CONSTRAINTS ON PAST CLIMATE ON MARS FROM THE NORTH POLAR LAYERED DEPOSITS

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Introduction:
The polar layered deposits (PLD) on Mars are km thick ice-rich deposits with a stratigraphy that preserves a record of past climate variations on Mars. The stratigraphy of the PLD is exposed at the surface within scarps and trough walls [1], and radar sounding of the subsurface has revealed the internal stratigrahy [2,3]. The stratigraphy is thought to result from climate variations forced by changes in the orbital parameters of Mars, particularly the obliquity, similar to Milankovitch cycles on Earth [4,5].

The thickness of the PLD and their stratigraphy provide important constraints on the processes controlling polar deposition of ice and dust and their variations through time in response to the orbital forcing. An important and challenging step in inferring a climate signal from the PLD is to establish the timescale of the stratigraphic record [6,7]. The age of the deposits are not well constrained by geological data [1], and although insolation has varied significantly over time and caused dramatic changes in climate[8], the effect on polar deposition rates of ice and dust and the resulting layering is not fully understood.

Here, it is investigated which constraints can be inferred from the NPLD stratigraphy on the water and dust cycles and their variations on longer timescales. We use a model of PLD formation driven by insolation [9]. The model simulates the evolution of the PLD based on simplified parameterizations of physical processes controlling ice and dust deposition rates. It captures characteristic features of the complex layer sequences observed in the north polar layered deposits (NPLD). The results suggest that local stability of water ice exerts a strong control on the polar ice deposition rate. The processes controlling dust deposition rates are complex, and may depend on global-scale processes. We discuss the dust deposition component of the model, and consider different parameterizations of the dust deposition rate. The model parameterizations are tested against the NPLD stratigraphy including both visual and radar data.

The model:
Our main objective is to identify the link between orbital forcing and the stratigraphy of the NPLD by considering the key processes controlling ice and dust deposition. Linking orbital variations to specific layers would provide an accurate dating of the layers, and the model schemes of ice and dust deposition rates would then provide records of past climate.

Our approach is to use a model of NPLD formation driven by insolation and based on physical processes [9]. The model uses simplified parameterizations, and involves a limited number of (unknown) model parameters. We determine the model parameters by an inverse method: we run the model through time forced by the insolation record for Mars and compare the resulting model stratigraphy with the observed stratigraphy of the NPLD. We systematically vary the model parameters to find sets of parameters that provide a model stratigraphy that fits the observed data.

In order to set up the model, we make several simplifying assumptions following earlier work [9]. We neglect effects of ice flow on the stratigraphy. We assume that the polar deposition rates are controlled by insolation, thereby neglecting all other forcing mechanisms, including long-term evolution of the Martian climate system not contained in the insolation record and variability in the climate system on shorter timescales. A reliable insolation record is limited to the last 20 Ma [10], thereby constraining the comparison with data to within this time interval. We assume that ice and dust deposition rates are independently controlled by insolation, and that the stratigraphy is an expression of the relative dust content of the layers.

The ice deposition component of the model is set up following methods from terrestrial ice sheet modelling. The mean annual deposition rate is the result of accumulation and ablation processes during the year, and they are controlled by different processes. We assume that the net annual deposition of ice is a result of a deposition term, which is assumed constant as a first simple approach, and a sublimation term, which is controlled by the local temperature.

The dust deposition component of the model is more complex. Dust deposition is the combined result of dust uplift, dust transport to the poles, and dust deposition. The processes depend on local and global scale conditions. The CO_2 and water cycles are potentially key contributors but their role on orbital timescales is not yet fully understood. As a first approach, we expressed the polar deposition of dust in terms of the meridional temperature gradient in northern summer, which is essentially an obliquity signal [11]. We also used other simplified parameterizations to test different hypothesis regarding dust deposition.

In this model, dust-rich layers form by two mechanisms: 1) increased summer sublimation during high-obliquity, and 2) variations in polar dust deposition rate controlled by orbital variations.

Results:

The model has been compared with visual and radar data in several steps.

The model was compared to the visual stratigraphy, which is known in high resolution, and thereby able to distinguish more subtle layers than radar images of the internal structure [9]. The comparison was done using a stratigraphic column from the north polar layered deposits (NPLD) obtained from a stereo pair of HiRISE images at (87.1°N, 92.6°W) [12], and showed that the model can be tuned to reproduce complex layer sequences observed in the visual images covering the top 500 m of the NPLD. The model was tested with average net deposition rates between 0.1 mm/yr and 10 mm/yr, and a set of model parameters were identified that consistently explains layer formation in accordance with the observations. The model dates the top 500 m of the NPLD back to ~1 million years before present with an average net deposition rate of ice and dust of 0.55 mm/year. This is consistent with a build-up of the NPLD over approximately 5 million years. Modelled layers produced by high sublimation rates at high-obliquity were linked precisely to observed layers. This suggest that the ice deposition processes are well understood, and that local stability of water ice exerts a strong control on the polar ice deposition rate. Observed fine layers could not be explained by the model but was linked to model sections with high-dust deposition rates. This suggests that the obliquity is not sufficient to explain the variability in the dust deposition rate.

The model was compared with radar data [9]. The model was ran through the entire time period covered by the insolation record (20 Myr) showing the build-up of the NPLD and formation of its stratigraphy [9]. The simulation suggested that the NPLD started to build up at 4.2 Ma, in agreement with a climate model [13]. The model stratigraphy was structured in packages similar to the observed radar stratigraphy, but the model stratigraphy lack dust-rich layers at certain depth intervals.

The comparison with data suggested that the dust processes were not adequately represented in the first approach using the obliquity as the only control. We discuss possible processes that could influence dust deposition, e.g. influence from conditions at low latitudes. We set up simple parameterizations of the dust deposition rate and compare them with observed data.

Conclusions:

We use a model of NPLD build up to infer constraints on climate and ice and dust processes from the NPLD stratigraphy.

We set up a model based on simple parameterizations of ice and dust deposition rates expressed in terms of insolation, and compare the model stratigraphy with the observed visual and radar stratigraphy. We used a simple expression of dust deposition rate expressed in terms of an obliquity signal, and identified a set of model parameters that linked the NPLD stratigraphy to the insolation record and thereby provided a timescale. The observations cannot uniquely constrain the model parameters, and deviations between the model and observations, suggest that more complex dust schemes are needed to explain the stratigraphy.

We consider more complex parameterizations of dust deposition rates and discuss how future work should include more data to provide additional constraints. We discuss the implications of the results for the evolution of the NPLD and the processes controlling ice and dust deposition at the poles. Our approach provides new constraints for the modelling of past climate.

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