Exploration of the Mars Polar Atmosphere Using the Mars Climate Sounder (MCS) and the Ensemble Mars Atmosphere Reanalysis System (EMARS)

Hartzel Gillespie (1), Steven Greybush (1), Daniel McCleese (2), Armin Kleinböhl (3), David Kass (3), R. John Wilson (4) and J. Tim Schofield (3)

(1) Penn State, (2) Synoptic Science, (3) JPL, and (4) NASA-Ames

Presented at MADA 2018
August 28, 2018
Why study the polar region with MCS and EMARS?

• Building on prior study of transient eddies, we are interested in further characterizing the spatiotemporal variability of the Martian atmosphere.

• Some phenomena in the polar region of Mars remain relatively unexplored, but are well-observed by MCS.

• EMARS provides full spatiotemporal coverage of many meteorological quantities, including ones not observed by MCS, but EMARS has difficulty representing some features observed by MCS. How can we improve?
Outline

• MCS and EMARS background
• Climatological polar structure
• CO$_2$ latent heating
• Thermal tides
• H$_2$O transport
Mars Climate Sounder (MCS)

- Limb-observing infrared radiometer
- 105 vertical levels of data retrieved, from the surface to 100 km
- Along-track and cross-track observations
- Temperature from MCS assimilated into EMARS
- Column dust in EMARS constrained by MCS
  (Montabone et al., 2015)
Ensemble Mars Atmosphere Reanalysis System (EMARS)

- Geophysical Fluid Dynamics Laboratory (GFDL) Mars Global Circulation Model (MGCM) (Wilson et al., 2002)
  - Grid spacing 5° by 6° (~150 km), with 28 vertical levels
  - Aerosols advected by model in both horizontal and vertical

- Local Ensemble Transform Kalman Filter (Hunt et al., 2007)
  - 16 ensemble members, water ice and dust varied among members
Climatological polar structure

- Data from 3 AM and 3 PM local time in EMARS are retained
- Zonal mean over 20 sols of EMARS, centered on Ls 270 (northern winter solstice)
- 3 AM is on the left, and 3 PM is on the right
- MCS plots are similar, but are averaged over 5 Ls (about 10 sols)
Equatorial ice clouds

MCS T Ls = 287

EMARS Anal T, Ls 270

EMARS Anal U, Ls 270

MCS Dust

Dust

MCS Ice

Ice

Vapor

AM PM

AM PM

AM PM
Equatorial dust

MCS T, Ls = 287

EMARS Anal T, Ls 270

EMARS Anal U, Ls 270

MCS Dust

Dust

MCS Ice

Ice

Vapor

AM AM AM PM PM PM
Polar warming

MCS T Ls = 287

EMARS Anal T, Ls 270

EMARS Anal U, Ls 270

MCS Dust

Dust

MCS Ice

Ice

Vapor

AM PM

AM PM

AM PM
"Cold pockets"
The polar MCS “dust” observation is an observation of solid CO$_2$. EMARS also suggests that CO$_2$ deposition occurs within the core of the polar vortex. We’d expect various atmospheric waves to have an effect on CO$_2$ deposition. Are these waves present in MCS or EMARS data?
CO$_2$ latent heating

- Hovmöller diagrams, with increasing time ascending instead of descending
- EMARS and EMARS control data from one model level and a range of latitudes specified on the plot are plotted
- Here, the largest value of CO$_2$ latent heating between 49 and 75 N is plotted at each longitude
- 1° Ls $\approx$ 2 sols (Martian days)
The amount of time between each burst of CO$_2$ seems to be close to 1 sol. A stationary wave of wavenumber 2 is apparent, but it’s hard to discern any horizontal motion of a CO$_2$ anomaly.
Vertical coordinate: $\sigma \sim 0.3$ (200 Pa, or 12 km)

In the model, the CO$_2$ is a superposition of a tidal influence, a stationary wave, and transient eddies. CO$_2$ occurs primarily near 60 E and 200 E here, while in EMARS, 120 E and 330 E were the maxima.
Difference between EMARS and MCS temperature and sublimation temperature of carbon dioxide at 80 Pa (22 km)

A stationary wave that appears to be a combination of wavenumbers 1 and 2 are present. Transient eddy activity is more difficult to discern, if it is present.

Notice that the EMARS and MCS stationary wave extrema are at similar longitudes. The EMARS control run places the extrema at different longitudes.
Thermal tides

MCS T Ls = 287

EMARS Anal T, Ls 270

EMARS Anal U, Ls 270

MCS Dust

Dust

V

MCS Ice

Ice

Vapor
Ensemble members are colored according to their dust and ice radiative factors. Black → red: more dust, Black → blue: more ice. Warmer members have more ice, and to a lesser extent, more dust.
EMARS represents the tidal signal measured by MCS well in the cold pockets, despite the temperature difference.

There are differences in the amplitudes of the various tidal modes among the ensemble members, which may aid in assimilating tidal information.
H$_2$O transport

Evidently, there is water within the polar vortex in both MCS and EMARS, though the distribution is different.

Is water in the polar vortex isolated from the rest of the atmosphere? How does H$_2$O enter the polar regions?
Ice values below 0.1 mg/kg not shown

The polar vortex is saturated in EMARS.

There is water vapor in the cold pockets, but it’s not cold enough in EMARS for clouds to form there.
The left plot is vapor transport by meridional wind, while the right plot is vapor advection by meridional wind, as a 20-sol zonal mean.

The most notable effect suggested by the two plots together is the movement of water vapor from 25 N to 50 N, at 20 Pa, by the meridional wind.
The left plot is vapor transport by meridional wind, while the right plot is vapor advection by meridional wind, as a 20-sol zonal mean.

The most notable effect suggested by the two plots together is the movement of water vapor from 25 N to 50 N, at 20 Pa, by the meridional wind.
Most of the transport is mean transport.

Some transport into the vortex is evident below 800 Pa.

Above 800 Pa, at the outer edge of the polar vortex, water is transported equatorward. A band of equatorward transport is also present within the polar vortex near the surface. These features suggest that the water inside the polar vortex is isolated from the rest of the atmosphere.

Plot of meridional transport of vapor + ice in EMARS
Units of meridional transport are mg m^-2 s^-1
20-sol time mean and zonal mean with hourly data
The color scales are different on each plot.
Conclusions

• The zonal mean structure of MCS and EMARS are somewhat similar, but some differences remain challenging to resolve.
• EMARS and MCS identify stationary waves in CO$_2$ deposition in different locations than in the EMARS control run.
• The combination of dust and ice variation among the EMARS ensemble members and information about Martian tides from MCS may inform future Mars modeling decisions.
• Water in the polar vortex is relatively isolated from water outside. Water seems to enter the vortex primarily in the lowest quarter of the mass of the atmosphere.
Open Questions

• What are the causes of the “cold pockets” present in MCS?
• How can we model and assimilate the Martian polar warming better?
• Can we use cross-track observations to assimilate the Martian thermal tides in a better way than conventional DA?
• Can we design a parameter estimation experiment to refine our estimates of Martian dust and ice radiative parameters?
• How can we use aerosol observations most effectively in assimilation?
Acknowledgments

• Funded by NASA grants NNX11AL25G, NNX14AM13G and 80NSSC17K0690.

• Work at the Jet Propulsion Laboratory, California Institute of Technology is performed under contract with NASA.
References


Spare slides
Some nomenclature for the experiments:

<table>
<thead>
<tr>
<th>Exp Name</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMARS All Obs</td>
<td>EMARS with along-track and cross-track MCS observations assimilated</td>
</tr>
<tr>
<td>EMARS</td>
<td>Alias for EMARS All Obs, unless specified otherwise</td>
</tr>
<tr>
<td>EMARS Alongtrack</td>
<td>EMARS with only along-track MCS observations assimilated</td>
</tr>
<tr>
<td>EMARS PoleXtrack</td>
<td>EMARS with along-track MCS observations assimilated as well as cross-track observations poleward of 45° assimilated</td>
</tr>
<tr>
<td>MGCM</td>
<td>No observations assimilated; freely running model</td>
</tr>
</tbody>
</table>
Difference is polar x-track minus default EMARS. That is, the difference comes from tropical cross-track data.
Difference is polar x-track minus alongtrack. That is, the difference comes from polar cross-track data.

These unnecessary. However, move EMARS CO2 next to MCS dust ahead of CO2 slides.
EMARS reproduces expected features of the diurnal tide amplitude, such as the large near-surface diurnal tide and greater amplitudes in the summer hemisphere than the winter hemisphere.
However, there is a difference between using 1-hour forecasts and 0-hour analyses. Most of the differences are in the highest part of the atmosphere or the phasing, which appears to largely be smoothed.
Red arrows indicate changes in the latent heating behavior of the type investigated by David Kass and presented during the last telecon. He suggested that these may have a dynamical origin, and these plots suggest a lack of diurnal tide influence on latent heating. It is especially notable that an event seems to occur at about Ls 248 in each year.
A stationary wave is also present in EMARS in the Southern Hemisphere, but with a substantially lower amplitude. MCS shows little evidence of a stationary wave, and most of the temperatures recorded at this pressure level are below the sublimation temperature of carbon dioxide, as approximated by James et al. (1992).
Skew-T plots

**BOLD LINES:**
Black, solid – EMARS analysis
Black, dashed – EMARS background
Blue – EMARS analysis frost point
Red – MCS observation
Green – CO$_2$ deposition point

**THIN LINES:**
Black – pressure (values at left)
Red, straight, positive slope – temperature (values at bottom)
Magenta, curved, negative slope – adiabats (611 Pa reference pressure)
Blue – water vapor mixing ratio (values at top)
Notice in this instance that EMARS Alongtrack is close to MCS, except near 5 Pa, at the bottom of the MCS “cold pockets”.
Sometimes, EMARS responds strongly to MCS observations.
The thick curve is the ensemble mean over 10 sols centered on Ls 270, the dots are the means of MCS observations, and the thin lines are ensemble members. Ensemble members are colored according to their dust and ice radiative factors. Black → red: more dust Black → blue: more ice
The thick black curve is the ensemble mean over 10 sols centered on Ls 270, the dots are the means of MCS observations, and the thin lines are ensemble members. Ensemble members are colored according to their dust and ice radiative factors. Black → red: more dust, Black → blue: more ice.
Notice, in particular, the differences in the frost point depression in the MGCM compared to EMARS. The near-surface negative frost point depressions are no longer present, which may contribute to the concentration of ice clouds at the edge of the polar vortex near the surface.