Temperature Variability in Titan's Upper Atmosphere: The Role of Wave Dissipation

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CGU Meeting, BEIJING, October 2018

Abstract

The mean isothermal temperature of Titan's upper atmosphere varies between 110 and 180 K based on the Cassini Ion Neutral Mass Spectrometer (INMS) measurements (Westlake et al. 2011, Snowden et al. 2013). Existing studies have investigated a number of driving forces including solar EUV heating, magnetospheric electron impact heating, and Joule heating, but none of them contributes to the observed temperature variability (Snowden & Yelle 2014). We investigate in this study the role of wave dissipation, as motivated by the observations of extensive wave structures in Titan's upper atmosphere (Cui et al. 2014). For this purpose, we construct a simple linearized model of wave propagation in Titan's upper atmosphere based on the WKB approximation (Matcheva & Strobel 1999), from which the energy flux and heating rate are calculated as a function of altitude for several selected wave modes likely present on Titan. Our calculations reveal a maximum heating rate of 40 eV cm^3 s^{-1} at around 1280 km, which is only half of the solar EUV heating rate at the same altitude. This implies that wave dissipation is not very likely to be a viable mechanism causing substantial temperature variability in Titan's upper atmosphere. We further speculate that such a temperature variability is an observational bias provided that the characteristic wavelength is comparable with the vertical extent over which the INMS sampled the ambient atmosphere along a typical Cassini encounter with Titan. A Monte Carlo simulation is implemented to verify the above speculation, but we find that, for a reasonable choice of wave parameters, the modeled temperature variability is far insufficient to account for the observations.

Introduction

- Earlier observational data came from Huygens probe and Cassini fly-bys indicated that the thermal structure of Titan's atmosphere is variable and highly complex. The analysis of INMS data in Snowden et al. (2013) showed that the median temperature on the upper atmosphere varied between 112 and 175 K. Therefore, the temperature of Titan's upper atmosphere varies approximately 60 K.
- de La Haye et al. (2007) found that the dayside temperature in Titan's upper atmo- sphere doesn't higher than the nightside value by assuming that the energy source only is solar heating radiation, then the solar heating radiation can not to explain this energy crisis phenomenon.
- The analysis by Snowden & Yelle (2014) indicated that magnetospheric particle precipitation only increases the temperature of Titan's upper atmosphere by 7 K, they are also found that Joule heating and the diurnal variation in HCN abundance can increase in temperature from 145 to 165 K above 1200 km.
- Müller-Wodarg et al. (2006) found that the energy and momentum were absorbed into Titan's upper atmosphere as wave dissipates, and found that the maximum energy carried by waves is about 1.25×10^9 eV cm^{-2} s^{-1}.
- Further analysis by Snowden & Yelle (2014) showed that wave propagation and dissipation can heating or cooling the thermal structure of Titan's upper atmosphere. However, they just estimated the viscous flux of kinetic energy at the order of 30 eV cm^3 s^{-1} at an altitude of 1300 km and the cooling rate due to the sensible heat flux is about -9 eV cm^{-3} s^{-1} for a weakly damped wave, and didn't to calculate in detail.
- The analysis of INMS data in Cui et al. (2013) showed that the observed waves in Titan's upper atmosphere are upward propagating gravity waves and the wavelength is ≈ 730 km and the wave period is ≈ 10 h.

Hydrostatic Gravity Wave Model

The vertical and horizontal wave velocities w′, u′ , the temperature perturbations T′ and the pressure perturbations p′ are the solutions of this theoretical hydrostatic gravity wave model. w′ is solved by assuming that WKB approximation: (Matcheva & Strobel (1999))

$$w' = \Delta W(z)e^{i\varphi} \qquad (1)$$

where the amplitude ΔW (z) and phase φ are defined as:

$$\Delta W(z) = \Delta W(z_0)\sqrt{\frac{k_{zr}(z_0)}{k_{zr}(z)}}\times exp\left[\int_{z_0}^{z}\left(\frac{1}{2H_\rho}-k_{zi}\right)dz\right] \qquad (2)$$

$$\varphi = k_x x + k_y y + \int_{z_0}^{z} k_{zr}dz - \omega_0 t \qquad (3)$$

- u', T' and p' are related with w' by the polarization relations:

$$u' = -\frac{ik_x}{k_h^2}\left(-ik_z+\frac{1}{2H_\rho}\right)w' \qquad (4)$$

$$T' = -\frac{i\Gamma}{\hat{\omega}+i\beta}w' \qquad (5)$$

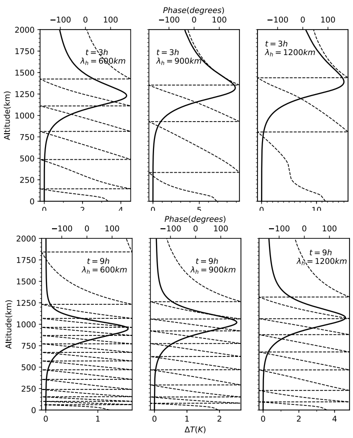
$$p' = \frac{i\rho_0\hat{\omega}}{k_h^2}\left(ik_z-\frac{1}{2H_\rho}\right)w' \qquad (6)$$

Propagation and Amplitude of Gravity Wave

- The analysis by Cui et al. (2013) show that the range of gravity wave period is 80 min to 10 h.
- We select 9 wave models and the properties of these waves are listed in table 1.

Table 1. Summary of gravity wave parameters and the maximum temperature amplitudes and the altitudes at which the waves have their maximum amplitudes

Period τ (h)	λ_h (km)	c_h (km s^{-1})	$(\Delta T)_{max}$ (K)	$z_{(\Delta T)_{max}}$ (km)
3	600	0.06	4.3	1230
3	900	0.08	8.9	1321
3	1200	0.11	15.0	1396
6	600	0.03	2.0	1046
6	900	0.04	4.4	1125
6	1200	0.06	6.5	1184
9	600	0.02	1.6	947
9	900	0.03	2.5	1021
9	1200	0.04	4.6	1076



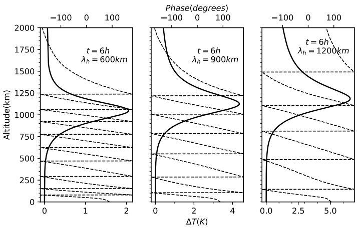


Fig. 1. Altitude profiles of amplitude (denoted by ΔT and given by the solid curve) and phase (dashed curve) of 3 h, 6 h, 9 h-wave models.

Heating or Cooling Rate of Gravity Wave

- The vertically propagating gravity waves can heating or cooling the Titan's atmosphere because they can transport energy and momentum stresses upwardly.
- The profiles of heating or cooling rate for 9 wave models are showed in fig.2. The maximum heating/cooling rates of the total vertical energy fluxes and their altitudes are listed in table 2.

Table 2. Summary of the maximum heating/cooling rates of the total vertical energy fluxes and the altitudes at which the waves have their maximum heating/cooling rates

Period τ (h)	λ_h (km)	Max heating rate (eV $cm^{-3}s^{-1}$)	z at max heatin g rate (km)	Max cooling rate (eV $cm^{-3}s^{-1}$)	z at max heating rate (km)
3	600	14.70	1155	-5.62	1285
3	900	16.62	1223	-7.30	1375
3	1200	41.91	1276	-8.82	1427
6	600	14.44	987	-8.76	1101
6	900	28.05	1059	-13.19	1184
6	1200	34.44	1105	-13.24	1238
9	600	19.70	893	-14.76	1002
9	900	21.95	961	-13.46	1076
9	1200	40.65	1013	-20.79	1133

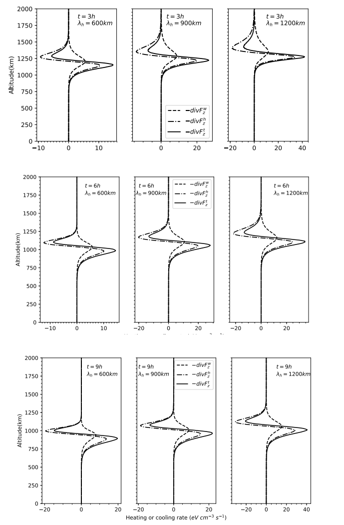


Fig. 2. Heating and cooling rates due to wave dissipation for 3 h, 6 h, 9 h-wave models.

Discussion

- Snowden estimated the viscous flux of kinetic energy on order of 30 eV cm^{-3} s^{-1} approximately near 1300 km altitude and the wave cooling rate due to the sensible heat flux is -9.0 eV cm^{-3} s^{-1} in Snowden & Yelle (2014), there are very close to the values by our calculation for the 3-h wave with horizontal wavelength λ_h = 1200 km.
- Besides, the heating energy flux of EUV is about 4×10^8 eV cm^{-2} s^{-1} above 1200 km altitude by Snowden calculation, and the analysing by Müller-Wodarg showed that the globally averaged EUV energy into the Titan's thermosphere is 3.5 to 5×10^9 eV cm^{-2} s^{-1} in Müller-Wodarg et al. (2006). However, in our calculations, the maximum of the total vertical energy fluxes for the 9 waves models is about 3.5×10^8 eV cm^{-2} s^{-1}, which is lower than the energy flux of EUV by Snowden and Müller-Wodarg calculated.
- To compare the heating energy flux between gravity waves and EUV in detail, we simply calculated the altitude profiles of the photoionization heating rate due to solar radiation, which is showed in figure 3.

- The maximum heating rate of above 9 waves models is 41.91 eV cm^{-3} s^{-1} at 1276 km altitude, while the total photoionization heating rate is 82.95 eV cm^{-3} s^{-1} at the same altitude, and the integrated the total photoionization heating rate is about 1.78×10^9 eV cm^{-2} s^{-1} above 1200 km altitude, these values are all higher than the values by dissipations of above 9 waves models.
- **These results indicates that the dissipations of gravity waves can't explain the large temperature variability in Titan's upper atmosphere.**

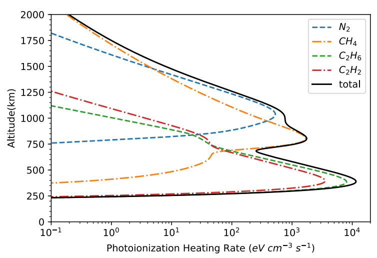


Fig. 3. Photoionization Heating Rate by N_2, CH_4, C_2H_6 and C_2H_2.

Monte Carlo Simulation

- For constituent i, the perturbation of density is expressed as:

$$\delta_i = \frac{n_i-\bar{n}_i}{\bar{n}_i} = A_i cos(k_i(z-z_0)+\phi_i) \qquad (7)$$

where A_i, k_i and ϕ_i are amplitudes, wave numbers, and phases. z_0 is the bottom altitude, n_i is the mean-state number density.

- Now we set ϕ_i~U (0, 2π), A_{N2} ~U (4%, 16%).
- To do the simulation, we select N=10^4 sample points randomly, and take vertical wavelength are 240,300,400 km.
- **The results from above MCS are also insufficient to explain the large temperature variability in Titan's upper atmosphere.**

Table 3. Summary of Results of MCS for N_2

Vertical Wavelength (km)	T_{min} (K)	T_{max} (K)	ΔT (K)
240	150.09	156.07	5.98
300	150.32	155.81	5.49
400	150.23	155.87	5.64

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