An Atmospheric General Circulation Model for Pluto with Predictions for New Horizons

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Received ___________; accepted ___________
ABSTRACT

Results are presented from a 3-D Pluto general circulation model (PGCM) that includes a subsurface model and volatile cycle. Conductive heating and cooling are present, as is non-local thermodynamic equilibrium (non-LTE) heating by methane at 2.3 and 3.3 microns, non-LTE cooling by heating by methane at 7.6 microns, and LTE CO rotational line cooling. The PGCM solves the Navier-Stokes equations, an energy equation, a mass equation, and an equation of state (the ideal gas law) using the infrastructure of the Massachusetts Institute of Technology terrestrial atmospheric general circulation model. As with previous versions of this PGCM, the temperature varies little in the horizontal, and the vertical wind is essentially motionless. The latitudinal wind has small scale structure that we believe to be numerical artifacts. The longitudinal wind is much different in structure than that of Zalucha and Michaels (2013, Icarus, 223, 819-831). In that work, the maximum wind speed was located between 150 and 200 km altitude, was centered over the equator, and was prograde; the poles were weakly prograde; and there was a region of retrograde winds at the equator and winter pole below the altitude region of the maximum wind speed. In the current work, longitudinal winds are of order 1 m/s below 10 km and have a wavenumber-1 structure in longitude. Above 10 km altitude to 75 km altitude (except in one case where this region extends to 130 km), the longitudinal wind is prograde everywhere. Near the summer pole there is a strong prograde jet, representing the global maximum wind speed. Above this region up to 175 km altitude, there is a region of weak, retrograde winds between -60 and 60 degrees latitude. Poleward the winds are prograde. From 175 km altitude to the base of the frictional layer (350 km altitude) there is a wavenumber-1 structure between -60 and 60 degrees latitude, with a local maximum of retrograde winds at 270
degrees longitude and a local maximum of prograde winds at 90 degrees longitude. This model is novel in that it has both detailed subsurface and atmospheric model components. Yet, there is little dependence of the model results on surface albedo, emissivity, or conductivity. In fact, the surface temperature and subsurface temperature are constant, and there is there a sign of volatile transport. This phenomenon may be an effect of the fact that an effectively infinite seasonal frost layer has been assumed in order to deal with the short (much less than a Pluto year) model runs. Predictions are also provided for the Alice and REX instruments on New Horizons and for ground-based stellar occultations. Due to the weak temperature gradients, Alice (both solar and background star consultations) and REX are predicted to observe nearly the same temperature profiles on immersion and emersion. In the stratosphere, differences of up to 20 K are possible, while at higher altitudes (100-350 km), the differences are as large as 10 K. For both methane concentration and initial surface pressure, it should be possible to distinguish between the 0.2 and 1.0 methane concentrations and 8 and 24 microbar initial surface concentrations used here. For the ground-based stellar occultation, there is a detectable difference between light curves with the different methane concentrations used here, but not for the initial surface pressures.

Subject headings: Kuiper belt objects: individual (Pluto) — methods: numerical — occultations — planets and satellites: atmospheres
1. Introduction

The modeling of Pluto’s atmosphere began with its discovery in 1988 by the stellar occultation technique (Elliot et al. 1989). These ranged from mathematically convenient models, such as that of Elliot & Young (1992), which assumed that the temperature dependence with height was a power law, to those of Yelle & Lunine (1989), which used conduction and radiative transfer in the non-local thermodynamic equilibrium (non-LTE) regime to describe heating by CH$_4$ at 3.3 $\mu$m and cooling by CH$_4$ at 7.6 $\mu$m in order to predict temperature with height. This type of radiative-conductive model was expanded to an additional CH$_4$ line at 2.3 $\mu$m and LTE cooling by CO rotational line emission by Strobel et al. (1996), and a troposphere with a user-specified height was added by Zalucha et al. (2011b). Meanwhile, a technique was developed by Elliot et al. (2003a) to invert stellar occultation light curve flux vs. time to temperature vs. height. This algorithm required a boundary condition at the “top” of the atmosphere (usually $\sim$ 100 km altitude, depending on the surface radius assumed), which was then used to integrate downward in the atmosphere (closer to the occultation midtime) assuming only hydrostatic equilibrium, the ideal gas law, that number density was proportional to refractivity, and the equations of light in the geometric limit of optics.

The general result of modeling efforts (e.g., Yelle & Lunine 1989; Hubbard et al. 1990; Elliot & Young 1992; Strobel et al. 1996; Hansen & Paige 1996; Elliot et al. 2003a; Zalucha et al. 2011a, b; Young 2012), spectroscopy (e.g., Owen et al. 1993; Tryka et al. 1993; Lellouch et al. 2009; Greaves et al. 2011; Lellouch et al. 2011), and stellar occultation observations (e.g., Elliot et al. 1989, 2003b; Sicardy et al. 2003; Pasachoff et al. 2005; Young 2012).

1The troposphere is a layer in the atmosphere, if present, in contact with the surface and defined by a temperature that decreases with height. Often, convective processes are present in this layer.
Elliot et al. (2007; Young et al. 2008; Person et al. 2008) is that Pluto’s atmosphere is primarily composed of \( \text{N}_2 \) with trace amounts of \( \text{CH}_4 \) and \( \text{CO} \). Pluto’s surface temperature is \( \sim 37 \text{ K} \). The evidence is inconclusive about the presence of a troposphere and its depth (Stansberry et al. 1994; Zalucha et al. 2011b); otherwise, the lower atmosphere (referred to as the stratosphere) is characterized by a sharp temperature inversion (temperature increasing with height) of \( \sim 5 \text{ K km}^{-1} \). The temperature becomes mostly isothermal at altitudes of \( \sim 100–600 \text{ km} \). Pluto’s surface radius and global mean surface pressure are not precisely known. The latter is thought to be between 6 and 24 \( \mu \text{bar} \) and changing with time\(^2\). Specifically, the temperature underwent an increase, perhaps by as much as a factor of two from 1988 to 2003, and has remained mostly constant since 2003. Based on modeling studies, it is hypothesized that Pluto’s atmosphere sublimates and condenses in vapor pressure equilibrium with surface ice as Pluto orbits the Sun.

An important aspect of the models mentioned so far is that they ignore the transport of heat by wind and adiabatic heating and cooling due to downward and upward motions of air. There is no \textit{a priori} reason to suspect that Pluto’s atmosphere lacks wind; thus modelers have begun investigating wind using what are called general circulation models (GCMs) for both Pluto and its sister world Triton (Mueller-Wodarg et al. 2001; Vangvichith & Forget 2011; Michaels & Young 2011; Miller et al. 2011; Zalucha & Gulbis 2012; Toigo et al. 2013; Zalucha & Michaels 2013). GCMs solve the Navier-Stokes equation, continuity of mass and energy, and an equation of state on a global scale with a horizontal resolution of a few degrees and a vertical range of several scale heights. They are advantageous because they solve the system of equations describing geophysical fluid dynamics, but disadvantageous because they are computationally expensive. The list of citations above represent six different efforts at transforming terrestrial GCMs to Pluto, using knowledge of other solar

\(^21 \mu \text{bar} = 0.1 \text{ Pa} \)
system bodies with atmospheres where applicable. The mystery of Pluto’s wind structure at present cannot be answered observationally, since by nature wind is difficult to observe remotely except in certain situations (e.g. cloud movements, ocean roughness, surface dunes), and Pluto is barely resolvable from Earth \cite{Buie2010}. Thus, GCMs are extremely important for knowing Pluto’s atmospheric circulation, which in turn affects its 3-D temperature field, surface pressure, and transport of volatiles. Currently there is no common consensus among these GCMs as to Pluto’s circulation.

Another milestone in Pluto science is about to occur, when NASA’s New Horizons mission becomes the first spacecraft to fly by Pluto on 2015 July 14. New Horizons, among other things, will constrain Pluto’s size, take detailed images of Pluto’s surface, and perform atmospheric measurements. The two main instruments on New Horizons that will study the atmosphere are Alice \cite{Stern2008} and the Radio science Experiment (REX, Tyler et al. 2008). Alice is an ultraviolet imaging spectrometer. Alice has two modes: one that will study the airglow emission (a collection of processes that occur in the upper atmosphere at night) of Pluto’s atmosphere and one that will perform occultations experiments. The particular configuration of the PGCM used in this study cannot predict airglow; thus, the latter capability is of interest here. The first type of occultation will be when Pluto occults the Sun, such that sunlight shines through Pluto’s atmosphere and is received by New Horizons. The second type of occultation will be similar, except Pluto will occult a background star. These types of occultations, described in Section 5, derive temperature based on the attenuation of light due to differential refraction of light through an atmosphere.

REX will perform a different type of occultation experiment. REX will receive radio waves sent from Earth as they pass through Pluto’s atmosphere. The observed frequency modulation, again due to differential refraction of light through an atmosphere, allows
for the retrieval of temperature with altitude. A key point of REX’s observations is the temperature will be measured down to the surface (and the surface radius of Pluto itself will be for the first time well constrained), something that ground-based stellar occultations cannot do. For Pluto, ground-based stellar occultations measure down to about 20 km altitude (e.g. Zalucha et al. 2011a). This inability to measure temperature to the surface has to do with the fact that the S/N ratio near the midtime of the light curve becomes too low, and these observations essentially “run out of light.” The fundamental difference between UV, solar, or IR occultations (as typically performed in ground-based studies) vs. radio occultations is what will allow for a temperature measurement near the surface for the first time, illuminating whether or not Pluto has a troposphere (lowest layer of an atmosphere in contact with the ground that is characterized by decreasing temperature with height), which is a current open question (Stansberry et al. 1994; Lellouch et al. 2009; Zalucha et al. 2011b).

In this paper, the development of the Zalucha & Gulbis (2012) (hereinafter known as ZG12) and Zalucha & Michaels (2013) (hereinafter known as ZM13) line of Pluto GCMs (PGCMs) is continued. The former was a 2-D PGCM (latitude, height, and time) and the latter was a 3-D PGCM (longitude, latitude, height, and time). The main difference with adding the longitude direction is that (transverse) waves in the longitudinal direction were allowed, which added another degree of freedom to dissipate artificial numerical noise, specifically inertial instabilities. ZM13 did not show any vertical or latitudinal motion for the years 1988–2006 (the current stellar occultation observational record). A prograde jet is present at the equator with a maximum magnitude of 10–12 m s$^{-1}$. The surface pressure predicted for 1988, when compared with observed stellar occultation light curves, was $8 \pm 4 \mu$bar. Likewise for 2002 and 2006 it was $20 \pm 4 \mu$bar, and for 2007 it was $16 \pm 4 \mu$bar. All years had a greater than 1% concentration of CH$_4$, which was higher than other measurements.
The first upgrade to the PGCM of ZM13 was to include the volatile cycle. This modification has already been tested, since this physical process is part of the Mars version of the GCM. A multilayer subsurface specification has also been added. The PGCM of ZM13 contained a slab model (i.e. one subsurface layer). Since on Pluto the insolation is so weak, the subsurface terms in the surface temperature balance equation become more important. The values of bulk surface and subsurface properties such as surface N$_2$ ice inventory, emissivity, thermal inertia, and subsurface temperature are not well constrained for Pluto. Here we vary related quantities, conductivity, albedo, emissivity, and subsurface temperature to see how they effect the atmospheric circulation. In Section 2 we describe the model, in Section 3 we describe the simulation setup, in Section 4 we show simulation results for key variables (temperature, wind, and surface pressure) and provide interpretation of the model results, in Section 5 predictions of visible-wavelength stellar occultation light curves that ground-based observers would expect to see at the time of the New Horizons encounter are made, and in Section 6 predictions of temperature profiles that will be observed by Alice and REX are made. The date for the ground-based predictions is arbitrary, as at present no ground-based stellar occultations are predicted to occur at that time. At present, it is not known if Pluto will stay in this state for several decades (given Pluto’s 248 Earth-year long year and sluggish atmosphere) or if there will be a sudden atmospheric collapse (Young 2012). In Section 7 a discussion is provided about speculations future regarding multi-year simulations.

2. The Model

The PGCM is based off of the Massachusetts Institute of Technology (MIT) atmospheric GCM (Marshall et al. 1997). The model solves the primitive equations of geophysical fluid dynamics in 3-D using the finite volume method on an Arakawa C-grid. These equations
are: horizontal momentum

\[
\begin{align*}
\frac{Du}{Dt} + \frac{\partial \Phi}{\partial x} - f v &= F_x, \\
\frac{Dv}{Dt} + \frac{\partial \Phi}{\partial y} + f u &= F_y,
\end{align*}
\] (1)

where \(D[\ ]/Dt = \partial[\ ]/\partial t + \nabla \cdot [\ ]\) is the total derivative, \(u\) is the velocity (relative to the body’s surface) in the longitudinal direction, \(v\) is the velocity in the latitudinal direction, \(x\) is linear distance in the east direction, \(y\) is linear distance in the north direction, \(t\) is time, \(\Phi\) is the geopotential \((gz, \text{where } g\) is the gravitational acceleration at the surface and \(z\) is height), \(f = 2\Omega \sin \phi\) is the Coriolis parameter (where \(\Omega\) is the body’s rotation rate and \(\phi\) is latitude), and \(F_x\) and \(F_y\) are external forcings, in this case friction and velocity drag;

vertical momentum in the hydrostatic approximation

\[
\frac{\partial \Phi}{\partial p} = -a,
\] (3)

where \(p\) is pressure and \(a\) is the inverse of density; an equation of state, in this case the ideal gas law

\[
p a = RT,
\] (4)

where \(R\) is the specific gas constant (the universal gas constant divided by the average molecular weight of the atmospheric constituents) and \(T\) is temperature; mass equation

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega}{\partial p} = M,
\] (5)

where \(\omega\) is the vertical velocity in pressure coordinates and \(M\) is the mass source or sink term due to condensation or sublimation; and an energy equation

\[
c \frac{DT}{Dt} + p \frac{Da}{Dt} = J,
\] (6)

where \(c_v\) the specific heat at constant volume and \(J\) is an external heating and cooling term described below.
In the MIT GCM, the vertical coordinate used is not exactly pressure as described in Eqs. 1–6 but instead a modified pressure coordinate. This coordinate system defines the vertical position of a point in the atmosphere as a ratio of the pressure difference between that point and the top of the domain to that of the pressure difference between the surface and the top of the domain. The thickness of each layer at each horizontal point is allowed to compress and expand and is described by a fraction of the original thickness, or a factor of 1.0. In practice, the fluctuations are small ($\leq |0.1|$).

The forcing terms in Eqs. 1 and 2 include a number of effects. The first is surface friction, represented by a simple drag law $-k_v u$ and $-k_v v$, where

$$k_v = k_f \max\left(0, \frac{p - p_b}{p_o - p_b}\right). \tag{7}$$

Here $p_b$ is the pressure top of the frictional layer and $p_o$ is the surface pressure. We allow $p_b/p_o = 0.7$ in accordance with the original Earth (and Mars) model, as we have no data to constrain it for Pluto. Also in the horizontal momentum forcing term is a "frictional" term at the model top. In a model atmosphere, a rigid lid (i.e., $\omega=0$) is applied at the model top that does not exist in the real world. This model top can cause spurious wave reflections off the lid that are nonphysical. In the real atmosphere, upward propagating waves will be damped by gravity (buoyancy) waves in the upper atmosphere. The properties of these waves can vary with time and space. Since we have no way to calculate such a coefficient, we run the model with a constant drag coefficient set at different orders of magnitude and spanning a different number of top levels to see which configuration does not damp the upper atmosphere so much that it acts like part of the rigid lid, while preventing wave reflections. In general, the coefficient’s magnitude must increase with height. It was found that the best value for the coefficient is for drag in the top three model levels (out of 30 model levels total), which are from the top downwards: 0.0001013799, 0.0000337933, 0.0000112644. Finally, an 8th-order Shapiro filter is included in the momentum forcing.
term to damp subgridscale, numerical noise.

The energy forcing term in Eq. 6, i.e., heating and cooling terms, were taken from Strobel et al. (1996). The 1-D heat equation is

\[ c_p \rho(r, t) \frac{\partial T(r, t)}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 K \frac{\partial T(r, t)}{\partial r} \right) + R_{\text{net}}(r, t), \]  

(8)

where \( c_p \) is the specific heat at constant pressure, \( \rho(r, t) \) is the air density, \( K \) is the thermal conductivity, and \( R_{\text{net}}(r, t) \) is the heating rate. For Pluto a primarily N\(_2\) atmosphere with smaller amounts of CH\(_4\) and CO was assumed. For an N\(_2\), CH\(_4\), and CO mixture,

\[ K(r, t) = K_\alpha T(r, t)^\alpha \]  

(9)

where \( K_\alpha = 5.63 \times 10^{-5} \text{ J m}^{-1} \text{ s}^{-1} \text{ K}^{-(\alpha+1)} \) and \( \alpha = 1.12 \) (Hubbard et al. 1990). The most mathematically complex part of the model is the specification of \( R_{\text{net}}(r, t) \), which is the sum of the non-LTE heating rate by solar near-IR absorption in the CH\(_4\) 2.3 and 3.3 \( \mu m \) vibrational bands, the non-LTE cooling rate due to the CH\(_4\) 7.6 \( \mu m \) vibrational band, and the LTE cooling rate by CO rotational line emission. In the ZG12 specification of the model, the disk-averaged insolation was been replaced with a fully longitudinally, latitudinally, and seasonally varying insolation. Finally a stratosphere only configuration (Zalucha et al. i.e., no troposphere is present as in 2011b) was assumed.

The PGCM is capable of undergoing mass changes due to freezing and sublimation by the primary atmospheric constituent (as \( \beta \)-phase N\(_2\) ice), represented by \( M \) in Eq. 5. If the atmospheric or surface temperature falls below the freezing point, the amount of heat needed to return it to the freezing point is calculated, and this heat is provided by latent heating due to mass freezing out of the atmosphere. This mass is instantaneously removed from the atmosphere (in the case of a surface temperature below freezing, the mass is taken out of the lowest model layer) and added to the surface ice inventory. If the surface is ice-covered and the temperature is predicted to be greater than the freezing point, the
excess energy is used to sublimate an amount of mass such that the surface temperature returns to the freezing point. The sublimated mass is added to the lowest model layer.

The subsurface, assumed to be H\textsubscript{2}O, has a temperature specified by

\[ \rho_{ss} c_{ss} \frac{\partial T_{ss}}{\partial t} = \kappa_{ss} \frac{\partial^2 T}{\partial z^2}, \]  

(10)

where \( \rho_{ss} \) is the density of the subsurface, \( c_{ss} \) is the specific heat of the subsurface, \( T_{ss} \) is the temperature of the subsurface, \( z \) is now extended below the surface (to negative values), and \( \kappa_{ss} \) is the thermal conductivity of the subsurface. A subsurface with 25 layers is assumed. Eq. (10) is a simple diffusion relationship. The discrete form of Eq. (10) is

\[ \rho_{ss} c_{ss} \frac{T_{j}^{n+1} - T_{j}^{n}}{\Delta t} = \kappa_{ss} \frac{T_{j+1}^{n} - 2T_{j}^{n} + T_{j-1}^{n}}{\Delta z^2}, \]  

(11)

where \( n \) indicates the time index and \( j \) indicates the level. Defining \( \beta = \kappa_{ss} \Delta t / \rho_{ss} c_{ss} \Delta z^2 \), the subsurface temperature is time marched by

\[ T_{j}^{n+1} = \beta T_{j+1}^{n} + (1 - 2\beta) T_{j}^{n} + \beta T_{j-1}^{n}, \]  

(12)

noting for the bottom level the third term on the right hand side disappears and the “2” in the second term on the right hand side becomes “1.”. Also, for the top level (\( j = 1 \)), \( T_{j+1}^{n} \) is taken to be the surface temperature. The surface temperature \( T_{s} \), in discrete form, is given by

\[ T_{s}^{n+1} = T_{s}^{n} + \frac{\Delta t}{c_{s} \Delta z \rho_{s}} \left[ S - \epsilon_{s} \sigma (T_{s}^{n})^4 - \kappa_{s} \frac{\Delta z}{\Delta z} (T_{s}^{n} - T_{1}^{n}) \right], \]  

(13)

where \( c_{s} \) and \( \rho_{s} \) are the specific heat and density of the surface layer, which may either be seasonal N\textsubscript{2} frost or the bare subsurface. Note that the subsurface does not sublimate or freeze in this model, consistent with the fact that no water ice has yet to be observed in Pluto’s atmosphere. The terms in Eq. (13) from left to right are insolation \( S \), emission by the surface with \( \epsilon_{s} \) being the emissivity of the surface and \( \sigma \) is the Stefan-Boltzmann constant, and conduction between the surface and the upper subsurface layer (where \( \kappa_{s} \)
is the conductivity of the surface). The layer thickness $\Delta z$, is one fourth the skin depth $Z = \kappa_{ss}/\Gamma_{ss}\Omega$. Here $\Gamma_{ss}$ is the thermal inertia of the subsurface, equal to $\sqrt{\rho_{ss}c_{ss}\kappa_{ss}}$.

In the horizontal, a cubed-sphere grid (Adcroft et al. 2004) with $32 \times 32$ points per cube face is used, equivalent to a grid spacing of $2.8^\circ$ at the equator. Compared to the more common cylindrical projection grid (i.e., a latitude and longitude grid), this type of horizontal grid eliminates singularities at the poles that force northward and southward winds to zero and removes the requirement for artificial Fourier filtering in the high latitudes (in order to maintain a practical time step). Note that the coordinate convention of ecliptic north, longitude increasing (Zangari 2015) is used, which is opposite of the current IAU convention. Lastly, a surface radius of 1180 km is assumed (Zalucha et al., 2011a).

3. Model Setup

The atmosphere of Pluto is “sluggish” in a thermal sense in that the radiative time constant is long, or in other words responds slowly to changes in radiative forcing. The timescale in the lower atmosphere is of order of a few weeks, while the timescale in the upper atmosphere can be a significant fraction of an Earth year. In Mars GCMs, where the radiative time constant is two to four Earth days, and in Earth GCMs, where the timescale is tens of days, the initial temperature structure may be set to any value as long as it is not too pathological, and the model will respond and equilibrate over a reasonable amount of wall clock time. For Pluto, beginning with a constant temperature and globally quiescent wind does not converge fast enough to be computationally reasonable, telling us at least that these initial conditions are far from the equilibrium state. The radiative-conductive equilibrium (i.e. steady state, quiescent wind) is then a logical choice for an initial condition as it may be quickly calculated and is assumed to be near the fully spun-up, quasi-equilibrium state. However the temperature gradients in this configuration are so
strong that a prohibitively small time step is required in the initial stages for stability. (GCMs do not employ variable time stepping methods, since this practice can result in different amounts of solar energy being observed from one day to the next.) A hybrid method to spin-up the model has been developed as follows.

First, the initial temperature was set to a constant value globally with quiescent winds. The surface and subsurface temperatures were held constant and the volatile scheme is turned off. Then, the technique of Newtonian relaxation was used to thermally force the model in place of the direct heating and cooling rates from the Strobel et al. (1996) model. Newtonian relaxation is a method by which the forcing term in the energy equation goes as

$$\frac{\partial T}{\partial t} = -\frac{(T - T_{eq})}{\tau},$$

(14)

where $T_{eq}$ is the radiative-conductive equilibrium temperature and $\tau$ is the radiative time constant. A value of $\tau = 30$ Earth days has been found to require a weak enough forcing while affording a minimal amount of wall clock time. The model was run in this configuration for 90 model Earth days. Then, using the MIT GCM’s restart feature, the model was restarted, now with the heating and cooling rates specified directly from Strobel et al. (1996) (i.e., not Newtonian relaxation), surface and subsurface evolution, and volatile scheme. From then the model was run from the year 1985 to 2015, i.e., spanning the observational epoch of stellar occultation observations and NASA’s New Horizons Pluto flyby.

Table I shows the parameters of each experiment (each simulation will be referred to by its simulation number hereinafter). The emissivity, albedo, and subsurface conductivity span the lower and upper values used by Hansen & Paige (1996). The surface pressure and CH$_4$ concentration span the values of Zalucha et al. (2011a) (note that the pressure values closely span the range found by Lellouch et al. 2009, who found a CH$_4$ concentration of 0.5%). The albedo and emissivity are the same for the surface and subsurface, while

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**Table I**

| Simulation | Parameters |
|------------|------------|
| 1          | Emissivity: 0.1, Albedo: 0.3, Subsurface Conductivity: 0.05 |
| 2          | Emissivity: 0.2, Albedo: 0.4, Subsurface Conductivity: 0.07 |
| 3          | Emissivity: 0.3, Albedo: 0.5, Subsurface Conductivity: 0.09 |

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the conductivity in Table 1 is for the subsurface. For the subsurface, the density and surface heat capacity are 936 kg m$^{-3}$ and 960 J kg$^{-1}$ K$^{-1}$, respectively; for the seasonal N$_2$ ice, the density, specific heat, and conductivity are 1000 kg m$^{-3}$, 1340 J kg$^{-1}$ K$^{-1}$, and 0.2 J m$^{-1}$ K$^{-1}$ s$^{-1}$, respectively. It was assumed that there was an effectively infinite amount of seasonal surface ice (i.e. N$_2$), to conform with surface observations showing detections of surface ice over the observational epoch. Surface models by Hansen & Paige (1996) show that for some configurations, seasonal ice is absent from some locations. The assumption of global N$_2$ ice will be relaxed in future papers in this series, when multi-year Pluto runs will be performed to spin-up the volatile cycle and in turn the distribution of ice on the surface.

4. PGCM Results and Discussion

4.1. Temperature

The surface temperature is $\sim$38 K, i.e. the N$_2$ freezing temperature, globally for all cases. This finding is not surprising, since the initial amount of surface frost was effectively set to infinity globally. The subsurface temperature is equal to the surface temperature and does not vary with depth. Furthermore, the subsurface temperature and other model variables do not seem to depend on any of the subsurface properties, i.e. emissivity, albedo, and conductivity. This result contradicts the findings of Hansen & Paige (1996), whose study spanned over a millennium, or over 4 Pluto years. It is possible the the short run time of our simulations (0.12 Pluto years) is not enough to produce significant change. Moreover, our results may differ when the initial condition of globally infinite surface frost is relaxed. A future paper in this series will explore multi-Pluto year simulations with different amounts and distributions of initial surface ice.
Given the results above, the simulation results in this paper depend most heavily on the initial surface pressure and CH$_4$ concentration. Thus, referring to Table 1, simulations 335–342 comprise one group, 343–350 another, 351–358 another, and 359–366 the last. Turing now to the atmospheric quantities, the temperature shows little longitudinal (i.e. diurnal) variation. This property is to be expected since Young et al. (2008) and ZM13 found that the timescale for radiative forcing is much longer than a Pluto day. In Figs. 1–4 the longitudinally averaged temperature as a function of altitude and latitude are shown for 2015 July 14. For all cases, the average altitude corresponding to that level is displayed by converting pressure assuming a scale height of 50 km. As also found by ZG12 and ZM13, the latitudinal temperature gradient is small. In Figs. 1 and 2, the temperature is warmer than Figs. 3 and 4 because the bulk effect of a higher CH$_4$ concentration.

The effect of initial surface pressure is somewhat less straightforward. Comparing Figs. 1 and 2, it would seem that lower initial surface pressure corresponds to higher temperature at a given level. Because CH$_4$ is represented in the atmosphere by a percentage of the total atmospheric mass, a higher initial surface pressure, i.e. more massive atmosphere, means a larger amount of CH$_4$ and in turn a warmer atmosphere. Yet, the opposite appears to be true. This contradiction is an artifact of the way temperature has been plotted. Had Figs. 1 and 2 been plotted with pressure as the ordinate, it would be apparent that higher initial surface pressure corresponds to warmer temperatures at all altitudes. At altitudes of ~250 to 500 km, the temperature is almost isothermal, except for subtle effect of heating by the CH$_4$ 2.3 and 3.3 $\mu$m lines and cooling by the 7.6 $\mu$m line. The temperature profile “wobbles” by about 10 km in this region, and the altitudes of local maxima and minima occur at different locations (see Fig. 8 of Zalucha et al. 2011a for an example) depending on the initial surface pressure.
4.2. Longitudinal Wind

In Figs. 5–8 the longitudinally averaged longitudinal wind (westward positive and prograde) is shown as a function of altitude and latitude for 2015 July 14. In all cases, the wind in the lowest 10 km is light (less than 2 m s\(^{-1}\)). This bulk measurement does not rule out small-scale phenomena such as plumes, dust devils, or flows from local topographic forcing; it is simply that the PGCM has a resolution of 50–60 km, which is too coarse to resolve such flows. Just above 10 km altitude the winds are westward at all latitudes until about 75 km altitude where they change sign near the equator (except in Fig. 7 where the sign change occurs at 130 km altitude). This equatorial region of eastward winds extends from about ±30° latitude. Note that this is approximately the width of Earth’s tropics, but we believe this delineation is purely coincidental, since Pluto has a much different rotation rate, size, and horizontal temperature gradient compared with Earth. The eastward winds are less than the westward winds, and the former do not exceed 4 m s\(^{-1}\) in magnitude at any altitude.

In all cases, the winds are westward in the southern (i.e., winter) hemisphere south of −30° latitude, with the exception of a narrow range of eastward winds between 200 and 250 km altitude for 8 µbar initial surface pressure and 0.2% CH\(_4\) concentration (Fig. 7). The maximum westward wind occurs between −75 and −70° latitude at an altitude of 60 km for CH\(_4\) concentrations of 1% and an altitude of 100 km. The maximum wind speed is of order 10 m s\(^{-1}\). It is unclear if these westward winds are due to the seasonal asymmetry in insolation, in cyclostrophic balance (balance between centrifugal and pressure gradient forces driven by the latitudinal temperature gradient) as in ZG12, or having to do with volatile transport. The winds in the northern (i.e. summer) hemisphere north of 30° latitude are mostly westward as well, but slightly weaker. The altitudes and latitudes of local maxima are mostly symmetric with the southern hemisphere.
Note that the structure of longitudinal winds does not at all resemble that of ZM13. While the maximum westward and eastward winds (12 m s\(^{-1}\) and 2 m s\(^{-1}\), respectively) are of the same order of magnitude, ZM13 found a westward maximum at the equator and 175 km altitude. Between 50 and 175 km altitude there was a region of weak eastward winds northward of \(\pm 30^\circ\) latitude, and weak westward winds south of this latitude. Below 50 km altitudes the winds were light and lacked structure with regards to direction. The only similarity is that the maximum of the westward winds is of the same order of magnitude of the present study. The differences between the model configurations are that ZM13 used the radiative-conductive scheme of Yelle & Lunine (1989) (no CO or 2.3 \(\mu\)m CH\(_4\) line), the drag at the model top that was several orders of magnitude stronger, no volatile cycle was used, and the spin up procedure that did not include the Newtonian relaxation step (see Sec. 2). It is difficult to pinpoint which one or more of these four elements causes the difference without a significant number of further simulations.

Figures 9–12 show horizontal cross-sections of longitudinal wind at key altitudes. Near the surface (upper left panels), the wind is weak, but there is a distinct wavenumber-1 pattern between westward and eastward directions. At the next altitude shown (56 km, upper right panels), the winds are everywhere westward. Near the south pole, as noted in the discussion of longitudinally averaged longitudinal winds, there is a strong westward jet that is of constant strength with longitude. Elsewhere (except very near the north pole), the winds are also westward, but there is a local minima near 270\(^\circ\) longitude and a local maxima near 90\(^\circ\). At 148 km altitude, the winds are weakly eastward between \(-30^\circ\) and 30\(^\circ\) latitude (except for an area of westward winds in the 24 \(\mu\)bar, 1% CH\(_4\) case) with a slight variation with longitude. The winds are relatively strongly westward near the poles. Finally, at 307 km altitude, there is a wavenumber-1 structure between \(-60^\circ\) and 60\(^\circ\) latitude, with a local maximum of eastward winds at 270\(^\circ\) longitude and a local maximum of westward winds at 90\(^\circ\) longitude. Poleward of these latitudes, the location of
the eastward and westward maxima are shifted by 180°.

4.3. Latitudinal and Vertical Wind

As in ZG12 and ZM13, the vertical wind is essentially motionless. ZM13 showed that the cause was the steep stratospheric temperature inversion, which creates very stable conditions and prevents any vertical movement. ZG12 and ZM13 also found that the latitudinal wind was essentially motionless. In this study, there is some motion up to 2 m s\(^{-1}\) in magnitude, mostly in the form of inertial instabilities (a numerical instability wherein the winds change sign with each vertical grid point) at the equator. It could be that vertical diffusion of momentum, a physical force that is not included in the PGCM as it is not a large term in the Navier-Stokes equations for Earth’s atmosphere, would damp the inertial instabilities in the real Pluto atmosphere, and should be included in future versions of the model.

Finally, there is no evidence of volatile transport in the latitudinal velocity field. This property is expected from surface models of Pluto (Hansen & Paige 1996; Young 2012) that include volatile transport and Mars GCMs. In Mars GCMs, there is a net flow from the sublimating pole to the freezing pole at all levels (named the condensation flow). As ZM13 pointed out, any volatiles sublimated from the surface would not be able to rise very high due to the aforementioned highly stably stratified lower atmosphere, and so volatile transport would be confined to a thin layer near the surface. The thickness of this layer is not known. Future work may include a model with a higher vertical resolution near the surface to locate any condensation flow.
5. Model Stellar Occultation Light Curves

Stellar occultation light curves produce a data product in the form of number of photon counts (flux) vs. time (see Elliot & Olkin 1996, for a review). To turn this data into a form that is more physically intuitive, the data are fit or inverted to obtain temperature vs. altitude (or radius from Pluto’s center). This inversion technique can induce large errors between the inverted temperature profile and the true temperature profile (as tested with synthetic light curves). Model fits assume a certain structure. Thus, when comparing light curve models, it is best to take a temperature profile and carry out the forward problem—calculate a model light curve and compare data and model in the flux vs. time (or flux vs. altitude) regime.

Chamberlain & Elliot (1997) and Zalucha et al. (2011a) describe in detail how to calculate a model light curve. Here the procedure is briefly summarized. Given a temperature profile as a function of pressure (in this case from the PGCM), we may use the ideal gas law and the law of hydrostatic balance to obtain number density as a function of distance from Pluto’s center. The number density is proportional to the refractivity, and using the laws of geometric optics, we may obtain the bending angle and its derivative with radius. Once these quantities are known, along with the distance from the observer to the occulting body, a light curve may be calculated.

Figure 13 shows an example of what ground-based observers would observe in the year 2015 given different atmospheric configurations. Extinction by aerosols or other particles has not been taken into account, since including them would be inconsistent with the PGCM not accounting for their radiative effects; thus, an upturn (i.e., the central flash due to diffraction around Pluto’s disk) is present near the middle of the light curve. The light curve has been cast as intensity vs. altitude in Pluto’s atmosphere. To convert a particular observing geometry and the quantities that are measured, i.e. flux vs. time, one uses the
equations:

\[ s(r) = r + D \theta(r) \]  
\[ t = t_{\text{mid}} \pm \sqrt{\frac{s(r)^2 - s_{\text{mid}}^2}{V^2}} \]

where \( s \) is the observer’s position in the shadow (observer’s) plane, \( r = z + r_s \) (where \( r_s \) is the body’s radius) is the distance from the body’s center in the body (Pluto) plane, \( D \) is the distance between the observer and the body, \( \theta \) is the bending angle, \( t_{\text{mid}} \) is the midtime of the occultation, \( s_{\text{mid}} \) is the distance of closest approach (i.e., impact parameter) in the shadow plane, and \( V \) is the relative velocity between the observer and the body. In Fig. 13, there is a clear difference between the light curves derived from PGCM simulations with different CH\(_4\) concentrations and a sight difference between light curves derived from simulations with different initial surface pressures. The shape of a light curve depends on the temperature gradient with height in the atmosphere (Elliot & Young 1992). The behavior of the light curves is consistent with the PGCM temperature results (Figs. 1–4), where there is a larger difference between the cases with different CH\(_4\) concentrations (c.f. 1 and 3, 2 and 4) than there is between different initial surface pressures (c.f. 1 and 2, 3 and 4). This behavior of the light curves is opposite that of Zalucha et al. (2011a), who found that when using the steady state version of the Strobel et al. (1996) model, the greatest difference appeared in light curves of different surface pressure and the difference between CH\(_4\) concentrations was secondary.

There is some difference in how the Strobel et al. (1996) was applied in Zalucha et al. (2011a) and this work. First, the original Strobel et al. (1996) version assumed disk averaged radiation, while in the process of implementing it into the PGCM, dependence on insolation in the column as a function of latitude, longitude, and season was added. Second, when the temperature is calculated in the PGCM, it is subject to not only the heating and cooling terms of Strobel et al. (1996), but also other temperature modifying terms:
advection, adiabatic heating and cooling, and numerical filters. These in turn interplay with the entire system of equations that comprise the GCM. We are certain we have implemented the Strobel et al. (1996) model into the PGCM, because if the calls to the dynamics and other modules are de-activated, the results of the stand-alone Strobel et al. (1996) model are recovered. In summary, a ground-based observer would be able to distinguish between CH$_4$ concentrations of 0.2% and 1% using the PGCM, but probably not between pressures of 8 and 24 $\mu$bar.

6. Predictions for New Horizons

When a radio occultation experiment is performed, radio waves of a known frequency are transmitted through an atmosphere and are measured by a receiver. The rays bend as they travel through the atmosphere due to diffraction of light in a medium. Unlike shorter wavelengths of light, the differential refraction (i.e. flux difference) of radio waves due to the density gradient in an atmosphere is too small to be measured. What is measured is the difference in Doppler-shifted frequencies due to light traveling through the atmosphere compared with empty space. The bending angle can be calculated given precise knowledge of the geometry of the transmitter and receiver (Hinson et al. 1999) in the limit of geometric optics. The bending angle as a function of impact parameter relative to the occulting body’s center may then be transformed into the refractive index as a function of radius from the occulting body’s center. The index of refraction, rather than the refractivity, is proportional to the number density, and using the ideal gas law and the assumption of hydrostatic balance, temperature as a function of height may be obtained. The solar and stellar occultation experiment to be performed by Alice use the same equations as in Section 5.

Table 2 shows the longitudes and latitudes that each of the New Horizons occultation experiments will probe. Figs. 14, 16 show the temperature profiles predicted to be observed
by Alice (sun), Alice (background star), and REX. There is little difference between the
immersion and emersion profiles and the different experiments, owing to the weak horizontal
temperature gradients described in Section 4.1. The effect of CH$_4$ concentration may be seen
(c.f. solid and dotted, dashed and dot-dashed lined) and initial surface pressure (c.f. solid
and dashed, and dotted and dot-dashed). Near 25 km altitude, the temperature profiles
derive by as much as 20 K, which will be distinguishable by New Horizons. Above 50 km
altitude, the maximum difference is as much as 10 K, which is still distinguishable, but in
some places the difference is zero. However, as we are comparing the whole temperature
profile and not individual points, the PGCM should be able to tell the difference between
different initial surface pressures and CH$_4$ concentrations. Further simulations may be
needed to pinpoint the combination of initial surface pressure and CH$_4$ concentration, which
can be carried out if necessary.

7. Conclusions

This paper has presented results from a PGCM based on the MIT GCM. It has
continued the work of ZG12 and ZM13, who also used the MIT GCM as a basis. This
latest version uses the radiative-conductive scheme of Strobel et al. (1996) for atmospheric
heating and cooling, which adds cooling by CO and heating by the 2.3 $\mu$m CH$_4$ line to the
Yelle & Lunine (1989) model used in previous versions; a volatile cycle; a subsurface model;
a drag force (to prevent reflections off the artificial model top and represent buoyancy
waves) at the model top that is several orders of magnitude weaker than previous versions;
and a spin up procedure that has Newtonian relaxation step at the beginning to more
gradually initialize the model, which allows for a larger time step (and thus a more efficient
use of super-computing time). The most important aspect of this model of Pluto is that it
has both a detailed subsurface and atmospheric model, something no model in the literature
possesses. Equally important, the PGCM can predict wind, a quantity that is difficult to measure remotely.

It was found that the surface and subsurface temperature were constant, and that there was no dependence on surface albedo, emissivity, or conductivity. It is possible that this finding will be chance once the assumption of effectively infinite surface N₂ ice is relaxed, and the bare water ice subsurface can be uncovered. As in ZM13, there is effectively no longitudinal (diurnal) temperature variation, and the latitudinal temperature gradient is small. The first property follows from the estimation that the radiative timescale is much longer than a Pluto day. However it has yet to be explained why a large latitudinal gradient is not possible on Pluto. This too could change when the assumption about the surface ice is relaxed.

The vertical wind is effectively motionless, due to high vertical stability of the lower atmosphere. The latitudinal wind sums to zero, but has inertial instabilities of amplitude 2 m s⁻¹ at the equator. The longitudinal wind has a completely different structure than ZM13 (and ZM12, but this is to be expected since that model was 2-D), but the maximum magnitude of order 10 m s⁻¹ is the same. In the current study, the longitudinal winds are of order 1 m s⁻¹ below 10 km. There is a wavenumber-1 structure in this altitude zone in the longitudinal direction. Above 10 km altitude upwards to 75 km altitude (except in one case where this region extends to 130 km altitude), the wind is westward everywhere. Near the south pole there is a strong westward jet, representing the global maximum wind speed. Above this region up to 175 km altitude, there is a region of weak (∼1 m s⁻¹) eastward winds between ±30° latitude. Poleward of this latitude the winds are westward. From 175 km altitude to the base of the drag layer (350 km altitude) there is a wavenumber-1 structure between ±60° latitude with a local maximum of eastward winds at 270° longitude and a local maximum of westward winds at 90° longitude. Poleward of these latitudes, the
location of the eastward and westward maxima are shifted by 180°.

Predictions for the temperature that would be observed by the New Horizons Alice and Rex instruments were provided. The location (i.e. latitude and longitude) that each instrument sampled did not produce significant difference in the temperature profiles, since temperature gradients in the PGCM results were weak. This includes immersion and emersion profiles. In the stratosphere, the temperature profiles differ by as much as 20 K, which will be distinguishable by New Horizons. In the mesosphere (the more isothermal layer above 100 km) the maximum difference is as much as 10 K, which is still distinguishable, but in some places the difference is zero. However, as we are comparing the whole temperature profile and not individual points, the PGCM should be able to tell the difference between different initial surface pressures and CH$_4$ concentrations.

In the predictions for ground-based stellar occultations, the difference between light curves of different CH$_4$ concentrations would be detectable, but the difference between light curves of different initial surface pressures would not. While this result is opposite that of Zalucha et al. (2011a), we can rule out coding error by de-activating everything but the call to the Strobel et al. (1996) module. The difference must lie in the fact that the Strobel et al. (1996) module of the PGCM has longitudinally, latitudinally, and seasonally varying insolation, and that the model is no longer in the steady state ($dT/dt = 0$), but interplay with the rest of the model (Navier stokes equations, mass and energy equations, ideal gas law, numerical filters).

Future work is to run this model for multiple Pluto years to spin up the volatile cycle, i.e. the location and depth of surface ice, rather than assume effectively infinite ice cover. Mars GCMs require about two Martian years to equilibrate the ice cycle. From Hansen & Paige (1996), it was found that the frost cycle was spun up after four Pluto years. This model had a one-layer atmosphere, so it is unknown at this time what
the effect of a complete surface and atmosphere model will require for spin up. A fully spun up volatile cycle might affect the results for winds and temperature, particularly the latitudinal wind, as air flows from the sublimating summer pole (an area of high pressure) to the condensing winter pole (an area of low pressure), as is seen in Mars GCMs. It might also be the case that a GCM is not capable of resolving the effects of the volatile cycle, either from too coarse a vertical resolution, since the extremely stable lower layer prevents vertical motion and thus confines the flow to very near to the surface, or “patchiness” of ice that seems to be apparent in HST images (Buie et al. 2010) that may have too fine-scaled structure for a GCM to portray. In this case a mesoscale model, with boundary conditions of the GCM, could be used to study local flows.

This work used the Extreme Science and Engineering Discovery Environment (XSEDE), which is supported by National Science Foundation Grant No. OCI-1053575. The author is supported by NASA grant NNX136AH77G. The author thanks Alan Stern, Dave Hinson, Leslie Young, and Henry Throop for providing coordinates of the New Horizons temperature retrievals; Leslie Young for discussions regarding the subsurface module; Tim Michaels for discussion regarding the computational aspects of the model; and Jake Simon for providing comments on the manuscript.
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This manuscript was prepared with the AAS \LaTeX{} macros v5.2.
Fig. 1.— Longitudinally averaged temperature (K) for 2015 July 14. The initial surface pressure is 8 $\mu$bar and the CH$_4$ concentration is 1%. The horizontal temperature gradient is weak compared with other bodies with atmospheres. This case is the warmest temperature due to the higher CH$_4$ concentration (which has a net heating effect on the atmosphere) and the fact that altitude is plotted on the ordinate rather than pressure.
Fig. 2.— Longitudinally averaged temperature (K) for 2015 July 14. The initial surface pressure is 24 $\mu$bar and the CH$_4$ concentration is 1%. The horizontal temperature gradient is weak compared with other bodies with atmospheres. This case is second warmest behind the 8 $\mu$bar case for reasons given in Fig. [I].
Fig. 3.— Longitudinally averaged temperature (K) for 2015 July 14. The initial surface pressure is 8 µbar and the CH$_4$ concentration is 0.2%. The horizontal temperature gradient is weak compared with other bodies with atmospheres. The temperature is colder for a given altitude than in Figs. 1 and 2 because of the lower CH$_4$ concentration.
Fig. 4.— Longitudinally averaged temperature (K) for 2015 July 14. The initial surface pressure is 24 $\mu$bar and the CH$_4$ concentration is 0.2%. The horizontal temperature gradient is weak compared with other bodies with atmospheres. The temperature is colder for a given altitude than in Figs. 1 and 2 because of the lower CH$_4$ concentration, but nearly identical to the 8 $\mu$bar case (Fig. 3).
Fig. 5.— Longitudinally averaged westward (prograde) wind (m s$^{-1}$) for 2015 July 14. The initial surface pressure is 8 $\mu$bar and the CH$_4$ concentration is 1%. Negative values are eastward (retrograde). The wind is strongest in the westward flow at $-75^\circ$ latitude between 50 and 100 km altitude. Around 50 km altitude, the winds are westward at all latitudes, while above this layer there is an area of weak eastward winds at the equator.
Fig. 6.— Longitudinally averaged westward (prograde) wind (m s$^{-1}$) for 2015 July 14. The initial surface pressure is 24 µbar and the CH$_4$ concentration is 1%. Negative values are eastward (retrograde). The structure of the winds is the same as Fig. 5 except the maximum westward winds are weaker and the maximum eastward winds are stronger.
Fig. 7.— Longitudinally averaged westward (prograde) wind (m s$^{-1}$) for 2015 July 14. The initial surface pressure is 8 $\mu$bar and the CH$_4$ concentration is 0.2%. Negative values are eastward (retrograde). This case differs the most from the other cases in that between roughly 200 and 250 km altitude, the winds are eastward everywhere. The maximum eastward wind is also located between these altitudes, higher than the other cases. Finally, the westward wind maximum is the strongest of the four cases.
Fig. 8.— Longitudinally averaged westward (prograde) wind (m s$^{-1}$) for 2015 July 14. The initial surface pressure is 24 $\mu$bar and the CH$_4$ concentration is 0.2%. Negative values are eastward (retrograde). The wind structure is similar to Fig. 5 except the westward maximum is slightly stronger, and the eastward maximum is located at a higher altitude.
Fig. 9.— Westward (prograde) wind (m s$^{-1}$) for 2015 July 14. The initial surface pressure is 8 $\mu$bar and the CH$_4$ concentration is 1%. Negative values are eastward (retrograde). In the top left panel (5.7 km altitude), the magnitude of the maximum wind is of order 1 m s$^{-1}$, and the eastern (western) hemisphere is eastward (westward). In the top right panel (56 km altitude), there is a strong flow (jet) of westward wind near the south pole, while elsewhere there is a local maxima of westward wind in the eastern hemisphere and a local minima in the western hemisphere. In the lower left panel (148 km altitude) and lower right panel (307 km altitude), again there is a jet of westward wind near the south pole. There is a weaker flow of westward winds near the north pole (and a localized area of eastward wind very close to the north and south poles). At 307 km altitude there is an area of weak westward flow in
Fig. 10.— Same as Fig. 9 but the initial surface pressure is 24 \( \mu \text{bar} \) and the \( \text{CH}_4 \) concentration is 1\%. 

Fig. 11.— Same as Fig. 9 but the initial surface pressure is 8 µbar and the CH$_4$ concentration is 0.2%.
Fig. 12.— Same as Fig. 9 but the initial surface pressure is 24 µbar and the CH$_4$ concentration is 0.2%.
Fig. 13.— Model stellar occultation light curves. Red: initial surface pressure 8 μbar and CH$_4$ concentration 1%, green: initial surface pressure 24 μbar and CH$_4$ concentration 1%, dark blue: initial surface pressure 8 μbar and CH$_4$ concentration 0.2%, cyan: initial surface pressure 24 μbar and CH$_4$ concentration 0.2%. A ground-based observer could distinguish between CH$_4$ concentrations of 0.2% and 1% using the PGCM, but probably not between pressures of 8 and 24 μbar.
Fig. 14.— Temperature profiles predicted to be observed by Alice during the solar occultation. Red: immersion, blue: emersion. Solid line: initial surface pressure 8 μbar and CH$_4$ concentration 1%, dashed line: initial surface pressure 24 μbar and CH$_4$ concentration 1%, dotted line: initial surface pressure 8 μbar and CH$_4$ concentration 0.2%, dot-dashed line: initial surface pressure 24 μbar and CH$_4$ concentration 0.2%. The immersion and emersion profiles do not differ greatly, which is to be expected since the horizontal temperature gradients are weak. The temperature profiles for different initial surface pressures and CH$_4$ concentrations differ by up to 20 K in some places, which will be detectable by New Horizons.
Fig. 15.— Same as Fig. 14, but for the stellar occultation to be observed by Alice
Fig. 16.— Same as Fig. 14, but for the radio occultation to be observed by REX.
Table 1: Surface parameters of PGCM simulations

| Run number | CH\textsubscript{4} concentration (%) | Surface pressure (µbar) | Surface emissivity | Surface conductivity (J m\textsuperscript{-1} K\textsuperscript{-1} s\textsuperscript{-1}) | Surface albedo |
|------------|--------------------------------------|-------------------------|--------------------|---------------------------------------------------------------------------------|----------------|
| 335        | 1                                    | 8                       | 1.0                | 0.00195                                                                         | 0.2            |
| 336        | 1                                    | 8                       | 1.0                | 0.00195                                                                         | 0.9            |
| 337        | 1                                    | 8                       | 1.0                | 4.88                                                                             | 0.2            |
| 338        | 1                                    | 8                       | 1.0                | 4.88                                                                             | 0.9            |
| 339        | 1                                    | 8                       | 0.2                | 0.00195                                                                         | 0.2            |
| 340        | 1                                    | 8                       | 0.2                | 0.00195                                                                         | 0.9            |
| 341        | 1                                    | 8                       | 0.2                | 4.88                                                                             | 0.2            |
| 342        | 1                                    | 8                       | 0.2                | 4.88                                                                             | 0.9            |
| 343        | 1                                    | 24                      | 1.0                | 0.00195                                                                         | 0.2            |
| 344        | 1                                    | 24                      | 1.0                | 0.00195                                                                         | 0.9            |
| 345        | 1                                    | 24                      | 1.0                | 4.88                                                                             | 0.2            |
| 346        | 1                                    | 24                      | 1.0                | 4.88                                                                             | 0.9            |
| 347        | 1                                    | 24                      | 0.2                | 0.00195                                                                         | 0.2            |
| 348        | 1                                    | 24                      | 0.2                | 0.00195                                                                         | 0.9            |
| 349        | 1                                    | 24                      | 0.2                | 4.88                                                                             | 0.2            |
| 350        | 1                                    | 24                      | 0.2                | 4.88                                                                             | 0.9            |
| 351        | 0.2                                  | 8                       | 1.0                | 0.00195                                                                         | 0.2            |
| 352        | 0.2                                  | 8                       | 1.0                | 0.00195                                                                         | 0.9            |
| 353        | 0.2                                  | 8                       | 1.0                | 4.88                                                                             | 0.2            |
| 354        | 0.2                                  | 8                       | 1.0                | 4.88                                                                             | 0.9            |
| 355        | 0.2                                  | 8                       | 0.2                | 0.00195                                                                         | 0.2            |
| 356        | 0.2                                  | 8                       | 0.2                | 0.00195                                                                         | 0.9            |
| 357        | 0.2                                  | 8                       | 0.2                | 4.88                                                                             | 0.2            |
| 358        | 0.2                                  | 8                       | 0.2                | 4.88                                                                             | 0.9            |
| 359        | 0.2                                  | 24                      | 1.0                | 0.00195                                                                         | 0.2            |
| 360        | 0.2                                  | 24                      | 1.0                | 0.00195                                                                         | 0.9            |
Table 2: Longitude and latitude coordinates for New Horizons occultations

| Coordinate         | Alice (Sun) | Alice (Background star) | REX |
|--------------------|-------------|-------------------------|-----|
| Immersion longitude| 150°        | 170°                    | 164°|
| Immersion latitude | 20°         | 40°                     | 15° |
| Emersion longitude | −10°        | −20°                    | −17°|
| Emersion latitude  | −20°        | −10°                    | −14°|