Investigating the radiative balance of Pluto's atmosphere. B. de Batz de Trenquelléon[1] and T. Bertrand[1,2] and A. Falco[3] and E. Lellouch[1] and E. Millour[3] and F. Forget[3], [1]LIRA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université Paris Cité, 5 place Jules Janssen, 92195 Meudon, France (bruno.debatz@obspm.fr), [2]LPG, UMR CNRS 6112, Université de Nantes, Université d'Angers, Nantes, France, [3]Laboratoire de Météorologie Dynamique (LMD/IPSL), Sorbonne Université, ENS, PSL Research University, Ecole Polytechnique, IP Paris, CNRS, 4 Place Jussieu, 75252 Paris Cedex 05, France.

Introduction: New Horizons revealed that complex processes of photochemistry and microphysics are taking place in Pluto's N_2 atmosphere [1, 2]. Similarly to Titan, the presence of CH_4 in Pluto's atmosphere leads to the UV photochemical production of more complex molecules such as C_2H_2, C_2H_4, and C_2H_6, as well as nitriles like HCN at high altitudes. These compounds can aggregate through collisions to form increasingly larger spherical particles, creating a haze of solid organic aerosols that encompasses Pluto [1]. The resulting haze particles can continue to grow through coagulation, forming fractal aggregates that lead to a bimodal distribution near the surface [3]. In addition, photochemical-microphysical modeling by [4] shows that condensation of HCN and various hydrocarbons occurs in Pluto's atmosphere on the tholin-like particles.

Our objective is to investigate the thermal balance of Pluto's atmosphere using the Pluto Planetary Climate Model (Pluto PCM, see Falco et al., this issue). We focus on three aspects of the thermal profile: (1) The strong negative gradient between the stratosphere at 110 K and the upper atmosphere at 70 K. (2) The strong thermal gradient (7 ± 3.5 K) from equator to North Pole tentatively observed (2σ) with ALMA [5], and the differences in temperatures observed by New Horizons between the entry and exit profiles above 5 km altitude [6]. (3) The 3 km-deep cold layer observed by New Horizons.

The thermal profile of Pluto's atmosphere has been measured from ground-based observations and from the REX instrument on-board New Horizons [6, 7]. It has been proposed by [8] that the thermal structure is primarily regulated by the heating and cooling properties of tholin-type haze, whose heating/cooling rates could exceed that of gases by two orders of magnitude. However, in scenarios where the haze is dominated by icy components, its radiative impact on the atmosphere is expected to be more limited [4]. Therefore, the main cooling mechanism responsible for the observed vertical thermal gradient remains uncertain.

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 [9, 10]. It takes into account the sublimation and condensation cycles of N_2, CH_4, and CO [9], 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). It now includes a microphysical model for organic haze, accounting for its formation (through methane photolysis), evolution (via 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.

Preliminary results: In this presentation we will present the results obtained with our model and compare them to observations (e.g. [5, 6]). Initially, we will focus on the spatial distribution of the haze and its physical properties predicted by the model. We will then examine the impact of the haze on the global climate, particularly on the heating and cooling rates of the atmosphere. Figure 1 illustrates the radiative, dynamic, and total heating/cooling rates of the atmosphere during the year 2015. Our model supports the findings of [8], showing haze heating/cooling rates between 10^{-8} and 10^{-6} $W.m^{-3}$ below 100 km — about 100 times higher than those of the gases. The switch to the 3D model allows us to observe that the Northern Hemisphere is heated by the absorption of solar flux by CH_4 and haze during the Northern summer, while the Southern Hemisphere, in winter, is cooled by the infrared emission of gas (CH_4 and CO) and haze. The dynamic trend acts in opposition to the radiative trend, redistributing energy throughout the atmosphere, so that the heating and cooling rates become nearly uniform across the entire atmosphere.

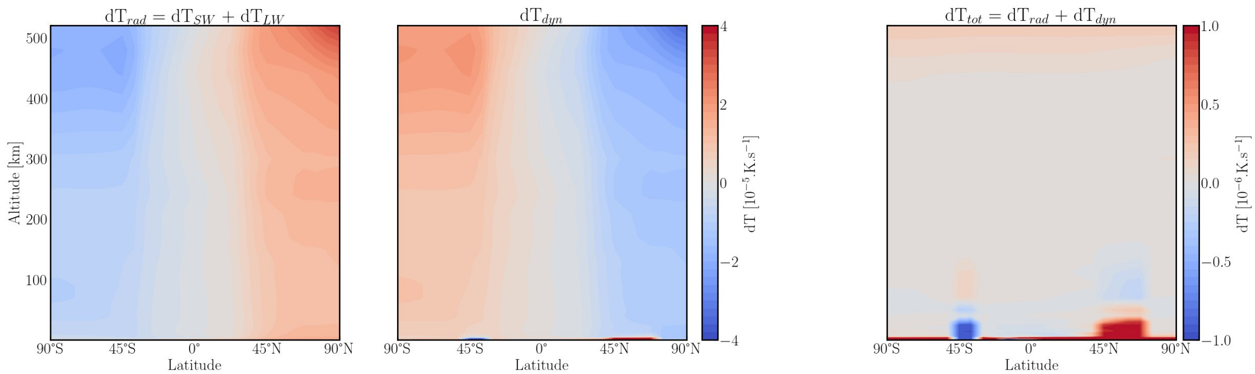

Figure 1: Radiative (left), dynamical (center), and total (right) heating/cooling rates predicted by the Pluto PCM for the year 2015 in Pluto's atmosphere. The radiative component is related to the absorption and emission by atmospheric constituents, while the dynamic component is associated with general circulation and atmospheric transport.

The paradox of latitudinal temperature gradients: We will then attempt to address the questions raised in the introduction, starting with the analysis of the 7 ± 3.5 K horizontal gradient observed by ALMA [5]. To do this, as initial state of the atmosphere we imposed a latitudinal thermal gradient in the northern hemisphere (with the North Pole being 10 K warmer than the equator) and ran the model. Figure 2 shows the temporal evolution of this gradient over the course of half a Pluton day. We observe that the gradient dissipates very quickly — within less than a quarter of a Pluton day — and that after just half a day, the atmosphere has fully stabilized and become nearly uniform in latitude.

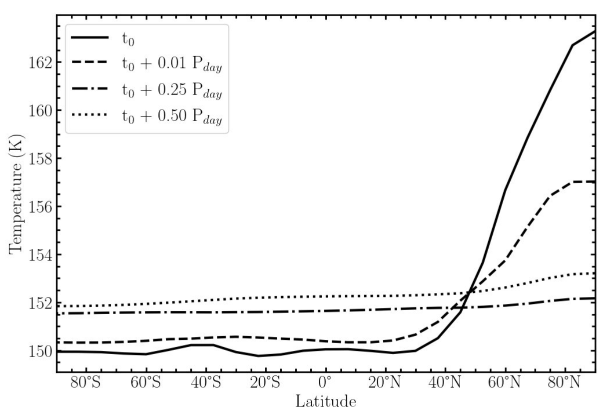

Figure 2: Latitudinal variation of the temperature averaged between 20 and 100 km in the Pluto PCM. The curves show the temporal evolution of the temperature over half a day on Pluto.

Although the radiative timescale is long, the atmospheric dynamics operate on much shorter timescales, enabling efficient mixing and redistribution of energy. As a result, where one might expect to observe a horizontal temperature gradient due to haze, none is present. Further investigation is therefore needed to help us understand this phenomenon. Additional questions related to the vertical thermal gradient and the deep cold layer will also be explored during this presentation.

Future work: In a future study, we will couple the haze microphysical model with a cloud microphysical model, allowing atmospheric hydrocarbons (CH_4, C_2H_2, C_2H_4, and C_2H_6) and nitriles (HCN) to condense onto haze particles. Accounting for the effects of condensation and the resulting new optical properties of the particles in the Pluto PCM's radiative transfer will provide us with a comprehensive understanding of the haze's impact on Pluto's global climate.

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References: [1] Gladstone G. R. et al (2016) *Science*, 351, 6279. [2] Cheng A. F. et al (2017) *Icarus*, 290, 112-133. [3] Fan S. et al (2022) *Nature Communications*, 13, 240. [4] Lavvas P. et al (2021) *Nature Astronomy*, 5, 289-297. [5] Lellouch E. et al (2022) *Icarus*, 372, 114722. [6] Hinson D. P. et al (2017) *Icarus*, 290, 96-111. [7] Dias-Oliveira A. et al (2015) *The Astrophysical Journal*, 811, 1. [8] Zhang X. et al (2017) *Nature*, 511, 7680. [9] Forget F. et al (2017) *Icarus*, 287, 54-71. [10] Bertrand T. et al (2020) *Journal of Geophysical Research (Planets)*, 125, 2.