Assimilation of ExoMars Trace Gas Orbiter thermal infrared observations into the LMD Mars GCM using the LETKF

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Thanks to Luca Montabone

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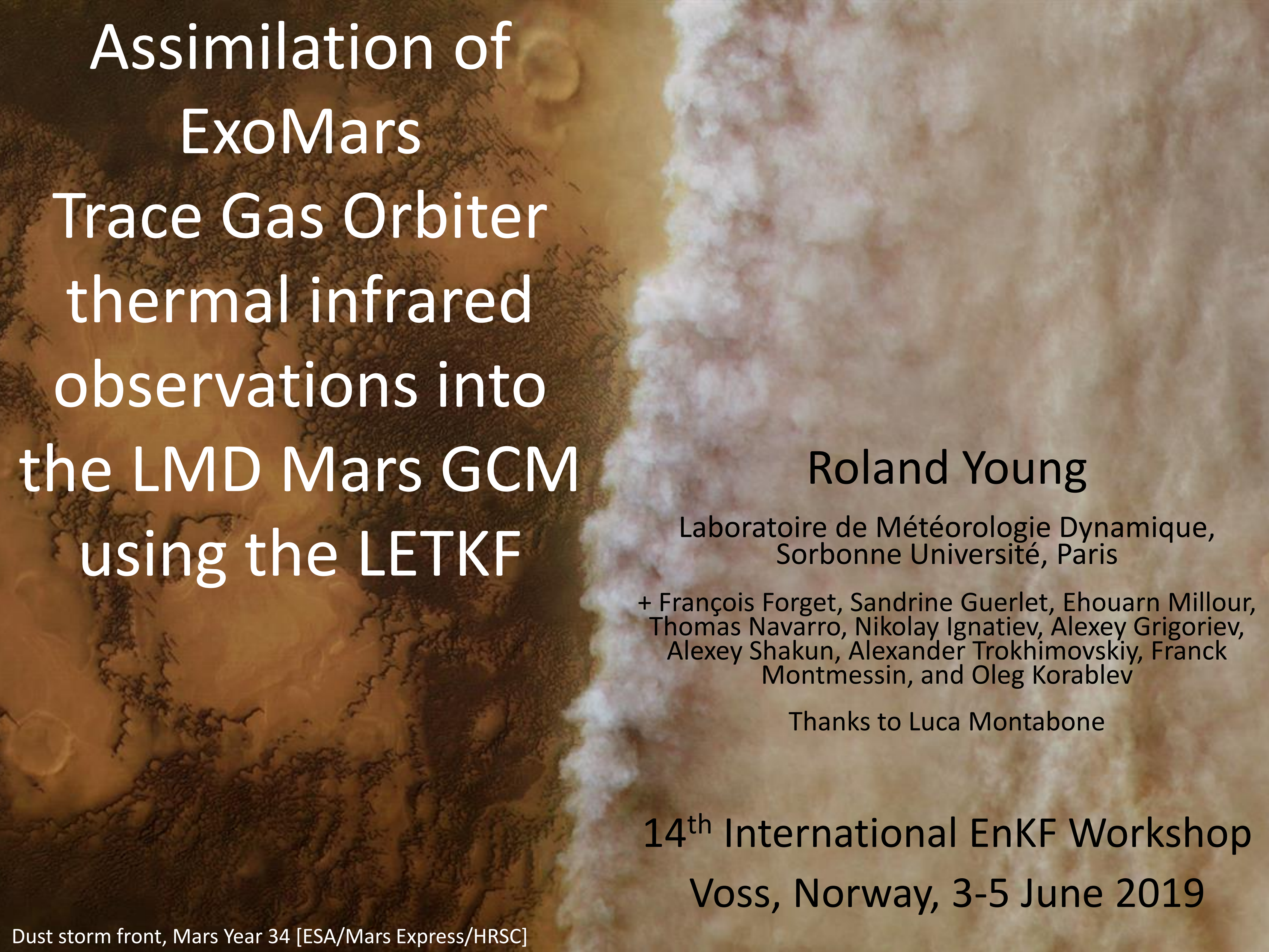


Dust storm front, Mars Year 34 [ESA/Mars Express/HRSC]

1/2 Earth's radius, 50% further from the Sun
Similar rotation rate, ~2x year length

Highest point 26km above surroundings
Southern hemisphere ~5km above northern hemisphere
Two tiny moons

96% CO_2 atmosphere
Permanent CO_2, temporary H_2O polar icecaps
1/3 of atmosphere condenses onto poles during winter

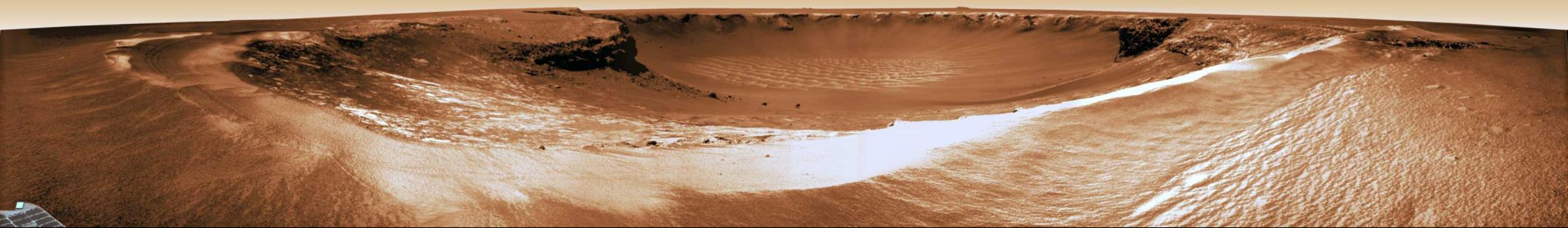
1% Earth's surface pressure → strong daily cycle
Similar axial tilt + elliptical orbit → strong seasonal cycle

Dust critical to the environment
Similar to water on Earth: keeps visible light out
keeps infrared light in

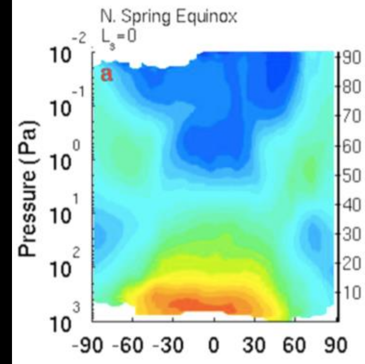
Tharsis Plateau from *Mars Express*

Mars

Victoria Crater from *Opportunity*



Climate, orbit, and seasons



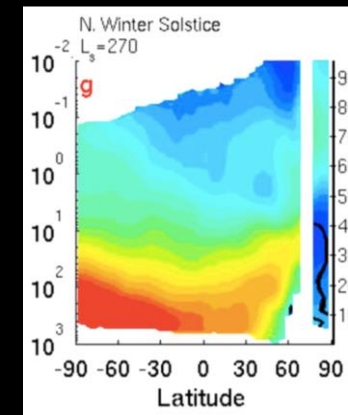
Cool poles
Warm equator
Start of clear season

Cold (150K) northern winter
Warm (250K) southern summer
Temporary northern CO_2 cap
Middle of dusty season

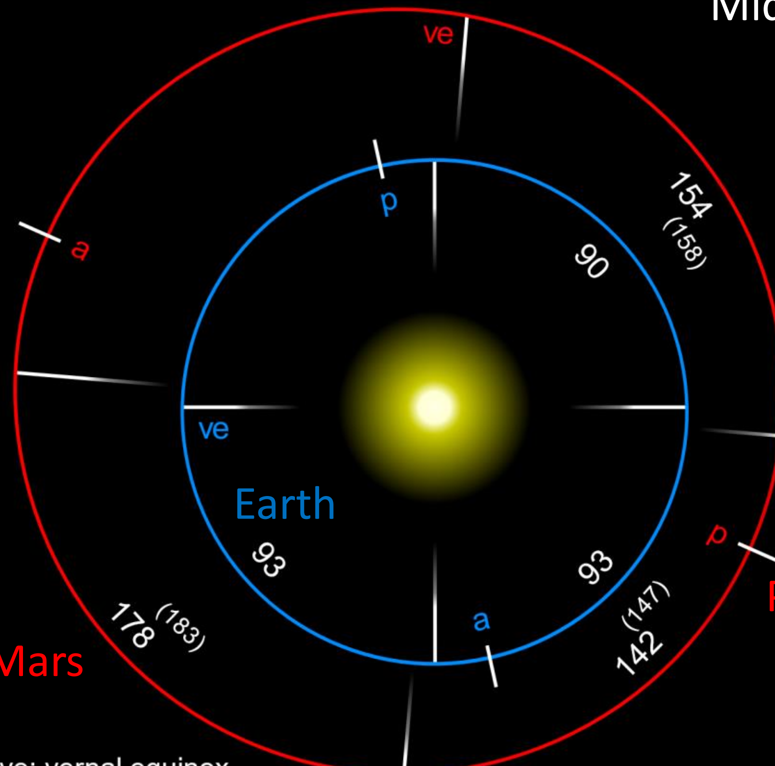
Competing effects determine climate (in ~order of importance):

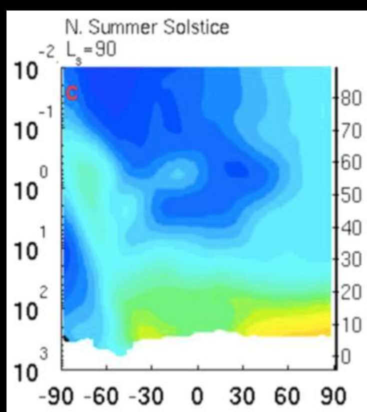
1. Season
2. Planet's distance from Sun
3. Dust activity
4. Surface altitude

L_s = 0 "March"



Aphelion





L_s = 90 "June"

L_s = 270 "December"

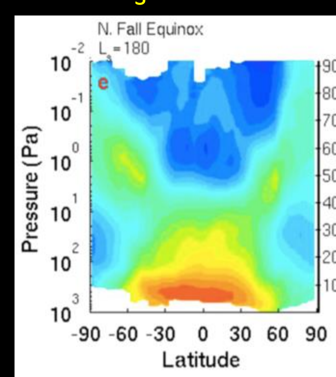
Perihelion

Mars

Very cold (120K) southern winter
Mild northern summer (200K)
Temporary southern CO_2 icecap
Middle of clear season

ve: vernal equinox
p: perihelion
a: aphelion

L_s = 180 "September"



Panels show night-time temperatures measured by *Mars Reconnaissance Orbiter*
[McCleese+ 2010]

Cool poles
Warm equator
Start of dusty season

1 year = 668.6 "sols" ≈ 687 Earth days

[Wikipedia/Areong]

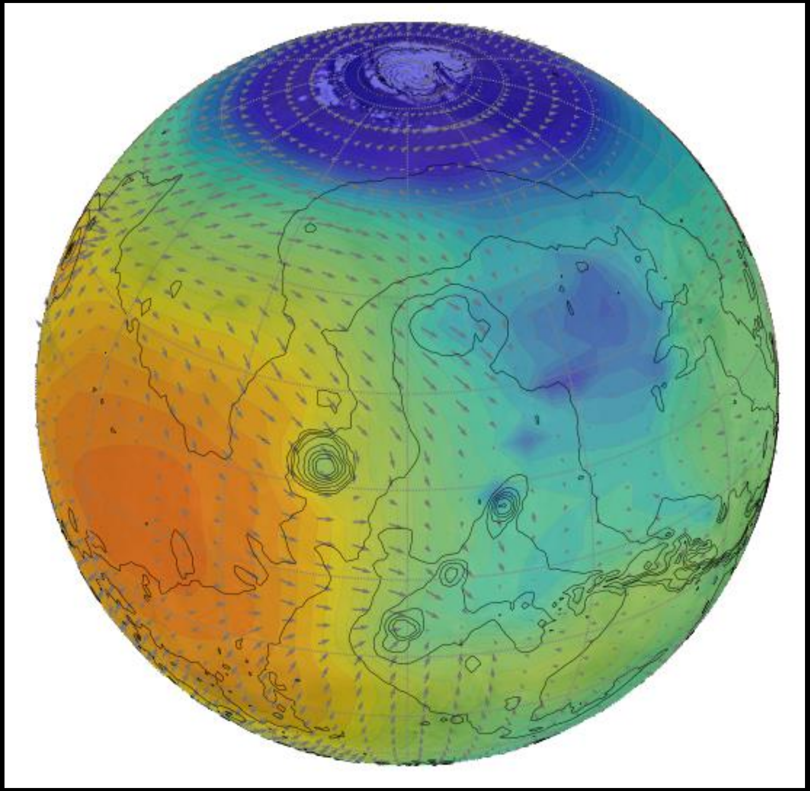
LMD Mars Global Climate Model

State of the art GCM for Mars:
100s of papers using the model or the *Mars Climate Database* by many groups worldwide

Solves the fluid equations on a rotating sphere ("hydrostatic primitive equations")
+ representations of the following physical processes:

Radiative transfer
Diurnal and seasonal cycles
"Two-moment" dust transport scheme
Radiatively active dust
Topography
Water cycle + icecaps
CO_2 condensation, clouds, + icecaps
Radiatively active water ice clouds
Boundary layer + small scale convection
Subsurface temperature model
Surface-atmosphere interactions
``Rocket'' dust storms (to come, next generation)
Gravity wave drag (to come, next generation)
Ionosphere
Thermosphere
Many non-condensable species
Etc…

[Green: Main sources of model error]



[http://www-mars.lmd.jussieu.fr]

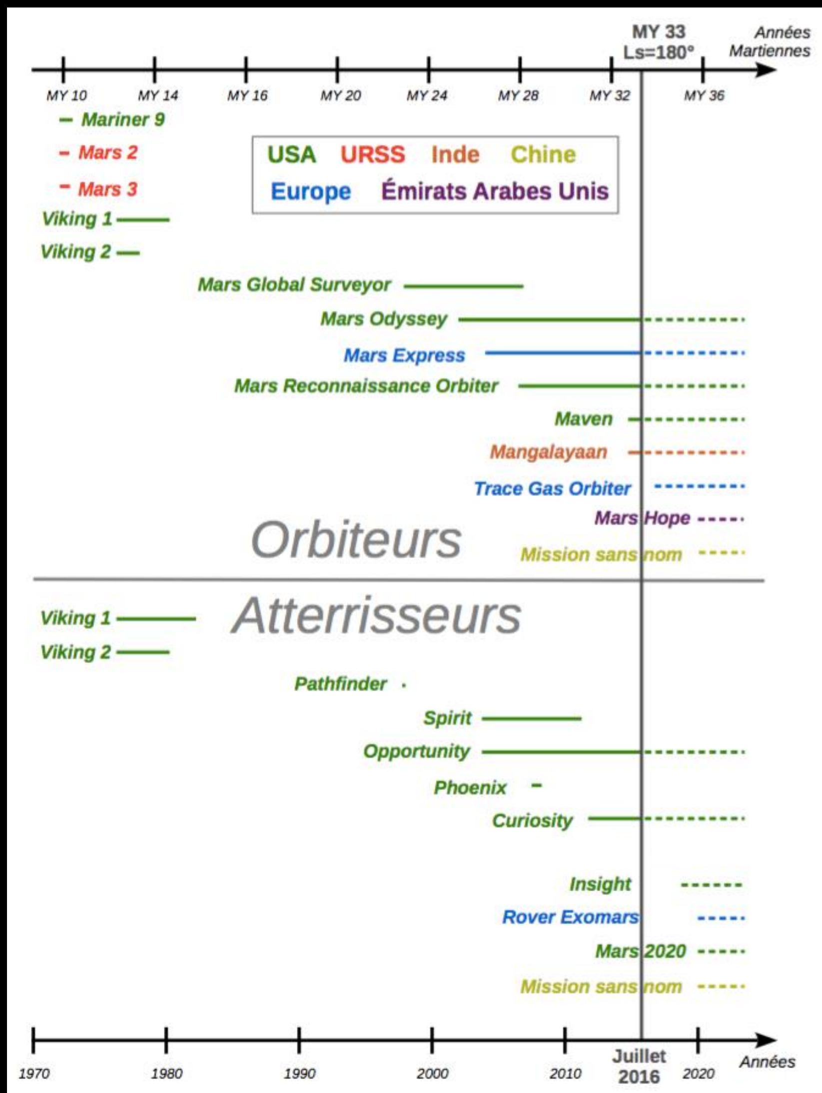
Development: Forget et al. (1999) and many subsequent references

Validated and tuned against many orbiter and lander datasets since Viking (1970s)

Past and current exploration of Mars

Spacecraft that have successfully reached Mars

Mostly Atmosphere studies



Mostly geological studies

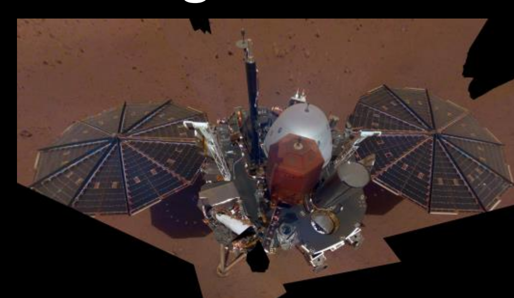
Currently 6 orbiters:

- 3 NASA, 2 ESA/Russia, 1 India
- Good spatial coverage
- Vertically-resolved measurements
- No wind/pressure measurements
- Limited local times of day

Currently 2 NASA surface platforms:

- Measurements of wind/pressure
- Excellent time resolution
- Full diurnal cycle
- Only one point

Insight lander

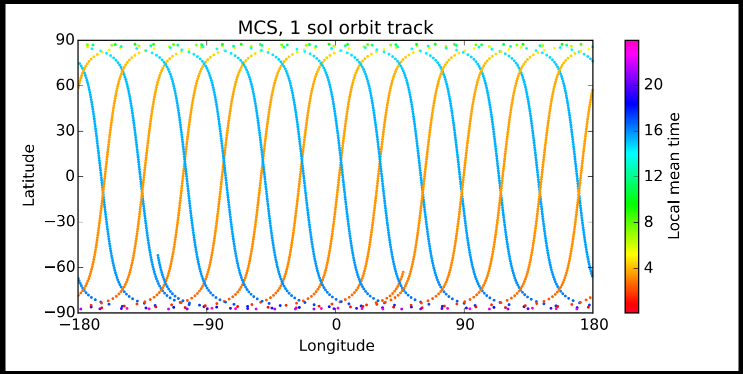


Curiosity rover

[Navarro 2016,NASA/PIA19920/PIA22876]

Mars data assimilation – state of the art

Orbit track for Mars Reconnaissance Orbiter, 1 sol



State-of-the-art is to assimilate data from *one* polar orbiting satellite

All assimilation schemes (since first work in 1990s) assimilate atmospheric temperature profiles
+ Dust column opacities since 2005 (most schemes)

Most extensive work has used analysis correction scheme
Ensemble methods (LETKF) in use since ~2010

One attempt to assimilate thermal IR radiances (2011)

Recent work focuses more on assimilating aerosols:

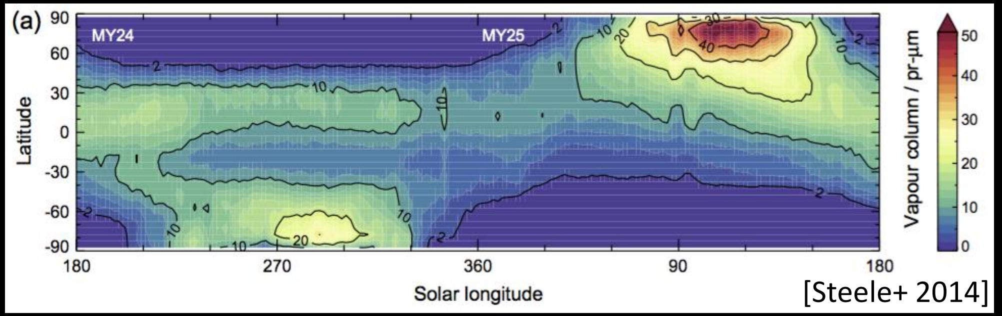
- Water ice profiles (2014)
- Water vapour column opacity (2014)
- Dust profiles (2015-)
- Ozone column opacity (2018)
- Carbon monoxide column opacity (2019)

No dedicated assimilation of lander data yet
(used mostly for verification)

There are many contemporaneous datasets
But most work has focused on assimilating one dataset, a few at most

Water vapour column assimilation

Mars' water cycle is dominated by seasonal evaporation / deposition at polar caps, and transport to and from them



[Steele+ 2014]

Ozone column assimilation

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[Holmes+ 2018]

Direct and indirect assimilation in the LMD Mars data assimilation scheme

Assimilation scheme: LETKF, 16 ensemble members, adaptive covariance inflation, no bias correction

Indirect assimilation: Directly assimilate quantity α: $\bar{\mathbf{x}}^{a}_{\alpha} = \bar{\mathbf{x}}^{b}_{\alpha} + \mathbf{X}^{b}_{\alpha}\mathbf{W}^{a}_{\alpha}$

Assimilate quantity β using observations of α: $\bar{\mathbf{x}}^{a}_{\beta} = \bar{\mathbf{x}}^{b}_{\beta} + \mathbf{X}^{b}_{\beta}\mathbf{W}^{a}_{\alpha}$

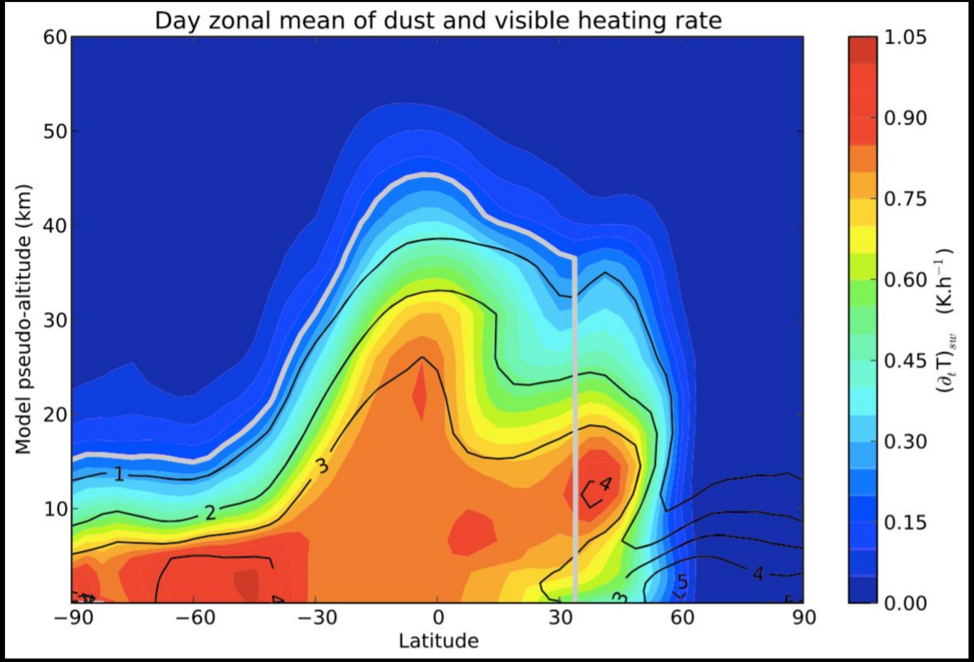
Directly-assimilated quantities (so far):

- Atmospheric temperature (vertical profiles)
- Density-scaled dust opacity profiles (MCS only)
- Density-scaled water ice opacity profiles (MCS only)

Indirectly-assimilated quantities:

- TuPs: Surface pressure [Observed: Atmospheric T at lowest model level]
- TuUV: Zonal and meridional velocities [Obs: T]
- TuD: Dust mass mixing ratio and number of particles [Obs: T where daily insolation > 100 W m^{-2} and local solar heating rate > 0.2 K hr^{-1}]

"Temperature updates Dust" (TuD) applied below the grey line



[Navarro+ 2014]

All other simulated quantities adjust dynamically during forecast step

ExoMars Trace Gas Orbiter

Main goal:
To search for rarefied gases e.g. methane, HDO, other compounds relevant to life

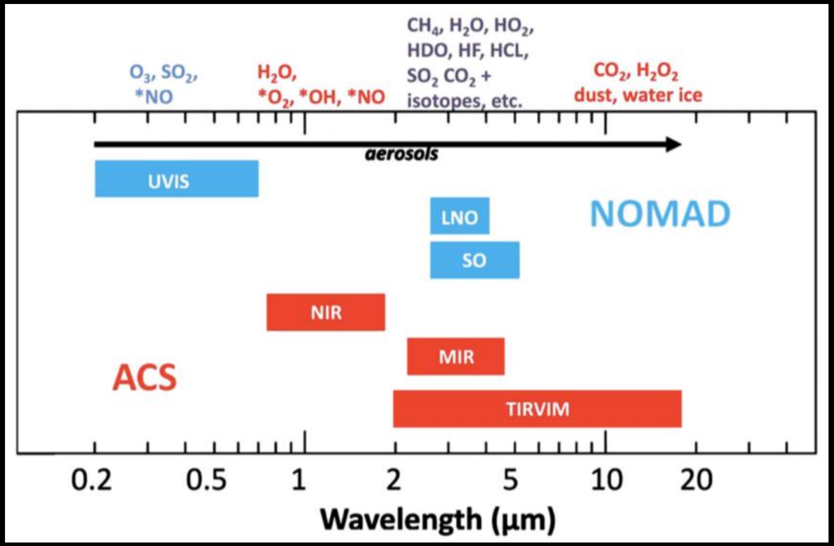
Inserted into Mars orbit on 19 Oct 2016

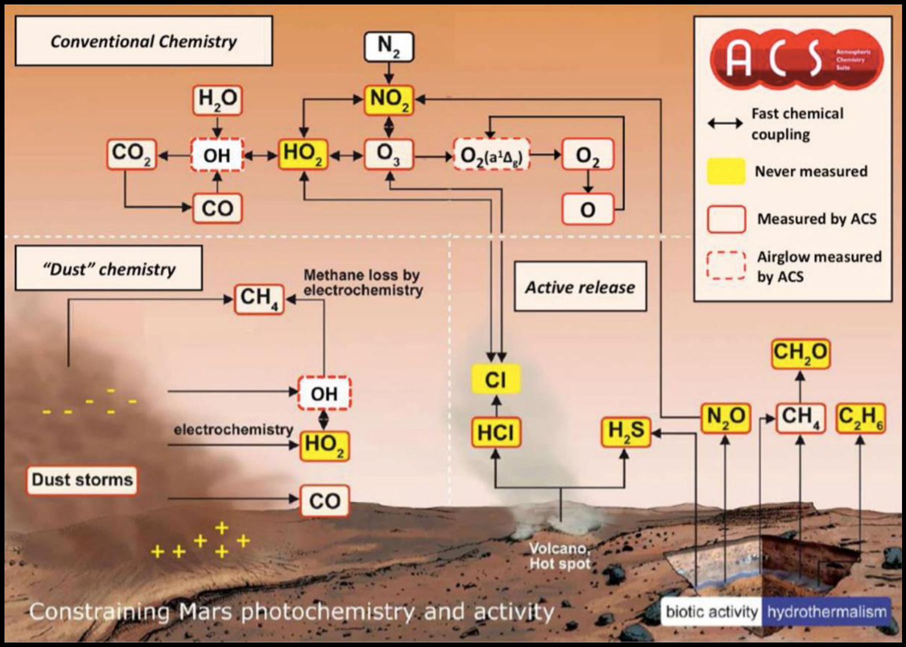
"Aerobraking" put spacecraft into low orbit during 2016-2017

Orbit sees all local times over a 55-sol cycle

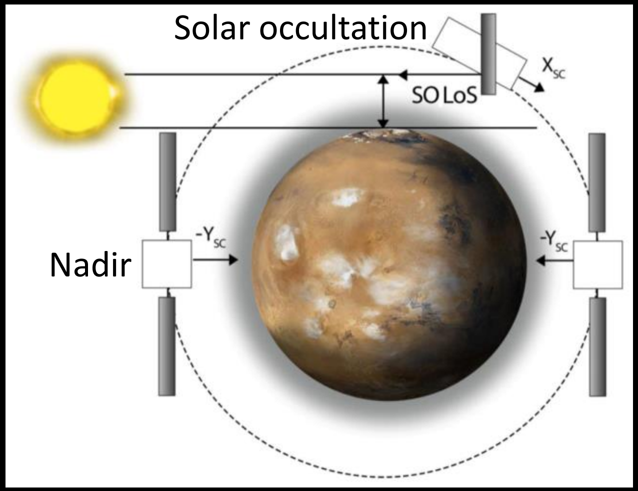
Reached final 400km circular 75° inclination orbit on 7 Apr 2018

Instruments:
ACS (three infrared spectrometers)
CASSIS (stereo visible imaging camera)
FREND (neutron detector — subsurface)
NOMAD (3 infrared/UV spectrometers)





Instrument viewing geometry

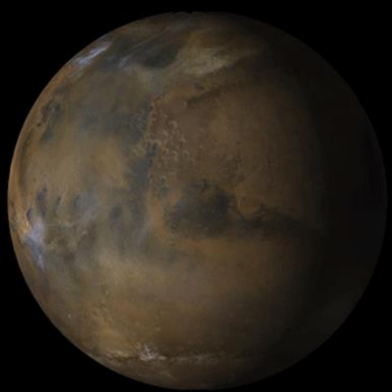


[Korablev+ 2018]

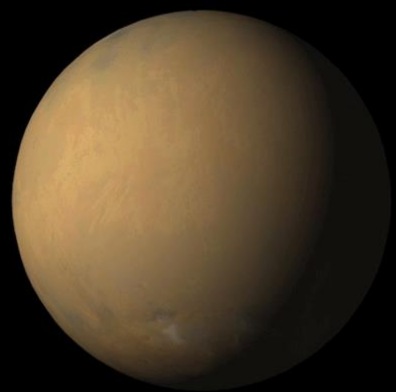
2018 Mars Global Dust Storm

Global Dust Storms occur every 3-4 Mars years

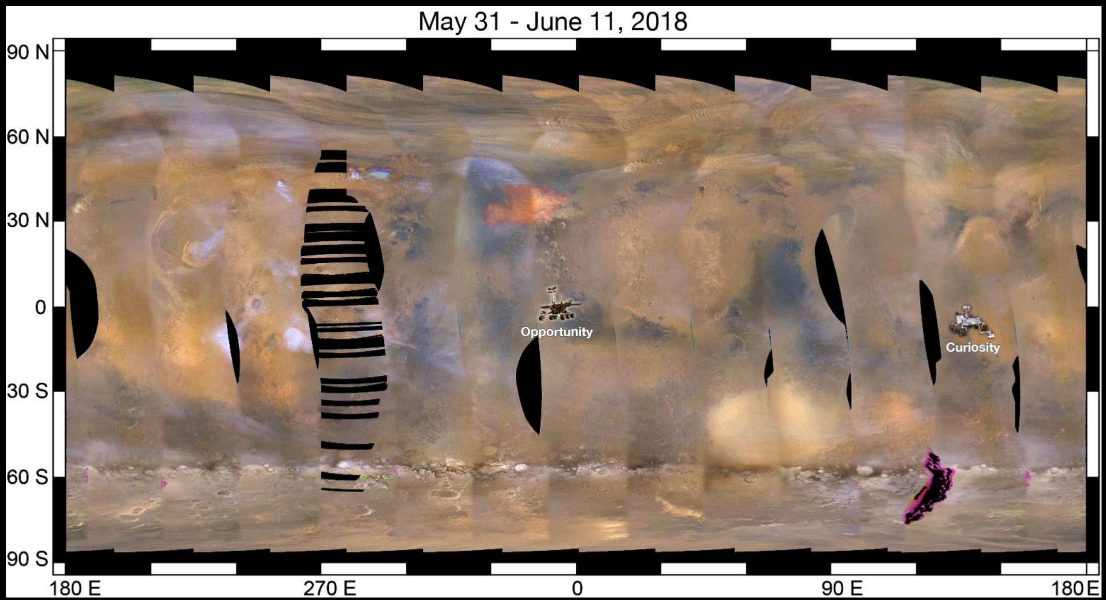
May 2018



July 2018



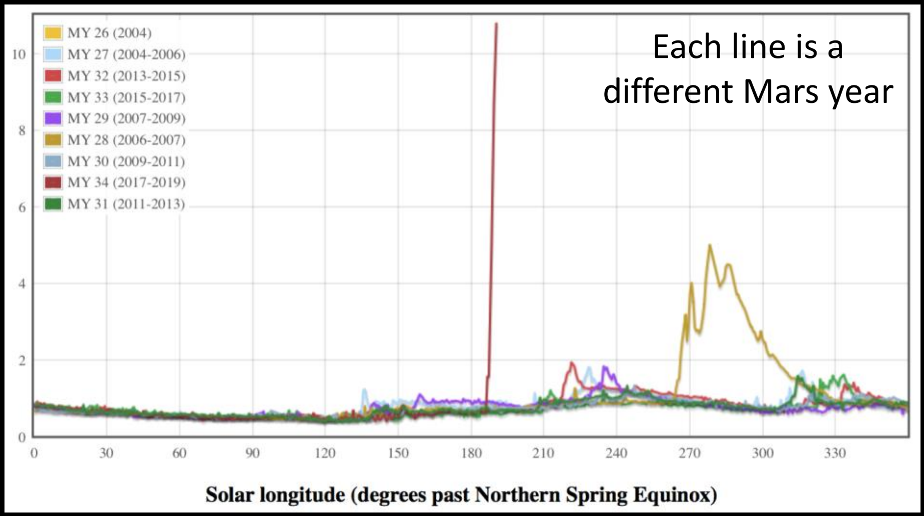
Development of the storm (dust in dark orange)



NASA Mars Reconnaissance Orbiter

The view from *NASA Curiosity*

Dust opacity measured by *NASA Opportunity*



[NASA/PIA22487]

Assimilation during the Mars Year 34 Global Dust Storm: 26 May – 15 July 2018

What effect does the Global Dust Storm have on Mars' general circulation?

Observations assimilated:

Atmospheric temperature profiles from ACS/TIRVIM, retrieved from nadir thermal emission spectra at LMD by Sandrine Guerlet

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Free GCM run alongside, using MCD 'climate' dust scenario

This model represents the atmospheric state and its evolution during a typical year *without* a global dust storm

Available ACS observations up to 15 July 2018

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MCS 9.2µm dust optical depth at 610 Pa, red = 2.4

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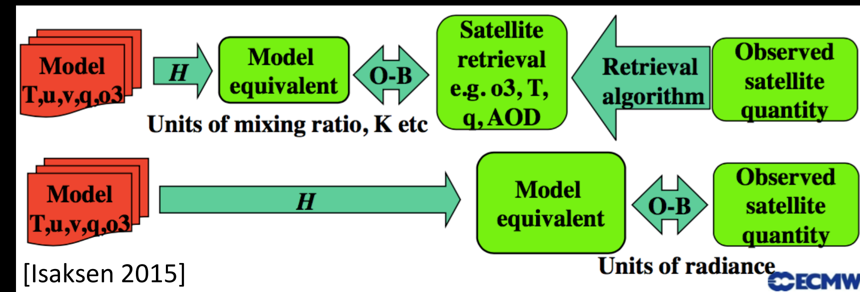
[Montabone+ 2019]

TIRVIM observation operator: $\mathbf{x}^{\mathrm{a}} = \mathbf{x}^{\mathrm{b}} + \mathbf{K}\left(\mathbf{y}^{\mathbf{o}} - H\left(\mathbf{x}^{\mathrm{b}}\right)\right)$

What would a retrieval look like if TIRVIM observed an atmosphere that took the form of the background $\mathbf{x}^{\mathrm{b}}$?

1. Interpolate $\mathbf{x}^{\mathrm{b}}$ to profile position and pressures, linear in lon, lat, $\ln(p/p_{surf})$, t.
2. Use averaging kernels to retrieve what ACS would see: $H(\mathbf{x}^{\mathrm{b}}) = \mathbf{x}^{\mathrm{p}} + \mathbf{A}(\mathbf{x}^{\mathrm{b}} - \mathbf{x}^{\mathrm{p}})$ [Rodgers & Connor, 2003]. Prior $\mathbf{x}^{\mathrm{p}}$ and averaging kernels $\mathbf{A}$ are same as for observations $\mathbf{y}^{\mathrm{o}}$.



[Isaksen 2015]

Highest sensitivity where kernel sum ≈ 1

Observations and forecast ≈ prior where kernel sum is small – instrument not sensitive here

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Interpolation and final observed background similar where kernel sum ≈ 1

Temperature evolution at 100Pa, 3PM local time

LETKF analysis obtained by assimilating ACS temperature profiles

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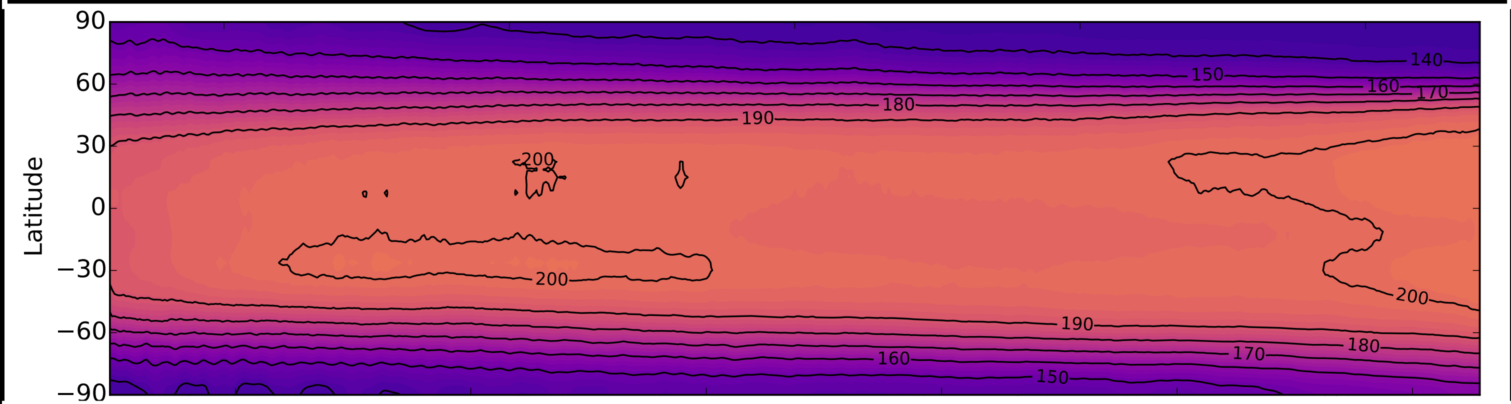
Free-running model using climate dust scenario



Independent temperature observations from MRO-MCS

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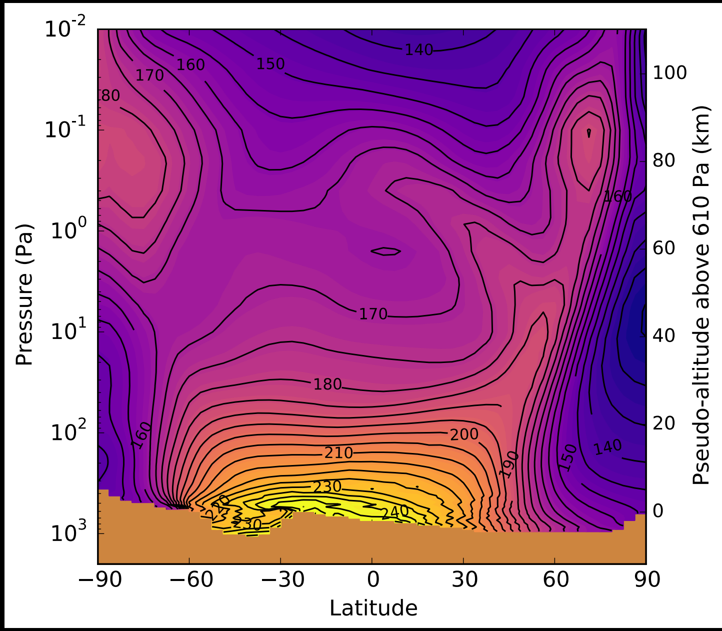
Temperature cross-section, 3PM local mean time, sols 412–416

Free-running GCM



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LETKF analysis

Difference: Analysis - GCM

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Independent MCS observations

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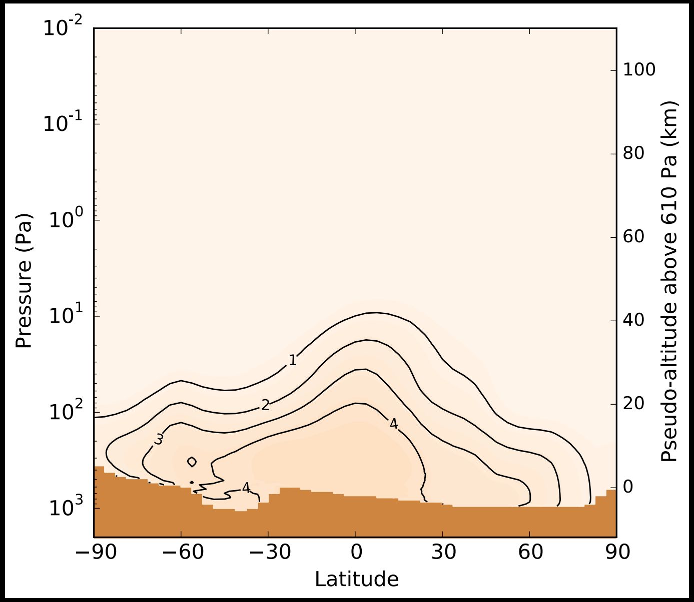
Dust distribution, 3PM local mean time, sols 412-426

Density-scaled dust opacity at 21.6μm

Units are 10^{-4} m^2 kg^{-1}

Dust updated using ACS temperature retrievals only

Free-running GCM



LETKF analysis

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Independent MCS observations

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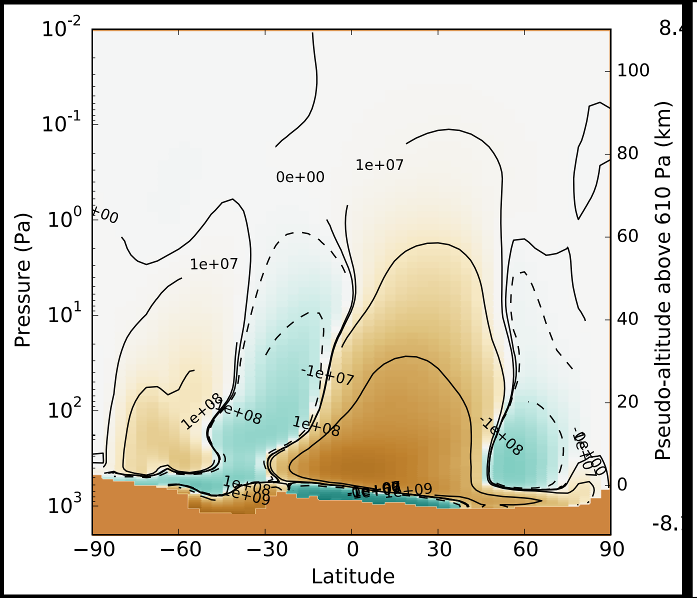
Effect of the Global Dust Storm on the meridional circulation

Meridional mass stream function: An unobserved quantity retrieved by the assimilation
Contours of the mass stream function show direction of airmass transport

Free-running GCM



LETKF analysis

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Difference: Analysis – Free GCM

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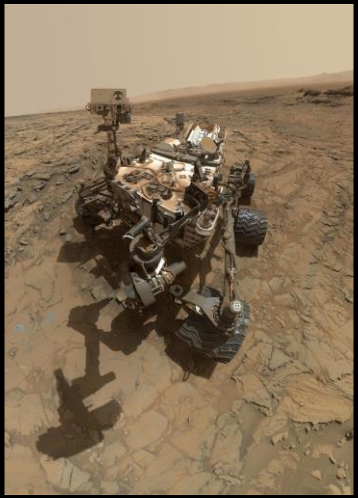
Zonal mean, averaged over sols 412–416
Brown = Clockwise
Red = More clockwise

Independent verification against Curiosity surface pressure data

NASA Curiosity rover



Surface pressure interpolated to Curiosity location and corrected for true surface elevation

Daily mean subtracted to show diurnal, semi-diurnal tide modes

Solid: Mean over 6 sols. Dashed: Mean ± 1 SD

Black: Before GDS, sols 377-383

Red: During GDS, sols 417-423

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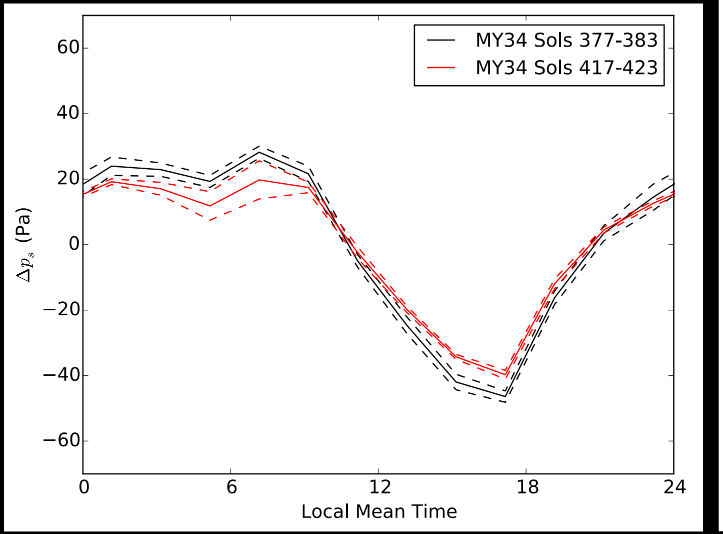
Free-running GCM



LETKF analysis

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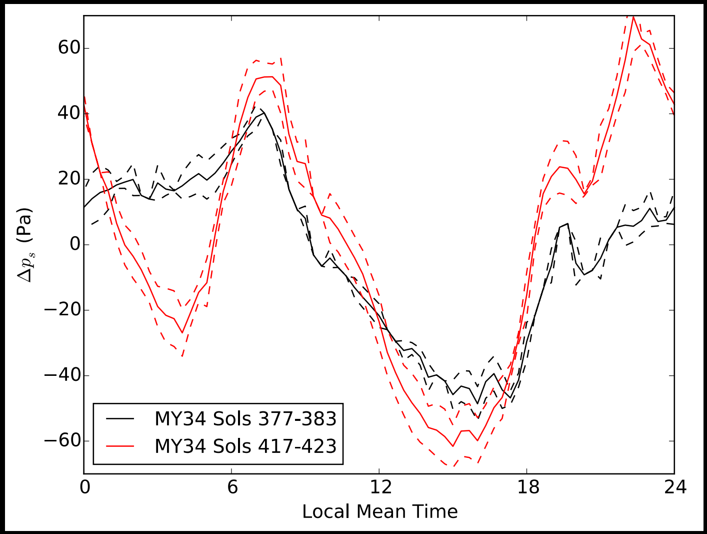
Curiosity observations



Next steps for ACS-TIRVIM assimilation

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ACS-TIRVIM operational mode
since ~September 2018

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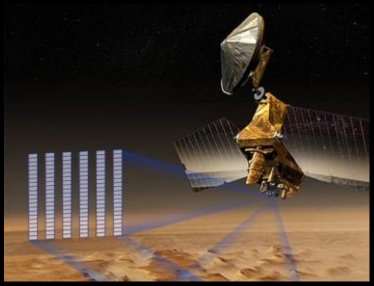
Assimilate ACS and MCS simultaneously throughout MY34

Assimilate surface temperatures – not done before at Mars

MCS and ACS-TIRVIM are complementary:



MRO-MCS:
High vertical resolution (limb sounder), more complete time coverage, but only two local times, can sound down to 10km altitude

ExoMars ACS-TIRVIM: Lower vertical resolution, complete local time coverage over 55 sols, poorer time coverage, but can sound nearer surface