Introduction:
The high obliquity and eccentricity of the orbit of Pluto induce seasonal cycles of condensation and sublimation of the main volatile ices: N₂, CH₄, and CO. In 2015, New Horizons revealed a complex distribution of these ices [1-7], including the thousand-kilometers nitrogen ice-sheet in Sputnik Planitia, a combination of N₂, CO and CH₄ deposits at mid-latitudes, massive methane-rich deposits forming the Bladed Terrain at low latitudes, a methane mantle at high latitudes, CH₄ snow-capped mountains near the equator, etc.

To understand the distribution and evolution of the nitrogen and methane ice reservoirs at the surface of Pluto and their origins, we have developed a hierarchy of models able to simulate the volatile cycles over multiple timescales: (1) A Global Climate Model [8,9] to represent the evolution of the 3D atmospheric circulation, the transport of gases and surface ices (N₂, CH₄ and CO) over up to several tens of Earth years (2) a 2D volatile transport model [10] able to simulate the N₂, CH₄ and CO cycles over several tens of thousands of years (tuned using the GCM) and 3) A long-term Pluto evolution model combining the volatile transport model simulations with the variations of Pluto’s orbit and obliquity to simulate the evolution of the volatile reservoirs over up to 50 million Earth years [11,12].

Such tools are based on universal equations, with the minimum of ad-hoc hypothesis. Yet we found that the modeled Pluto climate system and the evolution of its volatile reservoirs are surprisingly sensitive to a few model parameters such as the ice albedos and deep subsurface thermal inertia. Nevertheless, by choosing a set of selected values we could reproduce many characteristics of the planet observed by New Horizons in 2015.

The nitrogen cycle
On our modeled Pluto, most N₂ ice tends to accumulate in Sputnik Planitia due to its low elevation corresponding to an higher pressure and condensation temperature [10]. Outside the Sputnik Planitia basin, thick N₂ deposits are able to persist over tens of millions of years [11], in particular in the equatorial regions and in depressions, before being trapped in Sputnik Planitia. Long-term N₂ ice is not stable at the poles.

Within Sputnik Planitia, the N₂ ice budget is controlled by the diurnal, seasonal and astronomical cycles of Pluto. We found that the obliquity changes drive the long-term N₂ cycle. Over one obliquity cycle, the latitudes of Sputnik Planitia between 25°S-30°N are dominated by N₂ condensation, while the northern regions between 30°N-50°N are dominated by N₂ sublimation. According to the model, a net amount of 1 km of ice has sublimed at the northern edge of Sputnik Planitia during the last 2 million of years and must have been compensated by a viscous flow of the thick ice sheet [10]. By comparing these results with the observed geology of Sputnik Planitia, we can relate the eastern glacial flows and the erosion of the water ice mountains all around the ice sheet to the N₂ sublimation and condensation occurring at the astronomical timescale. The formation of the small pits and the brightness of the ice at the center of Sputnik Planitia are instead related to the annual timescale.

Another result is that the minimum and maximum surface pressures obtained over the simulated millions of years remain in the range of milli-Pascals and Pascals, respectively.

The methane cycle
By assuming fixed solid ice mixing ratios, we explored how changes in surface albedos, emissivities and thermal inertias impact volatile transport [12]. We found that bright CH₄ deposits can create cold traps for N₂ ice outside Sputnik Planitia, leading to a strong coupling between both N₂ and CH₄ cycles. Depending on the assumed albedo for CH₄ ice, the model predicts CH₄ ice accumulation (1) at the same equatorial latitudes where the Bladed Terrains are observed, supporting the idea that these CH₄-rich deposits are massive and perennial, or (2) at mid-latitudes, forming a thick mantle which is consistent with New Horizons observations. In our simulations, both CH₄ ice reservoirs are not in an equilibrium state and either one can dominate the other over long timescales, depending on the assumptions made for the CH₄ albedo. This suggests that long-term volatile transport exists between the observed reservoirs.

In Pluto’s current orbital configuration, if we assume a relatively bright CH₄ ice (albedo larger than 0.6), the model is able to reproduce the formation of N₂ deposits at mid-latitudes and in the equatorial depressions surrounding the Bladed Terrain, as observed...
by New Horizons. At the poles, only seasonal CH$_4$ and N$_2$ deposits are obtained, regardless of the chosen ice albedo.

The longitudinal distribution of the methane deposits (east of Sputnik Planitia rather than west where the ground is almost volatile ice-free) is not easy to simulate using a volatile transport model. This asymmetry must involve atmospheric dynamics and transport of methane as influenced by Sputnik Planitia [13].

Finally, we show that Pluto's atmosphere always contained, over the last astronomical cycles, enough gaseous CH$_4$ to absorb most of the incoming Lyman-alpha flux, which raises questions about the mechanisms leading to the formation of the dark organic materials observed on Pluto's surface.

Explaining methane snow-capped mountains.

Within the dark covered equatorial regions, CH$_4$ ice is not detected on most surfaces except on crater rims and mountain tops, sometimes providing strong resemblance to terrestrial snow-capped mountain chains. However, the process controlling the preferential accumulation of methane on mountains is completely different from what occurs on the Earth. To understand this, we performed high-resolution numerical simulations of Pluto's climate performed with the 3D Global Climate Model that includes the present-day CH$_4$ cycle.

The model predicts CH$_4$ condensation at high-altitude in the equatorial regions, where the CH$_4$-capped mountains are observed, on the ridges and crests of the Enrique Montes in eastern Cthulhu. This high-altitude condensation results from the fact that the atmosphere is much more CH$_4$-rich a few kilometers above the zero-datum (where the atmosphere is warm) than in the lowest atmospheric levels. The mountain top extending into the CH$_4$-rich levels are cold-traps for the gaseous methane. Why are the lowest levels methane depleted? Our model shows that this is controlled by the diurnal cycle of nitrogen (N$_2$) which induces a N$_2$-rich, CH$_4$-poor sublimation flow depleting the lower atmosphere in gaseous CH$_4$.

We derive more realistic simulations taking into account surface albedo feedbacks which highlight the stability of these CH$_4$ frosts. These results show that the presence of high-altitude CH$_4$ frosts on Pluto is controlled by an atmospheric process unique in the Solar System. The same mechanism could be at the origin of the sharp crests on top of the Bladed Terrain CH$_4$ deposits.

Conclusion.

At the Pluto System After New Horizons conference we will review what we have learned from these numerical simulations, but also put forward the observations that remains enigmatic and difficult to understand and predict with our numerical models.

References