**Tianwen-1 Landing Site Atmospheric Condition based on 2021 Local Dust Storms of Mars**

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**Highlight:**

1. Local dust storms injected dust into the rising branches of the cell of Hadley Circulation
2. Midlevel air temperature raised up to 200 K during the dust storm
3. Planetary circulation helps create the dustiness through variation of CBL
4. Air-born dust particles are of fine mode as well as coarse mode.

**Abstract:**

The present study is based on the local dust storms reported by Tianwen-1. In the year 2021 Tianwen-1 reported 6 local dust storms near mid-latitude (*Qu et al., 2021*). The current work tries to investigate the atmospheric changes over the lendable area during the reported dust events by Tianwen-1. Based on the temperature profile acquired by Mars Climate Sounder (MCS), we have estimated the Convective Boundary Layer’s (CBL) height. The estimated CBL height varies from 7 to 9 km during dust storms. Strong mixing below CBL creates dustiness over the observed area. The observed dust storm lasted for more than a sol significantly affecting the atmospheric structure and the planetary circulation, suggesting that the equatorward dust storm injected dust into the rising branches of the cell of Hadley circulation. Hence, though headily circulation dust mixing enhancement occurs in the middle atmosphere and the mid-level air temperatures rise. Further, we are trying to estimate the properties of the dust particle. The effective radius of the dust particle varies from 300 nm to 3000 nm. During the dust storm, air temperature increases up to 200 K. With the help of temperature data and retrieved water ice opacity data we have shown the formation of water ice clouds along the midlatitude of Mars. The formation of water ice clouds has been represented through the radiance data of available low-resolution images captured by the Visual Monitoring Camera (VMC).

**Keyword:**

Mars Climate Sounder, Hadley Circulation, Convective Boundary Layer, Visual Monitoring Camera

**Introduction:**

Martian dust storm ranges from microscopic scale-like local (longitudinal axis >100 km) to planet-encircling or like large dust storms with longitudinal axis >2000 km; (Martin and Zurek, 1993). The scientific community tried to understand the origin of dust storms and the planet's circulation pattern (Golitsyn, 1973; Gierasch and Goody, 1973). Large-scale dust storms like regional and Global dust storms used to last for more than a sol or even for weeks and microscopic scale-like local dust storms used to stay for more than half a sol. These dust events significantly affect the atmospheric structure and planetary circulation (Martin and Richardson, 1993; Smith et al., 2002; Wang et al., 2003; Cantor, 2007; Wang et al., 2007). Haberle et al. (1982); Strausberg et al., 2005;) suggested that the equatorward dust storm injected dust into the rising branch of the Hadley circulation. Hence, though Hadley circulation dust mixing enhancement occurs in the upper atmosphere, especially in the mesosphere, the mid-level air temperatures rise. So, accretion in the mid-level air temperature can be an indicator of dust storm occurrence. Moreover, regional dust storms generate thick haze over many areas. The haze may reach up to an altitude of 60 km and increase the normal dust opacity over the area (Cantor, 2007; Mishra et al., 2016). Water ice clouds and fog appeared in low-altitude topography on Mars without dust storms (Benson et al., 2010). The scientific community tried to find the dust movement initiated by dust storms and their impacts on the planet's circulation by opacity analysis (Heavens et al., 2011; Guzewich et al., 2015, 2017).

Based on the previous literature, Utopia Planitia has been considered the largest impact basin in the northern hemisphere of Mars. The Martian atmospheric dust actively influences the Martian climate and participates in the accretion of the albedo of the Martian surface due to the deposition of dust particles (Tang et al., 2021).

Previous studies already explored the combined behavior of thermal tides with water ice clouds that enriches the understanding further of the factors that involves to the formation of elevated temperature inversions. The previous literature adopted modeling studies to show that tropical effective temperature inversions may arise either dynamically from zonally modulated thermal tides (Wilson et al., 2003; Hinson and Wilson, 2000) or else radiatively from a dense water ice cloud layer (Colaprete and Toon, 2000, Haberle et al., 1999). During the dust storm, the planet possesses a huge temperature instability which further helps the formation of water ice clouds. In our present work, first, we investigate the atmospheric scenario during the local dust storms. Secondly, we investigate the temperature variation and opacities to see unreported dust activities throughout the planet. Thirdly, we investigate the temperature variation in relation to the water ice cloud from opacity data. Finally, we reported the whole atmospheric scenario during these 6 events of dust storms.

**Data and Methodology:**

**MCS data:**

MCS observed Martian limb, nadir, and off-nadir in nine broadband channels to detect dust, temperature, and condensates (McCleese et al., 2007, Kalita et al., 2021) from September 24, 2006 (LS = 111°, MY 28). We may extract vertical profiles of temperature (K), dust extinction (km-1; at 463 cm−1 wavenumbers), and water ice extinction (km-1; at 843 cm-1wavenumbers) through the limb observations with a moderate (5 km) vertical resolution from the surface to ~80 km altitude through MRO observation (Kleinböhl et al., 2009, Kalita et al., 2021). We used MCS DDR data for MY 33–34 in the present work, available in PDS by the following link,

<https://pdsatmospheres.nmsu.edu/data_and_services/atmospheres_data/Mars/Mars.html>

Vertically integrated dust extinction is available in a .tab file inside MCS observational DDR data product. We may use the dust extinction data to analyze the total observed dust opacity. Eventually, MCS retrievals in dusty conditions do not extend to the surface with maximum atmospheric mass (Guha et al., 2018, Kalita et al., 2021a, 2021b). So, the vertically integrated dust opacity is calculated by assuming a well-mixed profile using the lowest retired point. It is to be noted that this assumption yields the limb observed extrapolated data. We adopted the density-scaled opacity approach given in Heavens et al. (2011) to examine the variability in atmospheric parameters because it is a seasonally and latitudinally varying opacity profile that is a convenient approximation of what might be appropriate for Mars. Density-scaled opacity is readily related to the aerosol mixing ratio. Also, the profile forwarded by Forget et al. (1999) cannot estimate the vertical dust distribution at certain latitudes and seasons. Moreover, density-scaled opacity helps understand a particular dust profile's radiative and dynamic importance (Heavens et al., 2011, Kalita et al., 2021a,2021b).

Deposition of aerosol (dust and hexagonal water ice crystal) put an impact on the variation of CBL height. Further, we reported CBL height based on the MCS data. We computed the approximate height of the CBL based on the MCS temperature data. MCS data helped us to predict the intensity and height of the observed dust storm (Kalita et al., 2021a, 2021b). The present work also focused on the dust and water ice opacity for the MCC observed events and the temperature profile derived from MRO-MCS. For that, we need to estimate the dust extinction value. We estimated density-scaled opacity by scaling the opacity (dzτ in km-1; i.e., extinction per unit height due to dust or water ice) by atmospheric density (𝞺), i.e., dzτ / 𝞺 in m2 kg−1. We used DDR-version 5 data to estimate the required parameters through simulation (Kalita et al., 2021a, 2021b). We followed the Mie theory to calculate the effective radius of the particle. First, we calculate the density scaled opacity derived from MCS dust extinction and water ice extinction data. We used the data to estimate the mixing ratio of the dust particles, then using the Mie theory; we calculated the effective radius of the particle as

*(1)*

Also, the effective radius of water ice particle as,

*(2)*

The value of ‘Qext’ is 0.78 for water ice particles, and 0.350 in the case of a dust particle can be obtained from the Mie theory described by (Kleinböhl et al., 2009), where ‘reff’ is the effective radius of particles. Density ρ is obtained from MCS data using the ideal gas equation are the retrieved densities that have the value of 900 kg m-3 and 3000 kg m-3 respectively. The calculated effective radius of the particles varies from 1.40 to 3.2 μm. Also, we verified our calculation of effective radius with the MCD GCM output for that particular event*.* Further, we evaluated the static stability factor depending upon the temperature profile and calculated the CBL height during the observed period. First, we plot the static stability value (S) as a function of altitude. Observed S value should be in between 1 and 2 with corresponding height that helps us to estimate the CBL.

CBL height is difficult to calculate accurately. We consider the S value 1.5 to determine the CBL height. CBL height through occultation method is given by,

*(3)*

Where g is the acceleration due to gravity is the temperature gradient, and the Cp is the specific heat at constant pressure. Further, we subtracted the elevation of the area from occultation height to get the actual value of CBL (D) as,

*(4)*

**Mars Climate Database (MCD) web interface:**

To estimate the effective radius of the dust particle we use MCD-based mixing ratio values. The web interface is as follows,

<http://www-mars.lmd.jussieu.fr/mcd_python/>  
We put lat/long and altitude as input in the web interface and extracted the mixing ratio for the particular event. Further, we used the modeled value to calculate the effective radius of the particles. Also, based on the comparison between the detection wavelength and the radius of the particle we cautiously reported the mode of the particles.

**Visual Monitoring Camera Images:**

To monitor the release of the Beagle-2 lander, the Visual Monitoring Camera (VMC) was included on Mars Express originally. The VMC was switched on again on 2007 and effectively used for almost a decade purely for outreach purposes. In 2016, collaboration with scientists from the University of the Basque Country UPV/EHU in Bilbao proved the scientific value of the data through studies of plumes (SANCHEZ-LAVEGAETAL et al., 2015). The Visual Monitoring Camera is a Complementary metal-oxide-semiconductor (CMOS) sensor that takes images by default in grayscale. Further, VMC is fitted with a Bayer Pattern filter so that color information may be extracted in post-processing (archives.esac.esa.int)

The VMC low resolution images are processed to extract the luminosity value as follows,

luminosity(a,b)=image(a,b,1)\*0.299+0.587\*image(a,b,2)+0.114\*image(a,b,3) *(5)*

After that we converted those DN number to radiance value to detect the cloud.

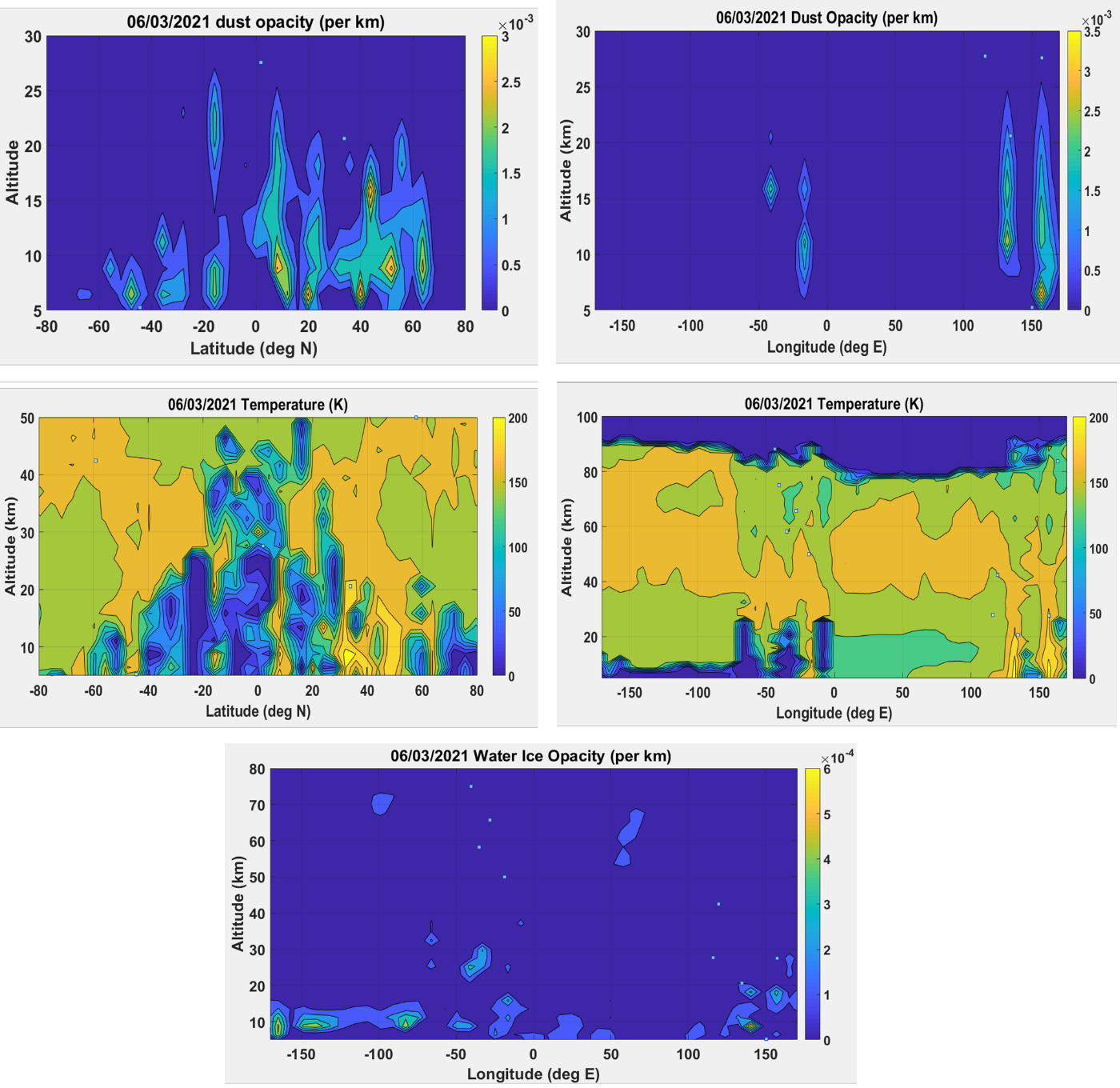
**Result and Discussion:**

The six local dust storms reported by Tiawnwen-1, in the year 2021 Tiwanwen-1 near midlatitude are as follows (*Qu et al., 2021*).

Table 1: Location and solar longitude information for the observed events

|  |  |  |  |
| --- | --- | --- | --- |
| Serial number | Dust storm type | Solar longitude(degree) | Center Location (lat/long) |
| 1 | Local | 13.1 | 47.0◦N, 101.2◦E |
| 2 | Local | 13.8 | 52.0◦N, 107.2◦E |
| 3 | Local | 21.3 | 61.3◦N, 130.1◦E |
| 4 | Local | 21.8 | 64.3◦N, 121.1◦E |
| 5 | Local | 27.1 | 54.6◦N, 104.9◦E |
| 6 | Local | 27.4 | 53.4◦N, 107.2◦E |

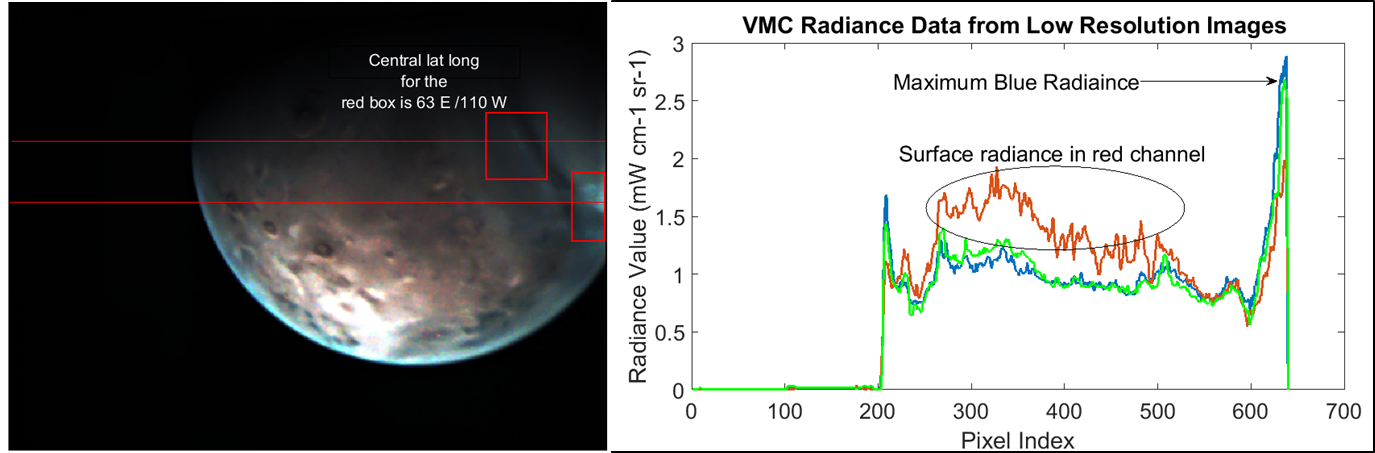
From the table we have the solar longitude and center location for the dust storms. The spreading area is reported >700,000 km2. The area corresponds to ± 20 lat/long from the central coordinate represented in the table 1. We processed the Mars Climate Sounder (MCS) observed opacity data and found a satisfactory results. In figure 1 we may see the dust opacity for the corresponding events.



**Figure 1:** The figure illustrates the MCS observed latitudinally and longitudinally distributed dust and water ice opacity data as a function of altitude on 06/03/2021. In the longitudinal distribution, we can clearly see the two branches of temperature with a high value (~200 K) corresponds to dust opacity. That indicates the rise in temperature during the dust storm. Also, a sudden increase in temperature below 20 km along -100 to -150 E results in the formation of a water ice cloud. Water ice opacity is 5x10-4 km-1 at the corresponding latitude.

The corresponding lat/long value is also verified with the represented opacity plot. On 06/03/2021 a high dust deposition is recorded over 52.0◦N, 130.2◦E. The mid-level air temperature also reaches up to 200K. Dust is injected up to a height of ~25 km. CBL is recorded as 8 km. Due to the rise in the height of CBL a strong mixing occurs between air and air-born dust. This redistribution creates dustiness over the Utopia Planitia. This largest basin of Mars possesses high albedo also due to the deposition of dust.

As we mentioned in figure 1 the water ice cloud formed over -100E to -150 E during the dust storm event due to an anomaly in temperature. Further, VMC images are represented to show the clouds. If we consider the tropical extension of Hadley circulation, we may indicate the branches with high-temperature values where dust is injected from the lower atmosphere.



**Figure 2:** VMC low-resolution images with clouds. We took two transects (red line) to extract the radiance data. The radiance data confirms the presence of a water ice cloud.

We may see cloud structure over -100E to -150 E due to temperature anomaly as shown in figure 1. The red boxes illustrate the cloud portion of the low-resolution images. Further, the events have been processed through MCD to see the mixing ratio, wind pattern, and temperature. Temperature is further verified with the observed data.

We tried to consult MARCI’s daily weather report to verify our events. Unfortunately, MARCI daily weather report is not available for that time period. Also, it is worth mentioning that we did not extract the reflectance value at the top of the atmosphere as we did in our previous paper (Kalita et al., 2021), because for that we need a deeper knowledge of VMC. In our present work, we presented low-resolution images to show the water ice cloud formed over other location during the events and we constrained ourselves up to the calculation of radiance value. We mainly focus on the temperature anomaly throughout the planet and their contribution for the formation of water ice clouds.

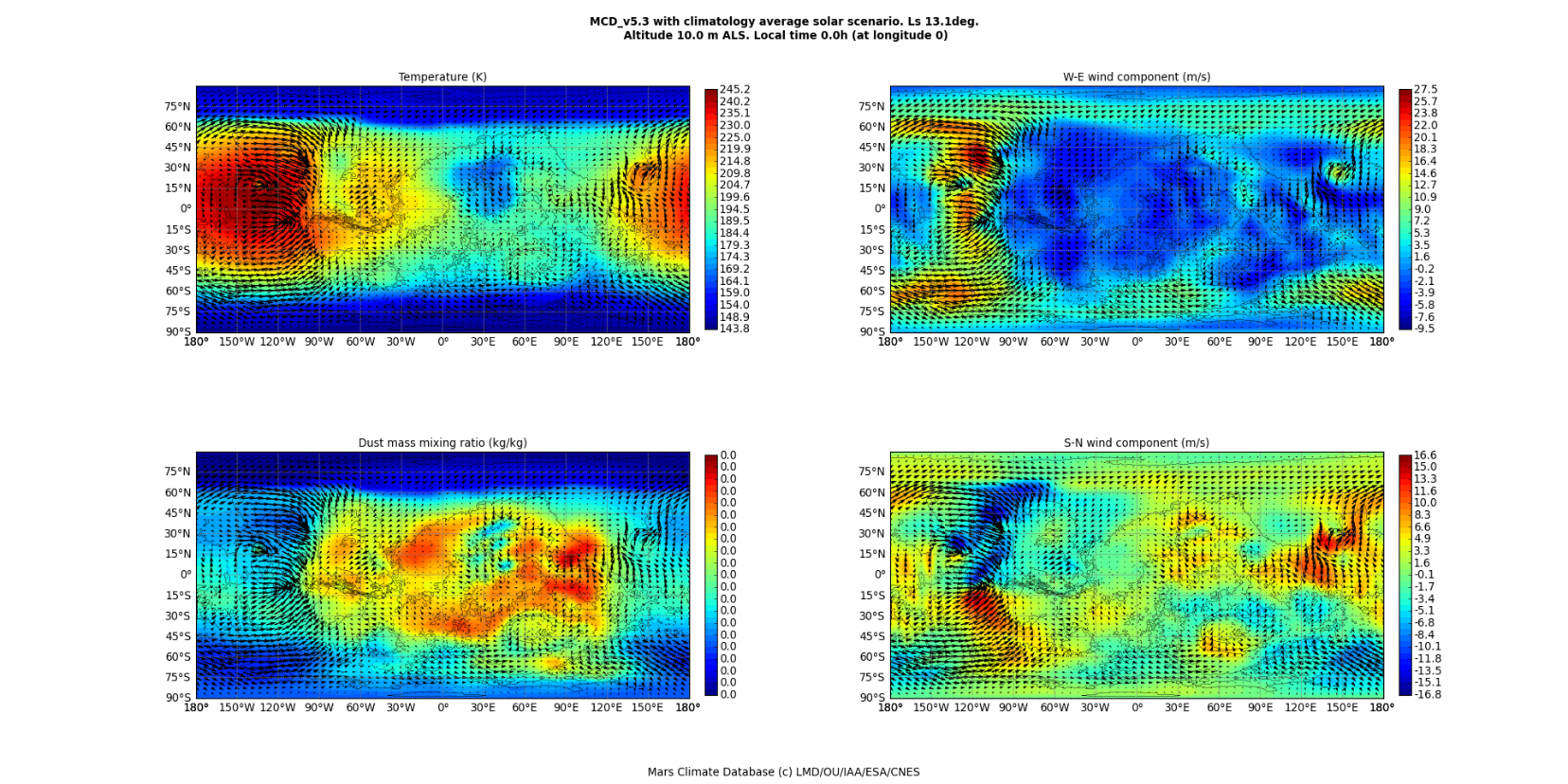


Figure 3 (a): MCD-based temperature, wind process, and mixing ratio plots. High westerlies drive the dust and are used to inject the dust into the rising branch of the Hadley circulation.

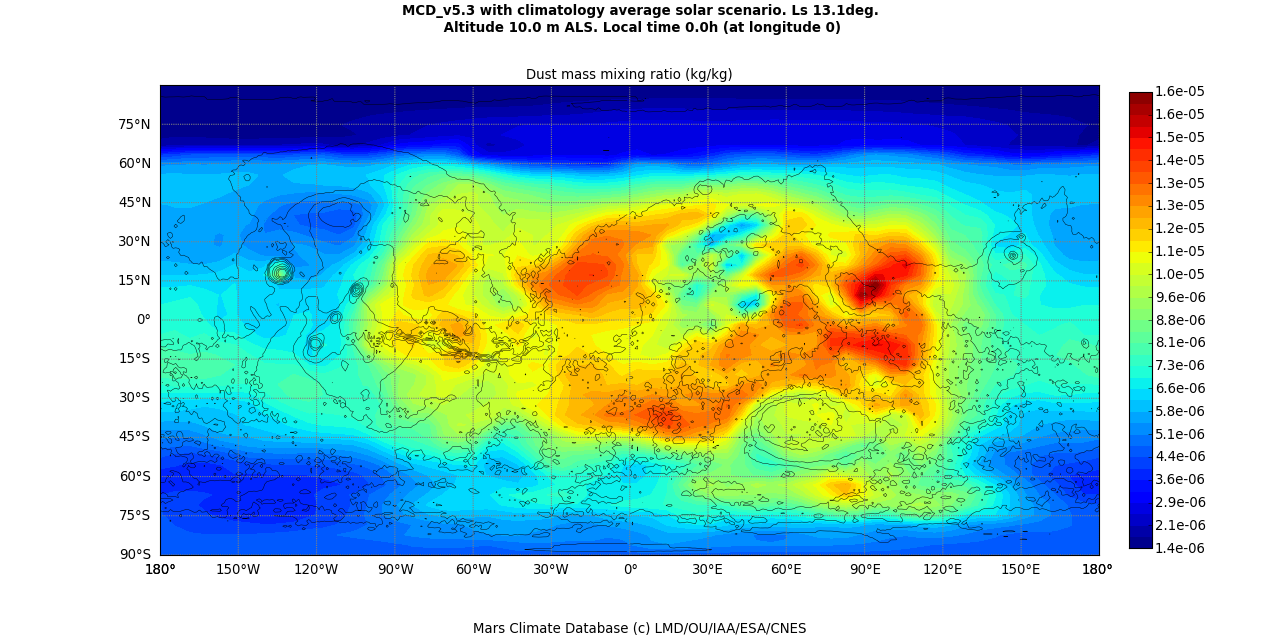


Figure 3 (b): The mixing ratio plot has been shown separately to illustrate how we used the mixing ratio data to extract the effective radius of the particles.

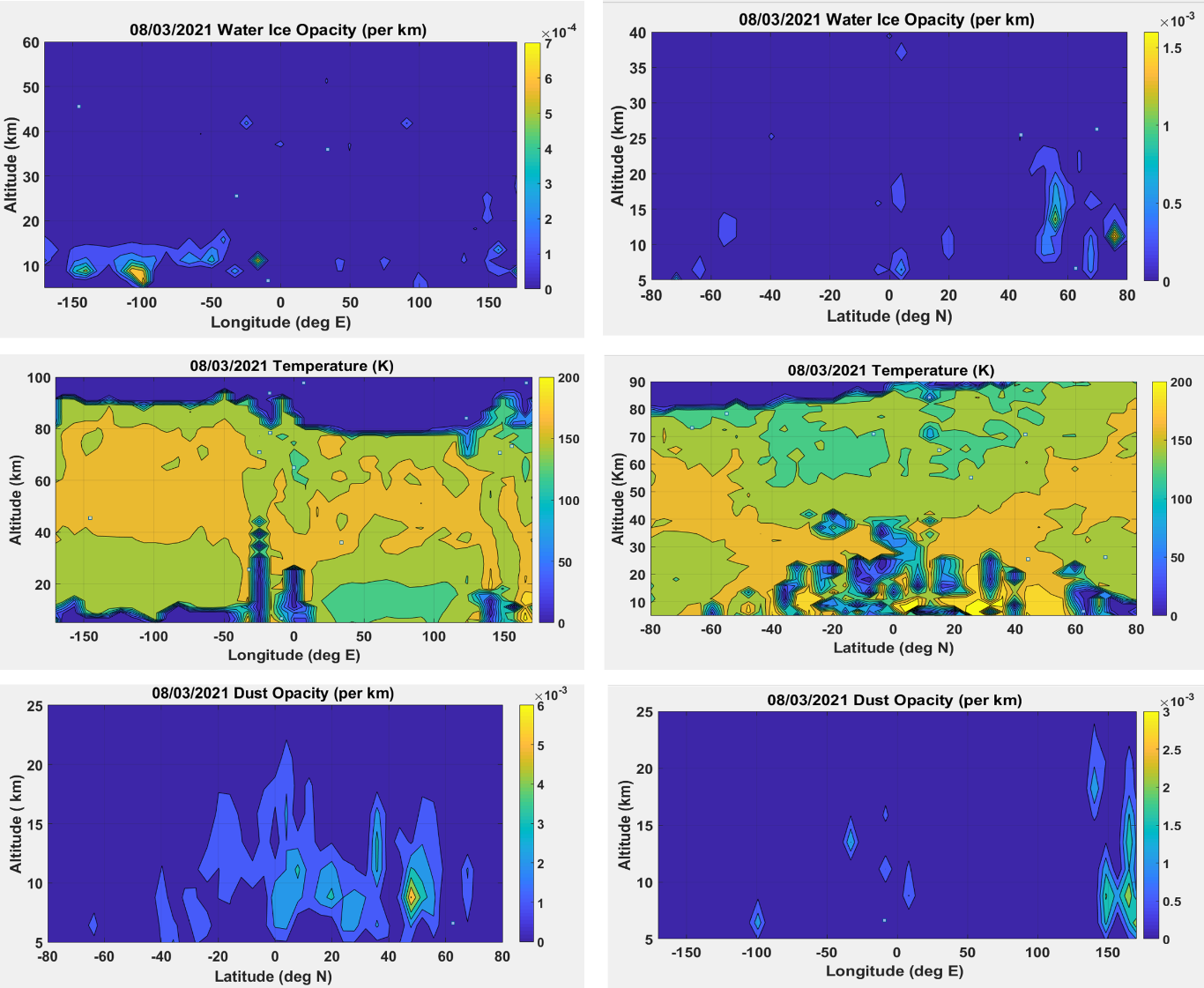
Similarly, on 08/03/2021 we analyzed the MCD and VMC data. High dust deposition is recorded over 52.0◦N, and 150.2◦E. The mid-level air temperature also reaches up to 200K. Dust is injected up to a height of ~20 km. CBL is recorded as 7.8 km. Due to the rise in the height of CBL a strong mixing occurs between air and air-born dust. This redistribution creates dustiness over the Utopia Planitia. High wind speed along W-E helps in the redistribution process. W-E wind varies from -35 to 35 m/s. Negative sign indicates the E-W wind flow over the observed area. Whereas, the S-N wind varies from -21 to 21 m/s. Both the events caries the evidence of coarse mode as well as fine mode particles.

Figure 4: The figure illustrates the MCS observed latitudinally and longitudinally distributed dust and water ice opacity data as a function of altitude on 08/03/2021. In the longitudinal distribution, we can clearly see the two branches of temperature with a high value (~200 K) corresponds to dust opacity. That indicates the rise in temperature during the dust storm. Also, a sudden increase in temperature below 20 km along -100 to -150 E results in the formation of a water ice cloud. Water ice opacity is 7x10-4 km-1 at the corresponding latitude.

We concluded the mode based on the observed wavelength and effective radius of the particles. The effective radius during 06/03/2021 varies from 400 nm to 2100 nm whereas on 08/03/2021 the effective radius varies from 350 nm to 3000 nm. We already mentioned that we may extract the dust extinction (km-1) at 463 cm−1 wavenumbers, and water ice extinction (km-1) at 843 cm-1wavenumbers. For the other four events, we have mentioned the details in table 2

**Table: 2 Illustrate the CBL height, wind speed, and temperature data for the local dust storm**

|  |  |  |  |
| --- | --- | --- | --- |
| Solar longitude | CBL height | Windspeed Maximum (m/s) | Maximum temperature (K) |
| 21.3 | 8.1 | 25 | 200 |
| 21.8 | 8.0 | 22 | 210 |
| 27.1 | 7.9 | 30 | 220 |
| 27.4 | 8.2 | 32 | 210 |

**Concluding Remarks:**

1. During the local dust storms, the temperature used to rise over the observed area.
2. Rise in temperature and wind speed, convection as well as Variation in CBL helps the dust to be redistributed over the observed location.
3. Strong Dust mixing and injection of dust into the rising branch of Hadley circulation leave the area dusty after the local dust storm.
4. Throughout the planet temperature anomalies helps the formation of water ice cloud.
5. Bellow 15 km a sudden change in the temperature helps the formation of the clouds.
6. Effective radius of the particles varies from 300 nm to 3000 nm, further, helping the accretion of the Albedo value through strong mixing and redistribution of dust.

**Acknowledgment:**

**All** authors are thankful to the MCC data product team, ISRO for providing access to the required data for the present analysis (<https://mrbrowse.issdc.gov.in/MOMLTA/>). Also, the authors are thankful to the SSPO(ISRO) for funding the project with fund reference ISRO/SSPO/MOM- AO/2016-2019. A special thanks to Dr. Satadru Bhattacharya, Planetary Sciences Division, and Space Applications Centre (ISRO) for his constant support. Authors would like to acknowledge the Department of Science and Technology for a supporting fund to the Department of Physics, Tripura University through DST-FIST fund reference SR/FST/PSI-191/2014. The authors are also thankful to the MCS data providing team for publicly available data at PDS.

<https://atmos.nmsu.edu/data_and_services/atmospheres_data/MARS/data_archive.html>. The authors are also thankful to the VMC data team members for the publicly available data [PSA Introduction - PSA - Cosmos (esa.int)](https://www.cosmos.esa.int/web/psa/psa-introduction).

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