INVESTIGATING THE RADIATIVE BALANCE OF PLUTO'S ATMOSPHERE

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Abstract. Similar to Titan and Triton, Pluto's atmosphere is subject to complex photochemical processes. The photodissociation of its primary constituents-nitrogen, methane, and carbon monoxide-in the upper atmosphere produces a variety of hydrocarbons and nitriles. Through aggregation, these compounds can give rise to photochemical aerosols, which form a global haze layer surrounding the dwarf planet. Observations and models have shown that these aerosols play a critical role in Pluto's climate. However, their mechanisms of formation, their global evolution, and their influence on the atmospheric system remain poorly constrained. To investigate the effect of haze on Pluto's climate, we coupled the Pluto PCM with a microphysical model of haze, resolving the processes of particle formation, coagulation, and sedimentation on a global scale. Our simulations show that haze formation primarily occurs at high altitudes in the northern hemisphere ($\sim$ 475 km), before being redistributed by the pole-to-pole circulation, enriching the southern hemisphere below 350 km. Beneath 150 km, the model predicts a transition from spherical particles to large fractal aggregates, revealing a bimodal distribution of Pluto's haze. Finally, our results confirm that photochemical aerosols exert a dominant influence on Pluto's thermal structure, driving the cooling of the upper atmosphere down to $\sim$ 70 K.

Keywords: Planetary Science, Pluto, Atmosphere, Model, Climate, Haze

1 Introduction

Pluto's atmosphere was first detected in 1988 through ground-based stellar occultation observations (Hubbard et al. 1988; Elliot et al. 1989; Millis et al. 1993). These early analyses already suggested the presence of aerosols populating the lower atmosphere of Pluto (Elliot & Young 1992). The atmospheric composition was initially inferred from spectroscopic analyses of surface ices composed of N_2, CH_4, and CO (Cruikshank & Silvaggio 1980; Owen et al. 1993), indicating that N_2 should be the dominant gas. This interpretation was later confirmed by the direct detection of gaseous CH_4 and CO (Young et al. 1997; Lellouch et al. 2011).

The New Horizons flyby of Pluto provided the first direct evidence for the presence of a global haze surrounding the planet (Gladstone et al. 2016; Cheng et al. 2017). The observations showed that the haze is structured into multiple layers, with thicknesses ranging from 1 to 10 km, and is more prominent in the northern summer hemisphere, where aerosol scattering appears brighter (Cheng et al. 2017; Jacobs et al. 2021). The haze aerosols are optically thin, detected with an optical depth of $\sim$ 0.01 at visible wavelengths, and traced up to 500 km altitude in the ultraviolet, with scattering intensity increasing toward lower altitudes. Rayleigh scattering signatures, along with the large ultraviolet cross section of the aerosols, suggest the presence of very small particles, on the order of tens of nanometers (Gladstone et al. 2016; Kutsop et al. 2021). However, the strong forward scattering observed in the visible spectrum, together with the large high- to low-phase brightness ratio, also implies the existence of larger particles exceeding 100 nm (Gladstone et al. 2016; Cheng et al. 2017). These observations can be accounted for by large fractal aggregates ($\geq$ 100 nm) composed of smaller monomers ($\sim$ 10 nm) (Cheng et al. 2017). Nonetheless, Fan et al. (2022) demonstrated that the enhanced backscattering detected near the surface can only be explained by the coexistence of two distinct aerosol populations: small

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spherical particles with radii of a few tens of nanometers, and large fractal aggregates of approximately 1 μm. Overall, Pluto's aerosols appear more similar to those of Titan, exhibiting a bimodal distribution, rich in organic compounds, and more absorbing than the aerosols observed on Triton (Hillier et al. 2021; Fan et al. 2022).

Zhang et al. (2017) demonstrated that, unlike Titan - where thermal equilibrium is primarily regulated by the interplay between gases and haze - the radiative transfer in Pluto's atmosphere is largely dominated by haze particles. Pluto's haze heating/cooling rates could exceed that of gases by two orders of magnitude and account for the pronounced cooling observed in Pluto's upper atmosphere (Hinson et al. 2017). These findings were recently confirmed by observations with the James Webb Space Telescope (Bertrand et al. 2025), which, by spatially resolving Pluto from Charon, concluded that Pluto's atmospheric radiative balance is controlled predominantly by haze particles rather than gaseous molecules, making Pluto's atmosphere unique within the Solar System.

Recently, the analysis of CO line maps obtained with ALMA provides tentative evidence for a non-uniform temperature field around 30 km altitude, with latitudes near the summer pole being 7 ± 3.5 K warmer than low latitudes (Lellouch et al. 2022). The origin of this heterogeneity remains uncertain: it may arise from radiative timescales shorter than previously thought, or from a process intrinsically linked to the dynamics or optical properties of the haze itself.

Several one-dimensional microphysical models have been developed based on New Horizons observations to constrain the properties of Pluto's haze aerosols (Gao et al. 2017; Lavvas et al. 2021). In addition, Bertrand & Forget (2017) investigated the three-dimensional impact of the haze using a Global Climate Model (GCM), although with a simplified parametrization of the haze. These studies highlight the need for a fully coupled approach between haze microphysics and GCM in order to better understand the spatial distribution of Pluto's hazes and their role in the planet's climate system. In this context, we present the development of the Pluto Planetary Climate Model (Pluto PCM) coupled with a microphysical model of haze, along with the first results on the global distribution of Pluto's hazes and their influence on the thermal balance of the atmosphere.

2 The Pluto PCM

The Pluto PCM is an ideal tool for understanding the thermal balance of Pluto's atmosphere and the role of hazes in its heating and cooling properties. This model is an updated version of the Legacy Pluto PCM described in Forget et al. (2017) and Bertrand et al. (2020). It takes into account the sublimation and condensation cycles of N_2 , CH_4 , and CO (Forget et al. 2017), their thermal and dynamical effects, the vertical turbulent mixing, molecular thermal conduction, and a detailed surface thermal model with different thermal inertia for various timescales (diurnal, seasonal).

The Pluto PCM now includes a microphysical model for organic haze, originally developed to study Titan's haze and its impact on Titan's climate (de Batz de Trenquelléon et al. 2025b,a). It describes the evolution of two distinct aerosol populations: the small spherical aerosols and the large fractal aerosols. The model therefore reproduces the bimodal distribution characteristic of Pluto's haze through its formation (through methane photolysis), evolution (via brownien coagulation), and transport (by sedimentation). This microphysical model has been coupled with the radiative transfer scheme of the Pluto PCM in order to assess the impact of the haze on Pluto's climate and to study their radiative effects on the atmosphere.

3 Results

3.1 Latitudinal distribution of Pluto's haze

Figure 1 shows the CH_4 photolysis rate, together with the concentrations of spherical and fractal aerosols in Pluto's atmosphere in July 2015, as predicted by the Pluto PCM. The CH_4 photolysis results are consistent with those reported by Bertrand & Forget (2017): photolysis occurs at all latitudes, with higher intensity above the northern summer hemisphere, which receives a stronger Lyman-α flux compared to the southern hemisphere. However, CH_4 photolysis is found to take place at higher altitudes than in the simulations of Bertrand & Forget (2017), peaking at approximately 475 km (compared to 250 km), with all Lyman-α photons absorbed above 200 km (compared to 150 km). This shift is attributable to the higher methane abundance in the atmosphere compared to Bertrand & Forget (2017) simulations.

We assume in the model that each absorbed Lyman-α photon photolyzes one in every two methane molecule, then producing haze precursors, as described in Bertrand & Forget (2017). These precursors subsequently evolve into spherical aerosols with a characteristic size of 8 nm, on a typical timescale of 10^5 seconds. Once formed,

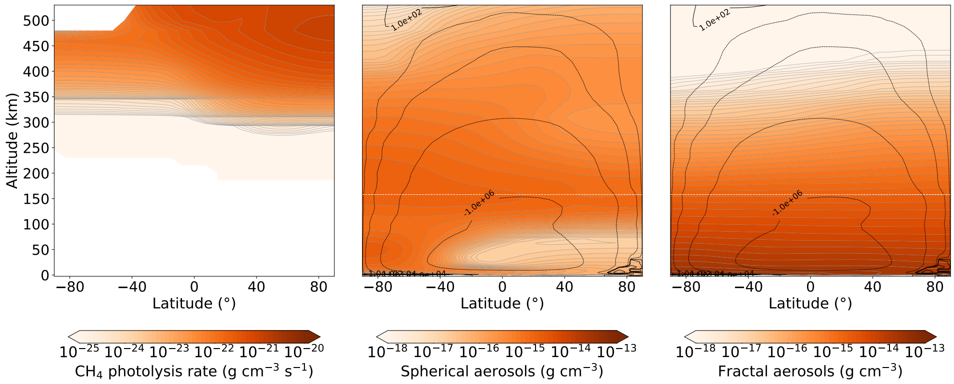

Fig. 1. Zonal average of photolysis rate of CH_4 (left), spherical aerosol distribution (center), and fractal aerosol distribution (right), as simulated by the Pluto PCM for July 2015. The meridional mass stream function (kg s^{-1}) is represented by black contour lines: solid contours indicate clockwise circulation, whereas dashed contours indicate counterclockwise circulation. The horizontal white dashed line marks the transition altitude below which fractal aerosols become dominant.

these small aerosols are transported through the atmosphere by sedimentation and dynamical processes, and grow freely through coagulation (Figure 1). Due to their small size and low mass, these particles are efficiently transported by the global meridional circulation (from north to south), rapidly enriching Pluto's southern hemisphere below 350 km of altitude down to the surface. Our results indicate that below 100 km of altitude, the concentration of spherical aerosols in the northern hemisphere remains particularly low.

Spherical aerosols undergo progressive growth during their descent through the atmosphere, typically reaching sizes of several tens of nanometers. Upon attaining 20 nm, a morphological transition may occur, leading to the formation of fractal aerosols. Indeed, below 150 km of altitude, the concentration of spherical particles decreases as the particles evolve into fractal forms. Consequently, at altitudes lower than 150 km, the particle population is predominantly composed of fractal aerosols down to the surface. As shown in Figure 1, fractal aggregates are less affected by atmospheric circulation and tend to enrich the near-surface layers more uniformly. Their effective radius, close to 0.2 μm and composed of 20 nm monomers, makes them heavier and thus more prone to rapid sedimentation compared to spherical aerosols.

The model predicts a surface opacity of ~ 0.04 at 700 nm. This value is slightly higher than that observed by New Horizons (~ 0.01 at visible wavelengths), suggesting either an overestimation of the haze abundance in the model or an excessive absorption resulting from the optical properties assigned to aerosols in the simulations.

3.2 Impact of haze on the thermal equilibrium of Pluto's atmosphere

The latitudinal temperature distribution predicted by the model for July 2015 is shown in Figure 2, together with the corresponding radiative and dynamical heating and cooling rates. The results indicate that radiative heating dominates in the northern hemisphere during summer, mainly due to solar flux absorption by aerosols, which leads to atmospheric warming. Conversely, the southern hemisphere is characterized by radiative cooling, associated with haze accumulation at the south pole during the polar night, which emit in the infrared and induce a net cooling. However, these radiative processes are partly counterbalanced by atmospheric dynamics: the northern hemisphere experiences adiabatic cooling caused by upward motions, whereas the southern hemisphere is subject to dynamical heating from downward motions. As a result, the atmosphere undergoes efficient mixing, leading to an almost latitudinally uniform temperature distribution (Figure 2).

The heating and cooling rates predicted by the model reach values on the order of 10^{-6} W m^{-3} near the surface, consistent with the findings of Zhang et al. (2017). These amplitudes are about two orders of magnitude larger than the estimated heating and cooling rates of gaseous components, confirming that hazes play a central role in controlling Pluto's atmospheric energy balance (Bertrand et al. 2025).

The model is now able to reproduce the strong negative thermal gradient between Pluto's stratosphere, at

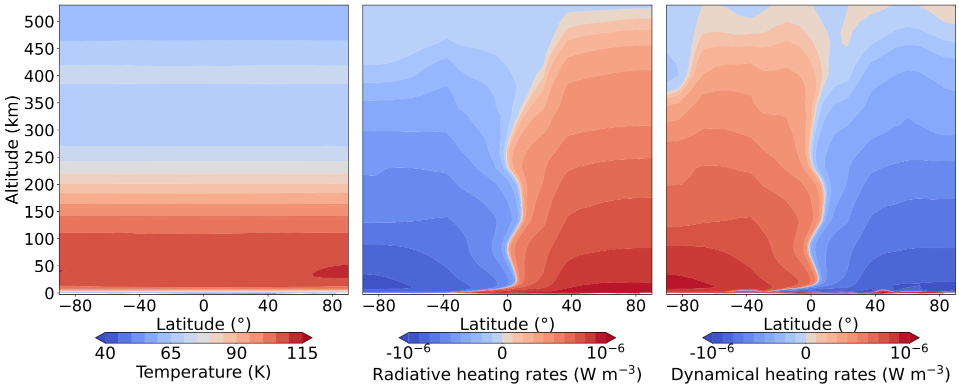

Fig. 2. Zonal average of temperature (left), radiative heating rates (center), and dynamical heating rates (right), as simulated by the Pluto PCM for July 2015.

approximately 110 K, and its upper atmosphere, where temperatures decrease to about 70 K. This behavior is thus explained by the cooling effect induced by the haze between altitudes of 50 and 500 km. In addition, the model reveal the presence of a warmer layer near 30 km above the north pole (Figure 2), consistent with ALMA observations (Lellouch et al. 2022). However, the latitudinal gradient predicted by the model remains much weaker than that inferred from observations ($\sim$ 1 K compared to 7 $\pm$ 3.5 K observed). This discrepancy is too large to ascertain whether the gradient originates from a continuous process, such as direct haze-induced heating, or from a transient mechanism, for example the haze-driven amplification of waves generated above the surface that could adiabatically warm this region.

4 Discussions and Conclusions

Based on the studies of Forget et al. (2017); Bertrand et al. (2020), we have extended the Pluto PCM by coupling it with a microphysical model of haze. This model explicitly accounts for aerosol production, coagulation, and sedimentation processes, assuming a bimodal distribution of aerosols (spherical and fractal). The model is now able of predicting the global formation and evolution of Pluto's haze. Results show that small spherical aerosols are produced above 400 km and then transported by atmospheric circulation and tend to accumulate over the southern pole, between the surface and 350 km of altitude. In contrast, large fractal aerosols dominate the lower atmosphere below 150 km, where they exhibit a more uniform distribution.

Moreover, our results confirm that hazes play a crucial role in Pluto's thermal balance. They govern atmospheric heating and cooling rates, exceeding the contribution of gaseous components by two orders of magnitude. The model successfully reproduces Pluto's observed thermal profile, with the upper atmosphere cooling down to about 70 K due to haze radiative effects. Finally, the simulations suggest the presence of a slightly warmer region above the northern pole compared to the equator, although further investigation is required to clarify the origin of this feature.

In conclusion, our results highlight strong similarities between Pluto's and Titan's hazes. In both cases, these hazes develop under very low-pressure conditions ($<$ 1 Pa) and are composed of photochemical aerosols characterized by a bimodal distribution: small spherical particles and larger fractal aggregates. However, because Titan is closer to the Sun, it receives a higher solar flux than Pluto. This results in a photochemical haze production rate approximately two orders of magnitude greater on Titan ($\sim 10^{-12}$ g cm^{-3} s^{-1}) than on Pluto ($\sim 10^{-12}$ g cm^{-3} s^{-1}). Consequently, Titan's atmosphere contains larger particles (spherical aerosols $\sim$ 50 nm and fractal aggregates of the order of a micron). Moreover, below 400 km altitude, all spherical particles in Titan's haze evolve into fractal aggregates. In contrast, in Pluto's atmosphere, both aerosol populations persist down to the surface. On both bodies, atmospheric dynamics influence the distribution of hazes, leading to an enrichment at the winter pole. Additionally, the radiative impact of these hazes plays a major role in the global thermal balance of Pluto and Titan. These findings emphasize the central role of hazes in global climate modeling and their importance for understanding the radiative balance of planetary atmospheres.

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