998).
about the circulation associated with these heating patterns, temperatures). Continued observations of clouds may reveal more low this maximum (and remain lower than southern summer conditions, while northern polar temperatures increase but remain be-

temperatures to shift northward but remain at low to mid-latitudes, while northern polar temperatures increase but remain be-

low this maximum (and remain lower than southern summer temperatures). Continued observations of clouds may reveal more about the circulation associated with these heating patterns, potentially constraining the poleward extent of tropospheric upwelling.

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References


