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Cryosphere as the thermometer of Cenozoic Earth system evolution

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In times of high concerns for on-going future global sea level rise, major unknown on the ice sheets response to large fast or not increase in greenhouse gas, well above near past natural variability, and associated atmospheric and oceanic circulation changes remains. The geological records of the Cenozoic evolution of the Earth system offers the possibility to better understand the interactions between the various components of the Earth system, as their evolution (continents locations, mountain ranges, ocean basins, gateways, cryosphere extent), at very long time scale seems linked or causes a gradual drop in atmospheric CO_2 from above 1000 ppm to below 300 ppm. Cryosphere is the perfect testimony of the Earth system evolution over this time period. In fact, geological records suggest that the Antarctic ice sheet started to glaciate with CO_2 concentrations around 800-700 ppm at the beginning of the Oligocene ($\sim$34 Ma presumably). The Greenland ice sheet started to glaciate with concentrations around 400-300 ppm at the end of the Miocene ($\sim$8-7 Ma) and finally Northern Hemisphere ice sheets started to grow during the Pliocene, with CO_2 concentration around 300 ppm. Geological records also suggest that two noticeable periods of climatic optimum occurred, one during the Mid Miocene (17-14 Ma) and one during the Pliocene (3.3-3Ma), leading to a significant global climate warming and to a reduction of the existing cryosphere (both sea ice and ice sheets extent and volume). Few indicators of paleo-beaches dated back to the mid-Pliocene peak at about 15-20 meters above present-day sea level and Mid-Miocene sea level so far remains unconstrained. During those remote periods, the morphology of some of the modern oceanic gateways or mountain ranges or polar continental margins where different than today leading to differences in synoptic oceanic, atmospheric circulation and ice sheet dynamics. Here we review the last advances in geological records and modeling to show that Cenozoic is a perfect play ground to investigate and model the sensitivity of the ice sheet to different climatic conditions as the relative importance of climatic processes might vary from one period to another. Various hysteresis then enter into play, i.e. ice sheet hysteresis resulting from CO_2 changes and orbital changes and on top of this, global to regional processes triggering ice sheet instability, such as the impact of warm oceanic water on the marine-based part of ice sheets. Understanding those mechanisms is key to our future as the short-term ice sheet sensitivity also derives from very long-term evolution of surrounding landscape and long-term evolution of the climate system over orbital scale.