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Monitoring atmospheric dust spring activity at high southern latitudes on Mars using OMEGA

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ABSTRACT

This paper presents a monitoring of the atmospheric dust in the south polar region during spring of Martian year 27. Our goal is to contribute to identifying the regions where the dust concentration in the atmosphere shows specific temporal patterns, for instance high, variable, and on the rise due to lifting or transport mechanisms. This identification is performed in relation with the seasonal ice regression. Based on a phenomenological examination of the previous results, hypothesis regarding the origin of aerosol activity of the southern polar region is proposed. This is of paramount importance since local dust storms generated in this region sometimes grow to global proportions. The imaging spectrometer OMEGA on board Mars Express has acquired the most comprehensive set of observations to date in the near-infrared (0.93–5.1 μm) of the southern high latitudes of Mars from mid-winter solstice ($L_s = 110°$, December 2004) to the end of the recession at $L_s = 320°$ (November 2005). We use two complementary methods in order to retrieve the optical depth of the atmospheric dust at a reference wavelength of 1 μm. The methods are independently operated for pixels showing mineral surfaces on the one hand and the seasonal cap on the other hand. They are applied on a time series of OMEGA images acquired between $L_S = 220°$ and $L_S = 280°$. As a result the aerosol optical depth (AOD) is mapped and binned at a spatial resolution of 1.0° pixel^{-1} and with a mean period of AOD sampling ranging from less than two sols for latitudes higher than 80°S to approximately six sols at latitudes in the interval 65–75°S. We then generate and interpret time series of orthographic mosaics depicting the spatio-temporal distribution of the seasonal mean values, the variance and the local time dependence of the AOD. In particular we suspect that two mechanisms play a major role for lifting and transporting efficiently mineral particles and create dust events or storms: (i) nighttime katabatic winds at locations where a favourable combination of frozen terrains and topography exists, (ii) large scale ($\approx$ 10–100 km) daytime thermal circulations at the edge of the cap when the defrosting area is sufficiently narrow. As regards to the source regions around the cap, the sector with the highest AOD values / variability / increase spans longitudes 180–300°E around $L_S \approx 250°$. Later ($L_S \approx 267°$) the cryptic sector becomes the most productive while the longitude sector 300–60°E remains moderately dust-generative. Our work calls for new simulations of the martian surface-atmosphere dynamics at mesoscales to reproduce the observations and confirm the interpretations.

1. Introduction

The southern high latitudes of Mars are of great interest in spring and summer because of their role in the dust cycle. Local dust storms generated in this region sometimes develop to global storms, and a prominent dust collar encircles the polar cap. Several experiments aboard orbiters have recently contributed to elaborate and refine this picture.

The TES and MOC instruments of Mars Global Surveyor have provided a regular, but Sun-synchronous, record of dust activity in the south polar region.

Toigo et al. (2002) and Imamura and Ito (2011) produced global maps of dust distribution by integrating TES individual 9 μm optical depth measurements averaged over a 5°-L_s period (respectively 10°-L_s) and binned in $5 \times 5°$ boxes (respectively $5 \times 10°$, latitude, longitude). Both sets of maps depict very distinct space and time patterns of activity around the polar cap edge for the first common Martian year (MY) 24. These seasonal trends are sometimes in contradiction. For the following Martian years 25 and 26, Imamura and Ito (2011) reported a great stability of the dust opacity disturbance compared to MY 24. Thermal mapping of dust

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by TES was originally limited to regions where the temperature and thus the emitted signal are sufficiently high, thus precluding the monitoring of the seasonal polar cap itself. Nevertheless Horne and Smith (2009) modified the standard TES aerosol retrieval algorithm to retrieve atmospheric dust and ice optical depth values for each daytime spectrum in the TES database with a surface temperature below 210 K. As a result maps of the seasonal and spatial variation of dust and water ice optical depth activity over both poles are presented, averaged over a 2°-L_s period and binned in $2 \times 2^\circ$ boxes from late MY24 to early MY27. For the southern high latitudes the greatest observed dust activity each year takes place above the growing seasonal cap from late summer to the beginning of winter. At other seasons dust opacity is in general much lower but some interannual variability, e.g. the beginnings of MY 25 global storm, blurs this pattern.

Following the early work of James et al. (2001) that already noted correlation of storm event locations with the receding southern polar cap, Color MOC wide angle images were mosaicked together by Toigo et al. (2002) to produce daily global maps. Such snapshots show very dynamic dust activity near the edge of the retreating south seasonal ice cap throughout mid- and late-southern spring, then a decline going to midsummer. Visible MOC snapshots are limited in time coverage and do not provide quantitative values of dust opacity.

The imaging spectrometer OMEGA aboard Mars Express allowed to overcome some limitations of the previous experiments since it acquired a comprehensive set of global observations in the near-infrared (0.93–5.1 μm) of the southern high latitudes of Mars in spring and summer. A detailed study of the contribution of water ice aerosols to the OMEGA dataset is provided by Langevin et al. (2007). This study is based on the water ice absorption bands at 1.5, 2, and 3 μm. In 2005 (MY 27) from mid-spring to mid-summer most OMEGA observations are nearly free of water ice either as aerosols or on the surface of the southern seasonal cap. Vincendon et al. (2008) performed the mapping of the optical depth of dust aerosols above areas of the south polar cap constituted of pure CO_2 ice as a function of L_s for dates when the contribution of water ice aerosols can be neglected. The average trend of the temporal evolution is a low optical depth between $L_s = 180^\circ$ and $L_s = 250^\circ$ ($\tau(2.6\ \mu m) = 0.1$–0.2), an increase of atmospheric dust activity observed between $L_s = 250^\circ$ and $L_s = 270^\circ$ ($\tau(2.6\ \mu m) = 0.3$–0.6), and then a decrease up to $L_s = 310^\circ$. Vincendon et al. (2008) observed rapid time variations which are specific to a given location in conjunction to large spatial variations of the optical depth observed over scales of a few tens of kilometres.

Monitoring of dust activity in the high southern latitudes by the previous experiments was accompanied by an important effort in modelling and simulation in order to interpret the observations in terms of processes. The results of General Circulation Models (GCM) suggest that nonconvective wind stress lifting produces the peak in the atmospheric dust opacity during southern spring and summer and that convective (dust devil) lifting is responsible for the background opacity during other seasons (Basu et al., 2004; Kahre et al., 2006). However the coarse spatial resolution achieved by GCM limits our understanding, fostering specific simulations conducted at mesoscales. The main picture that emerges from the latter studies is that flows capable of lifting dust from the surface can be achieved by a variety of conditions, the most likely being cap edge thermal contrasts (Toigo et al., 2002) but also topography (Siili et al., 1999). Regional or synoptic baroclinic instabilities as well as vertical convection in the boundary layer could also play a role (Imamura and Ito, 2011). These conditions as well as dust loading itself in the atmosphere can interfere constructively or destructively.

The previous compilation of observations and simulations shows that some uncertainties and opened questions remain regarding dust activity in the high southern latitudes. First Toigo et al. (2002) and Imamura and Ito (2011) indicate different area where the mean atmospheric dust loading is well above background levels for the same MY 24. Such discrepancy entails an uncertainty on the location of the main source regions as a function of time. Second the relative importance of the expected mechanisms for dust lifting at local and regional scales has not yet been clearly established. Third, dust activity around and inside the seasonal cap has only been reconstructed conjointly by Horne and Smith (2009) although with a very coarse spatial resolution and only as a mean of cross-validating their two retrieval techniques. A more spatially detailed and integrated monitoring could be of paramount importance to investigate the atmospheric dynamics across the cap edge. Finally the main frequency of dust cloud generation and the time they take to dissipate are also apparently inconsistent when examining the results of Toigo et al. (2002) and Imamura and Ito (2011): daily as opposed to every 10–20 sols; a few hours as opposed to 10 sols. Could that be reconciled?

In this paper we bring some new insights about dust activity in the southern polar region by monitoring the dust both inside and around the seasonal cap based on the OMEGA dataset acquired during MY 27. At the same time, special attention is paid to the exact characteristics of the cap edge based on the work of Schmidt et al. (2009). The mapping of the optical depth of atmospheric dust in the near infrared above mineral surfaces is made possible by the development of a new method that is proposed in Douté et al. (2013) and that is shortly described in Section 2. Allied to the complementary method by Vincendon et al. (2008), it is applied to analyse the time series of OMEGA observations thus producing hundred of opacity maps. The latter are integrated into a common geographical grid and processed by a special data procedure so as to generate a time series of mosaics. The mosaics depict the seasonal dust loading as well as the day-to-day variability and local time dependence of the dust optical depth according to solar longitude (Section 3). The mosaics are fully described and examined in Section 4. As a result a synthetic view of dust activity in the south polar atmosphere in mid-spring to early-summer is established and discussed in Section 5. Finally, in Section 6, the main points of our study are summarised.

2. Methods for retrieving the optical depth

2.1. Above ice free surfaces

In summary (see Douté et al., 2013 for more details) the first method that we operate is based on a parametrisation bringing in the mean effective optical path length of photons through the atmosphere composed of particles and gas. The effective path length determines, with local altimetry and the meteorological situation, the absorption band depth of gaseous CO_2. In the following we assume that the top-of-atmosphere (TOA) reflectance factor R^k measured by OMEGA is

$$R^k(\theta_i, \theta_e, \phi_e) \approx T^k_{gaz}(h, lat, long)^{\epsilon(\theta_i, \theta_e, \phi_e, \tau^{k0}_{aer}, H_{scale}, A^k_{surf})} R^k_{surf+aer}(\theta_i, \theta_e, \phi_e)$$

where the quantity $R^k_{surf+aer}$ is the reflectance factor that would be measured in the absence of atmospheric gases. The reflectance factor is defined as the ratio of the radiance coming from the planet by the radiance that would come from a idealised lambertian surface observed under the same geometrical conditions (illumination and viewing). The parametrisation can be expressed as follows. The gas contributes to the signal as a simple multiplicative transmission filter which is the aerosol free vertical transmission $T^k_{gaz}(h, lat, long)$ scaled by the mean effective optical path length ϵ. The transmission T^k_{gaz} is calculated ab-initio using a Line-By-Line radiative transfer model fed by the compositional