WEATHER FORECASTS ON MARS: CO2 SNOWFALLS RELATED TO THE BAROCLINIC WAVES IN THE NORTHERN WINTER POLAR ATMOSPHERE. Takeshi Kuroda[1] , Alexander S. Medvedev[2], Yasumasa Kasaba[1] and Paul Hartogh[2], [1]Department of Geophysics, Tohoku University (6-3 Aramaki-aza-Aoba, Aoba, Sendai, 980-8578 Japan, tkuroda@pat.gp.tohoku.ac.jp, kasaba@pat.gp.tohoku.ac.jp), [2]Max Planck Institute for Solar System Research (Justus-von-Liebig-Weg 3, Göttingen, 37077 Germany, medvedev@mps.mpg.de, hartogh@mps.mpg.de).

Introduction: The seasonal CO_2 polar cap is formed from ice particles that have fallen from the atmosphere as well as those condensed directly on the surface. The possible occurrence of CO_2 snowfall in the winter polar regions have been observed, and previous simulation studies have indicated that the longitudinal irregularities of CO_2 ice clouds in the northern polar region seemed to be linked to local weather phenomena. Transient planetary waves are the prominent dynamical feature during northern winters in the martian atmosphere, and this study focuses on revealing the mechanism of how the dynamical influence of transient planetary waves affects the occurrences of CO_2 ice clouds, snowfalls and formations of seasonal CO_2 polar cap in high latitudes during northern winters. We simulated the the formation of CO_2 ice clouds in the winter polar atmosphere using a Mars general circulation model (MGCM), and showed the mechanisms for the time and spatial variabilities of the occurrences of ice clouds and deposition rates on the surface [1].

Outline of the MGCM: We used the DRAMATIC (Dynamics, RAdiation, MAterial Transport and their mutual InteraCtions) MGCM, which is based on a Japanese terrestrial general circulation model with a spectral solver for the three-dimensional primitive equations [2] and has been applied to the studies of dynamical features on the Mars' atmosphere [3-7]. In this simulation the horizontal resolution is set at about 5.6° × 5.6° (~333 km at equator), the vertical grid consists of 69 σ-levels with the top of the model at about 100 km. Realistic topography, albedo, thermal inertia and roughness data for the Mars surface are included. Radiative effects of CO_2 gas (considering the Local Thermodynamic Equilibrium at all heights) and dust, in solar and infrared wavelengths, are taken into account.

We have implemented a simple scheme representing the formation and transport of CO_2 ice clouds into our MGCM. If our model predicts a temperature drop below the carbon dioxide supersaturation level, an ice cloud forms, and latent heat is released to maintain the degree of supersaturation. The CO_2 saturation temperature T_s is calculated as the function of pressure p with the Clausius-Clapeyron relation for perfect gas [8]:

$$T_s = \left(\frac{1}{T_0} - \frac{R\ln(p/p_0)}{L}\right)^{-1}$$

where R is the gas constant; T_0 = 136.3 K is the reference saturation temperature at p_0 = 1 hPa; and L = 5.9×10^5 J kg^{-1} is the latent heat of CO_2. The significant degree of supersaturation required to heterogeneously nucleate CO_2 cloud particles is accounted for by using $1.35\times p$ instead of pressure [9]. The sedimentation velocity for CO_2 ice particles w is calculated from Stokes' law with the modifications [10]. The radius of cloud particles r is defined as a function of height z [1].

Results: Figure 1 compares the observed and simulated zonal mean temperature and aerosol mass mixing ratios in the northern hemisphere averaged over the winter season between L_s = 255° and 285° during relatively low-dust conditions. Observations represent the Mars Climate Sounder onboard Mars Reconnaissance Orbiter (MRO–MCS) Derived Data Version 2 [11] for Mays Year (MY) 29, and the dust signals in retrievals in winter polar regions are likely to be caused by CO_2 ice clouds [12]. We consider such dust signals as the evidence for CO_2 ice clouds.

Figure 1a demonstrates the presence of atmospheric ice particles northward of 70° N between 10 and 100 Pa (15–40 km). Simulations of temperature and mass mixing ratios of CO_2 snow, shown in Figure 1b, are in good agreement with the observations, at least in the case of the zonal mean values. The MGCM simulated also the CO_2 ice clouds below 15 km, which are consistent with the Mars Orbiter Laser Altimeter onboarm Mars Global Survayor (MGS-MOLA) cloud echo observations [13]. In addition to the ice clouds in the polar night region, the model also simulates mesospheric CO_2 clouds in mid-latitudes, which are consistent with the Thermal Emission Imaging System (THEMIS) measurements onboard Mars Odyssey [14]. Note that the MRO-MCS does not observe these particles (Figure 1a), because its detections are limited to altitudes below 10 Pa [12].

Figure 2 shows the composite features of the simulated mixing ratio of CO_2 ice clouds, atmospheric temperature at 15 and 30 km altitudes, and CO_2 ice deposition rate on the surface at 80° N around winter solstice. It is apparent that the occurrence of CO_2 ice clouds is very much aligned with cold phases of the baroclinic waves with zonal wavenumber of 1 and 5–6 sols period. Although the amplitudes of wave-induced variations in temperature are of the order of a few degrees Kelvin, they are sufficient enough to modulate the CO_2 cloud formation by dropping the local air temperature below the condensation threshold.

It is clear that the deposition rate is also modulated by transient planetary waves. In the lower atmosphere, harmonics with zonal wavenumber of 2 and shorter periods (~3 sols) becomes dominant [4,15]. Calculations show that about 42 % of the ice cap is created due to the snowfalls, while the rest is by direct condensation.

It takes ~0.2 sols for particles to descend from 25 km to the surface, which is much shorter than the periods of the transient waves. Thus, the fate of ice particles during sedimentation depends on the thermal structure below. Regions where the warmer and colder anomalies alternate vertically, which results in the sublimations of CO_2 clouds formed in upper atmosphere, except at 30° W–60° E where the deposition rate is at its largest. At 30° W–60° E, CO_2 ice particles formed below ~20 km can reach the surface.

Summary and Conclusions: Our simulations using a MGCM showed that the CO_2 ice clouds are formed at altitudes of up to ~40 km in the northern polar region during winter, and their occurrence correlates to a large degree with the cold phases of transient planetary waves. Ice particles formed up to ~20 km can reach the surface in the form of snowfall in certain longitude regions, while in others these particles likely sublimate in the lower warmer atmospheric layers.

Given the regular nature of such waves, our results suggest that statistics of the occurrence of such snow events in high latitudes of Mars may be reliably predicted, further in advance than the snow storms on Earth. For missions to Mars exploring this region with rovers, such weather forecasts would offer the possibility of choosing a route that avoids heavy snow storms.

References: [1] Kuroda T. et al. (2013) *GRL, 40*,1484–1488. [2] K-1 Model Developers (2004) *K-1 Tech. Rep., 1*, 1–34, Univ. of Tokyo. [3] Kuroda T. et al. (2005) *J. Meteor. Soc. Japan, 83*, 1–19. [4] Kuroda T. et al. (2007) *GRL, 34,* L09203. [5] Yamashita Y. et al. (2007) *GRL, 34*, L16819. [6] Kuroda T. et al. (2008) *GRL, 35,* L23202. [7] Kuroda T. et al. (2009) *J. Meteor. Soc. Japan, 87,* 913-921. [8] Hourdin F. et al. (1995) *JGR, 100,* 5501–5523. [9] Glandorf D. L. et al. (2002) *Icarus, 160,* 66–72. [10] Kasten F. (1968) *J. Appl. Meteor., 7,* 944–947. [11] Kleinböhl A. et al. (2009) *JGR, 114,* E10006. [12] McCleese D. J. et al. (2010) *JGR, 115,* E12016. [13] Colaprete A. et al. (2003) *JGR, 108,* 5081. [14] McConnochie T. H. et al. (2010) *Icarus, 210,* 545–565. [15] Banfield D. et al. (2004) *Icarus, 170,* 365–403.

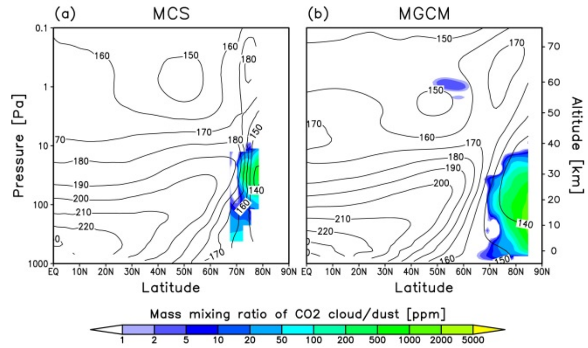

Figure 1: (a) MRO–MCS observations of the zonal mean temperature (contours) and dust (snow) mass mixing ratio (color-shaded, only north of 65° N) averaged between L_s = 255° and 285° of MY29. (b) Same as in (a), except for the simulation with the MGCM. Shades of color represent the mass mixing ratio of CO_2 ice.

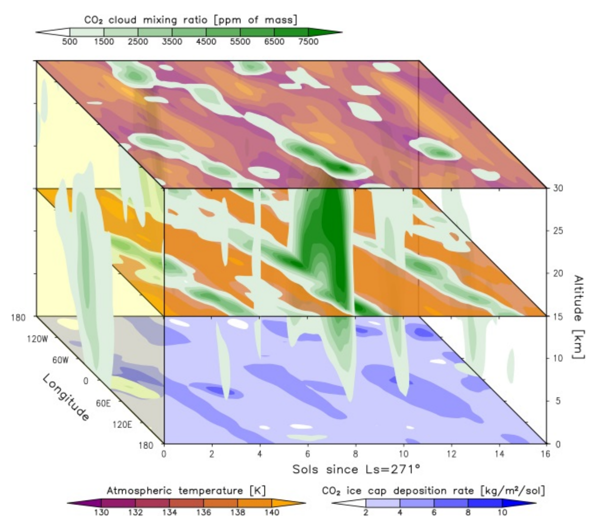

Figure 2: Composited features at 80° N simulated by the MGCM: Mass mixing ratio of CO_2 ice clouds (Hovmöller diagrams at 0, 15 and 30 km altitudes and longitude-altitude cross-sections for every 4 sols since L_s = 271°), atmospheric temperature at 15 and 30 km altitudes, and CO_2 ice cap deposition rate on the surface. All values represent as daily-averaged.