

**Introduction:** It has long been understood that secular variations of spin and orbit parameters of Mars strongly influence the climate of the planet [e.g., 1] through variations in their spatial and temporal insolation pattern. Changing parameters that control the insolation are obliquity  $\theta$ , eccentricity  $\epsilon$ , and, for epochs of large eccentricity, season of perihelion, which can be quantified as areocentric longitude of the Sun from the moving equinox at perihelion  $L_p$ . Among these three parameters, obliquity has the strongest impact on major climate characteristics. The obliquity of Mars oscillates quasi-periodically, varying up to  $\sim\pm 10^\circ$  amplitude and a period of  $\sim 0.12$  Ma about a mean value, which, in turn, experiences wide variations at the  $\sim 5$  Ma time scale. These long-term variations are dynamically chaotic, hence they cannot be traced by calculation back in time farther than  $\sim 10$  Ma. Recent calculations [2] showed that it is probable that the typical obliquity in the Martian geological past was higher than the present. The same calculations showed that it is probable that the planet spent some part of its geological history at low obliquity (in comparison to the present  $\sim 25^\circ$ ). It cannot be excluded that there were geologically long (10s or even 100s Ma) periods when obliquity oscillated about values as low as  $10^\circ$ - $15^\circ$ . **Fig. 1** presents an example of such possible oscillations from [2]. Due to the dynamically chaotic nature of the obliquity variations, only the geological record can reveal if there were such periods in the geological history of Mars.

It has long been understood that at low obliquity, collapse of the atmosphere occurs [e.g., 3], because insolation of polar regions is very low, and the atmospheric pressure is buffered by permanent solid CO<sub>2</sub> deposits at the poles. The dependence of pressure on obliquity to first order can be found from a simple radiative balance model: year-average surface temperature at the pole is obtained from the equation relating year-average insolation and thermal radiation, and year-average pressure is obtained from the equation relating year-average surface temperature and CO<sub>2</sub> frost point [e.g., 3].

To understand better the nature and distribution of solid CO<sub>2</sub> deposits at low obliquity, we constructed a second-approach radiative-balance model for CO<sub>2</sub> deposition.

**Model:** Our second-approach model resolves latitudes and seasons. Very similar models were used long

ago to model seasonal CO<sub>2</sub> caps on Mars. We calculate day-average insolation for a given latitude and time of year. For temperature equal to the CO<sub>2</sub> frost point, we calculate the rate of CO<sub>2</sub> condensation or sublimation from the energy balance, which involves insolation, thermal radiation and release or consumption of sublimation latent heat. To derive the rates from this energy balance, we need to assume thermal infrared emissivity of solid CO<sub>2</sub> deposits,  $E$ , and visible albedo,  $A$ . We assume that  $E = 1$  is sufficiently accurate. Following [3] we took a "nominal" value of  $A = 0.65$  and studied the effect of its variations. Of course, no sublimation occurs in the model calculations when there is no solid CO<sub>2</sub> on the surface. We trace the amount of CO<sub>2</sub> at the surface at each latitude through the year and recalculate CO<sub>2</sub> frost point depending on the atmospheric pressure, which is simply taken from the amount of gaseous CO<sub>2</sub> on the planet. We start from the total amount of CO<sub>2</sub> approximately equal to the present and no solid CO<sub>2</sub> at the surface. Our model reproduces reasonably well the deposition and removal of seasonal CO<sub>2</sub> caps and seasonal pressure variations at the present epoch.

We ran our model through an example of spin-orbit variations with persistently low mean obliquity (**Fig. 1**) for "real" time series for  $\theta$ ,  $\epsilon$ , and  $L_p$  from [2]. Our results confirmed that (1) the first-order model (for the same  $A$ ) gives quantitatively accurate estimates of mean atmospheric pressure for a given obliquity; (2)  $\epsilon$  and  $L_p$  have little influence on atmospheric pressure at low obliquity; (3) the onset of both perennial CO<sub>2</sub> deposit formation and total atmosphere collapse strongly depends on  $A$ ; (4) the spatial extent of perennial CO<sub>2</sub> deposits is smaller at lower obliquity.

**The role of surface topography:** We included surface topography in our model. This provides a principal advance in comparison to previous studies. In addition to the latitude and season, we consider surface slopes of different steepness and orientation in our insolation calculations. We took the actual latitude-dependent frequency distribution of slope steepness and orientation from high-resolution polar gridded MOLA topography. Slopes were calculated at  $\sim 200$  m baseline (slopes at lower latitudes, where MOLA data are insufficient for slope calculation at this baseline, play no role in our calculations, because perennial CO<sub>2</sub> deposits never form at lower latitudes). Poleward from  $86^\circ$  latitude, where there is no dense MOLA coverage,

we assumed the surface to be horizontal. With this modification, we ran the model in the same way, as described above.

**Results:** The results differ drastically from the case of a perfectly spherical planet. **Fig. 2** shows the example of the calculated evolution in the obliquity - pressure domain. The total year-average mass of solid CO<sub>2</sub> deposits is proportional to the deviation of the pressure from 800 Pa. The pressure shows wide hysteresis: it increases with the obliquity increase much slower than it decreases with the obliquity decrease. The periods of relatively high obliquity are too short to evaporate all surface CO<sub>2</sub> deposits, and the pressure does not return to its maximal value even at high (24°) obliquity peaks. This behavior is caused by deep cold traps that are provided by surface topography. Steep (>~10°) pole-facing slopes at the 70-80° latitude zone are the coldest places on the planet for obliquity below 20°. Massive CO<sub>2</sub> deposits are accumulated in these cold traps. The total area of these places is small, and the integral rate of sublimation, being proportional to the area, is also small. This leads to survival of much solid CO<sub>2</sub> on the surface during a geologically long time. There is not enough time to bring the system to the equilibrium atmospheric pressure during obliquity maxima.

**Discussion and conclusions:** Results of model calculations (such as shown in Fig. 2) should not be used as firm predictions of the pressure evolution and deposit distribution, because there are too many uncertainties in the model parameters. Albedo *A* strongly depends on the microphysics of the CO<sub>2</sub> deposit surface and can change with time, as it is actually observed for present-day seasonal deposits. At relatively higher obliquity, when polar areas become warmer and some H<sub>2</sub>O vapor appears in the atmosphere, the patchy residual CO<sub>2</sub> deposit can act as traps for H<sub>2</sub>O frost. This would increase *A* and protect the deposits from sublimation. All these effects are not included in the model. In addition, the model does not include the feedback between CO<sub>2</sub> deposition and topography: the topographic cold traps are modeled as having infinite capacity, while in reality most of them are related to small-scale topographic features and will be quickly filled with solid CO<sub>2</sub>.

Despite the incompleteness of this model, our main conclusions are robust. First, the distribution of the perennial CO<sub>2</sub> deposits and atmospheric pressure is not a simple function of obliquity, but crucially depends on the geologically long pre-history of climate variations and solid CO<sub>2</sub> deposits.

The second conclusion is that massive CO<sub>2</sub> deposits at pole-facing slopes at high latitudes are formed during low obliquity periods. Geologically long oscil-

lations of obliquity around low values should lead to formation of associated H<sub>2</sub>O ice deposits in these places, which can produce morphologically observed traces at the surface. Identification of morphological evidence of such deposits could potentially point to actual geological epochs of low obliquity in Mars history.

**References:** [1] Ward (1992) In *Mars*, Univ. Arizona Press, 298-320. [2] Laskar J. et al. (2004) *Icarus* 170, 343-364. [3] Kiefer H. and Zent A.. (1992) In *Mars*, Univ. Arizona Press, 1180-1218.

