Mesoscale and microscale modeling of the Martian atmosphere

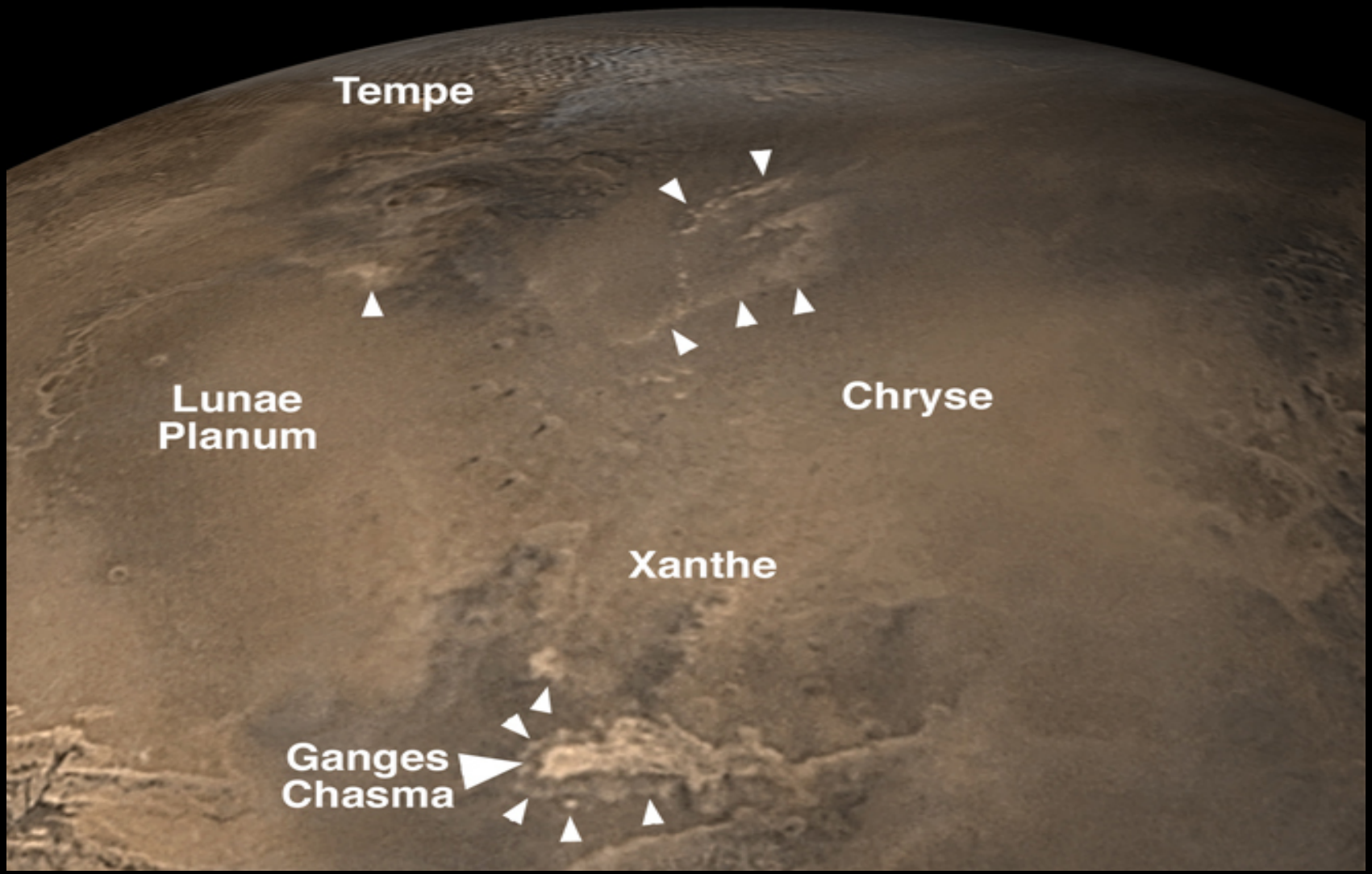
A. Spiga
and many co-authors

CPS Kobe mini-workshop
February 5, 2013

Outline

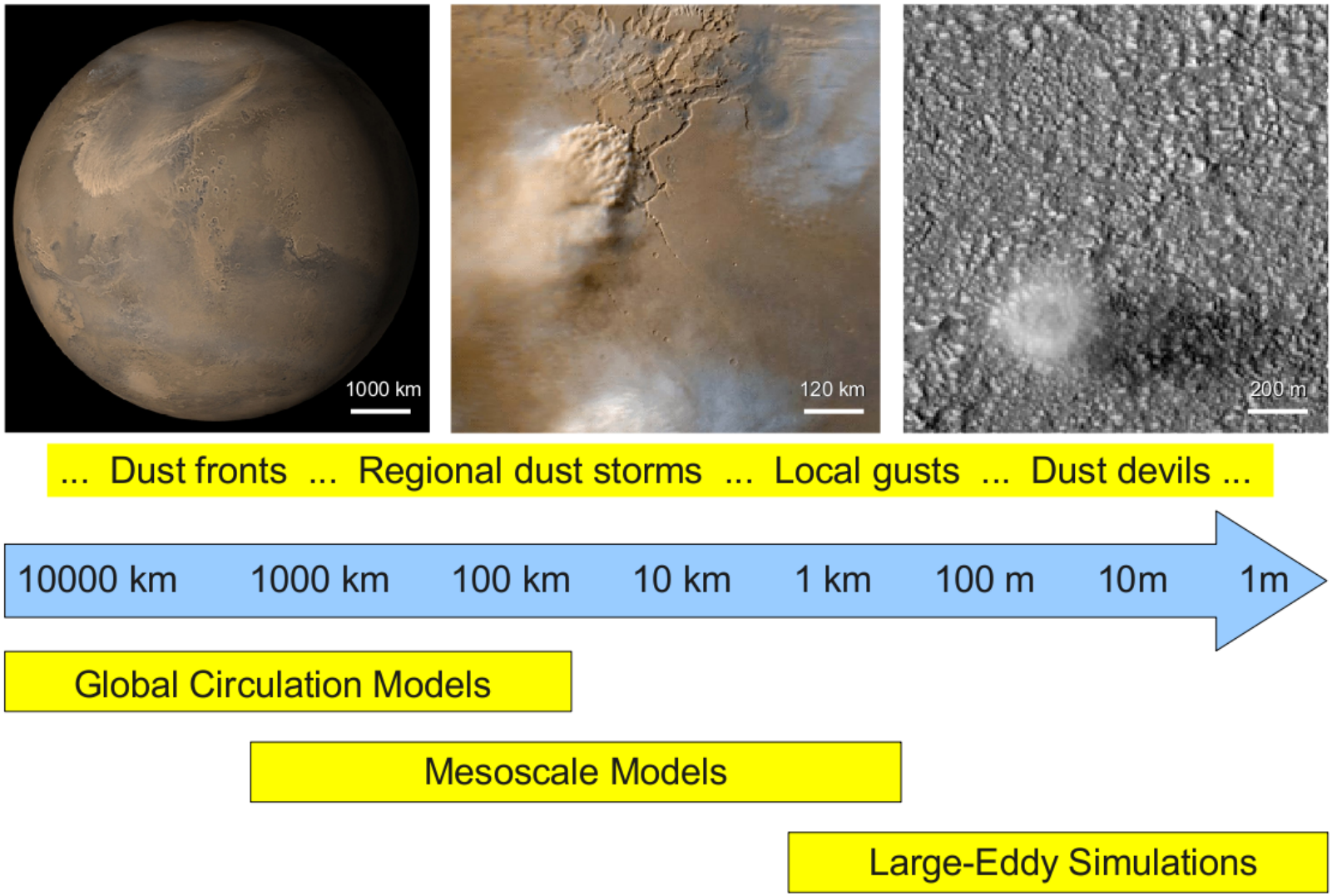
Outline

The Martian mesoscale "zoo"



[MGS/MOC imagery, Malin Space Science Systems, 02/2002]

Echelles spatiales et modèles adaptés



[Spiga and Lewis, 2010]

Mars Global Circulation Model: LMD-MGCM

LMDz dynamical core

integration of conservation laws for momentum, mass, energy, tracers

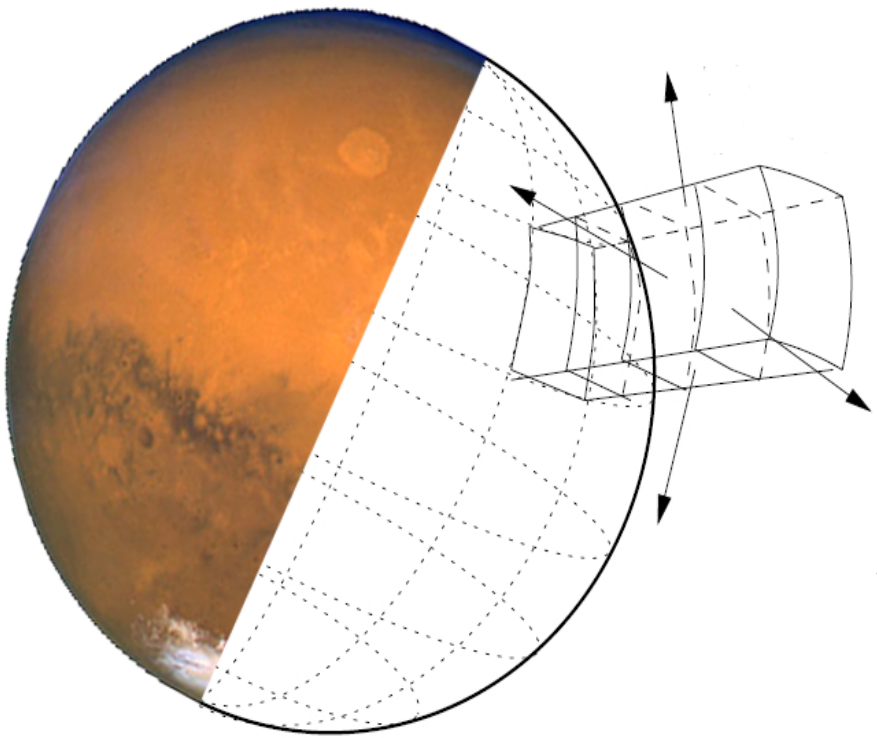
LMD Mars physics

radiative transfer (dust and CO_2), soil model, vertical mixing, microphysics (H_2O and CO_2), lifting/sedimentation, chemistry

MGS dataset

topography, thermal inertia, albedo dust scenario

Grid spacing $\sim$ 200 km



[Forget et al., JGR 1999]

Mars Mesoscale Model: LMD-MMM

WRF dynamical core

integration of conservation laws for momentum, mass, energy, tracers

LMD Mars physics

radiative transfer (dust and CO_2), soil model, vertical mixing, microphysics (H_2O and CO_2), lifting/sedimentation, chemistry

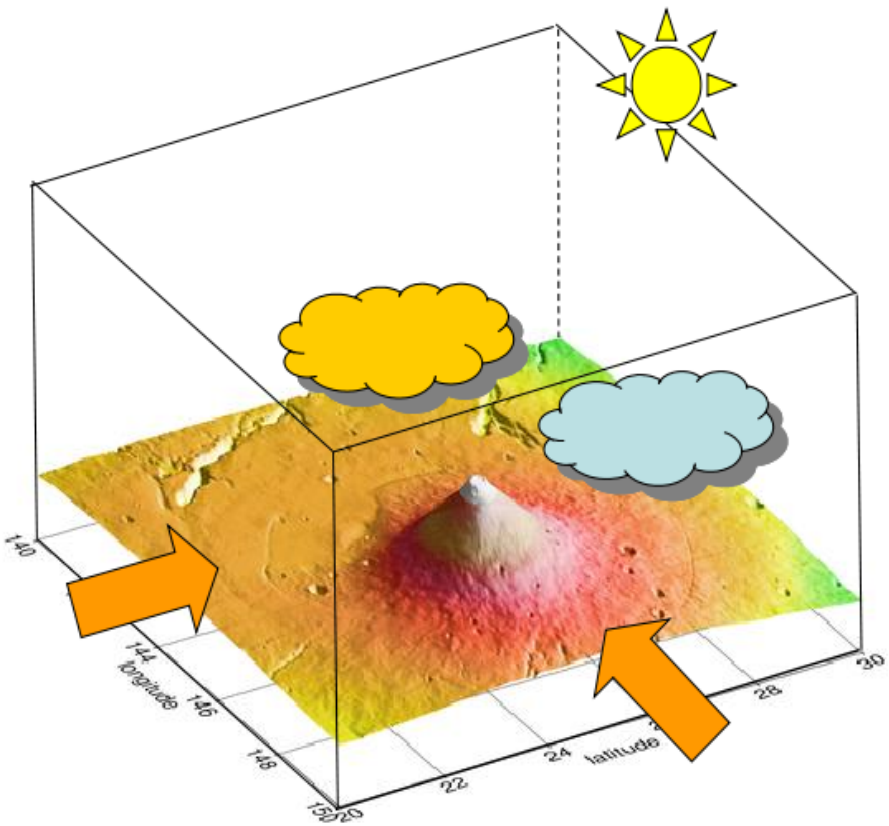
LMD Mars GCM fields

initial and boundary conditions

MGS hi-res dataset

topography, thermal inertia, albedo dust scenario

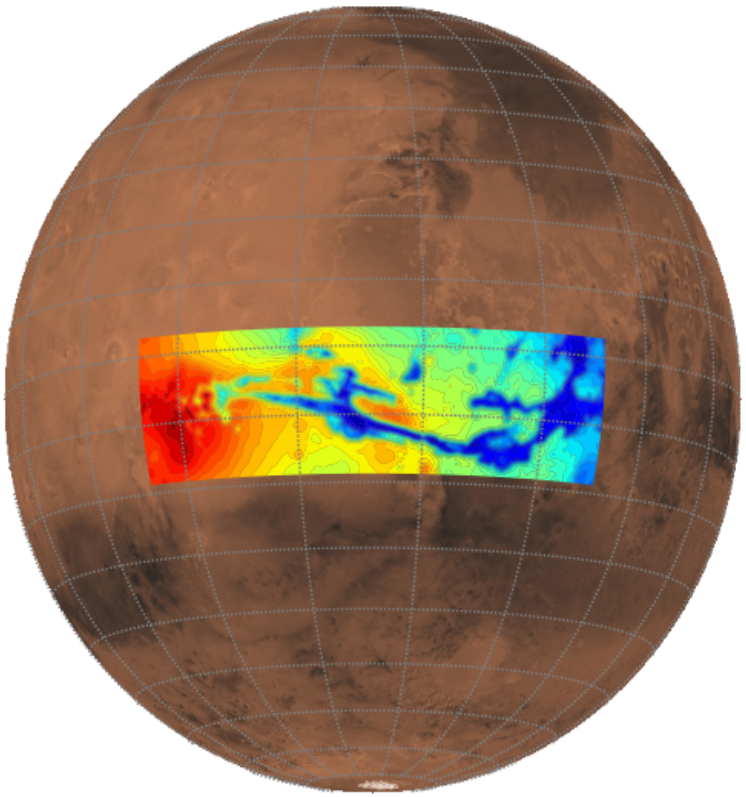
Grid spacing $\sim 10 - 1$ km



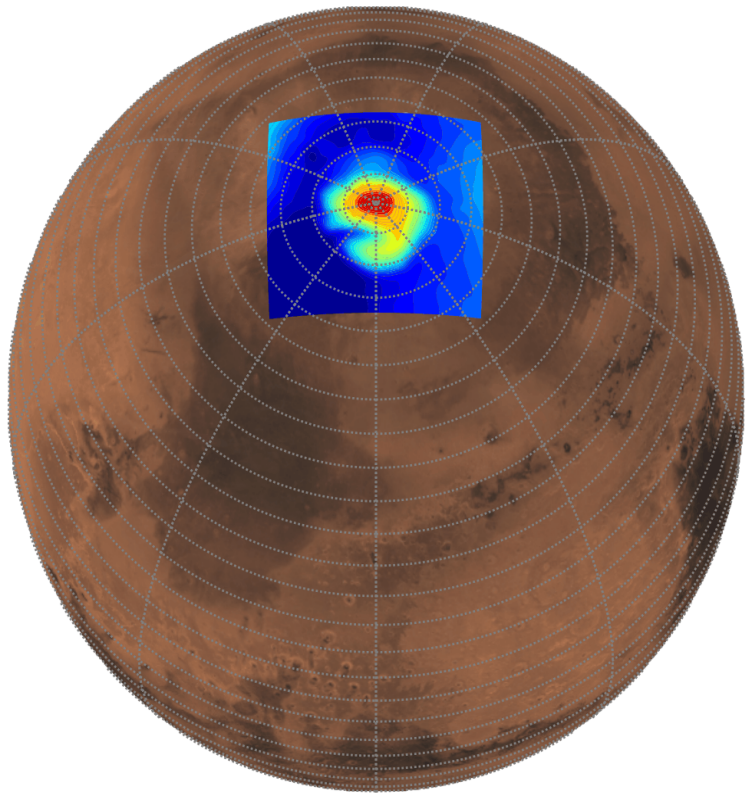
[Spiga and Forget, JGR 2009]

Mesoscale domains

Valles Marineris



North polar regions



Mars Large-Eddy Simulations: LMD-LES

WRF dynamical core

integration of conservation laws for momentum, mass, energy, tracers

LMD Mars physics

radiative transfer (dust and CO_2), soil model, vertical mixing, microphysics (H_2O and CO_2), lifting/sedimentation, chemistry

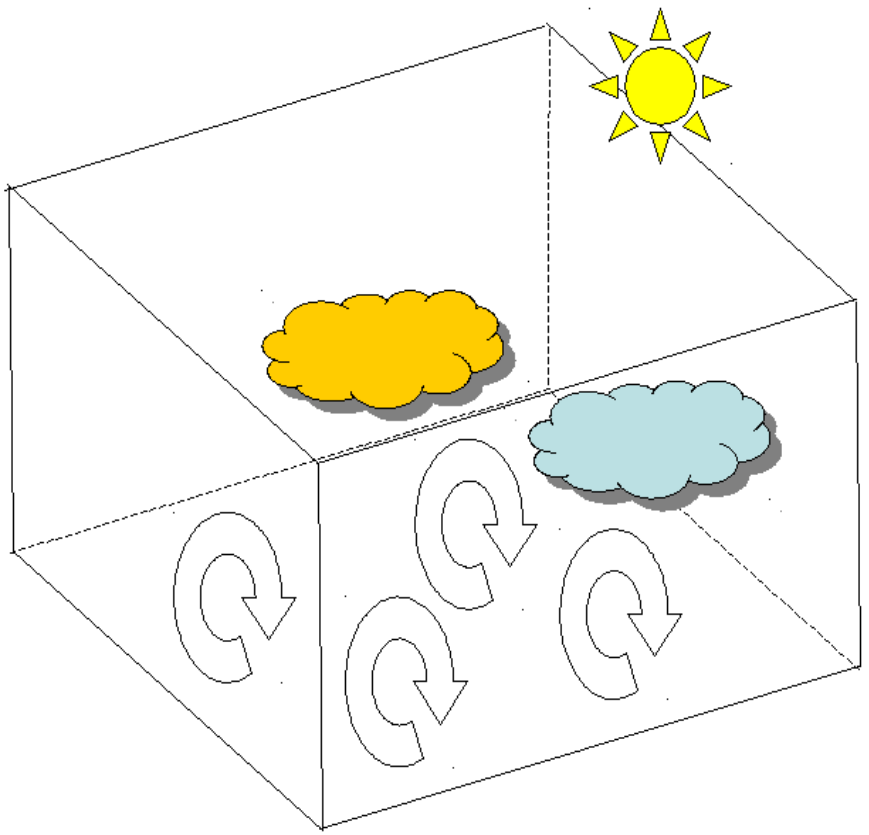
LMD Mars GCM fields

initial profiles only, periodic boundaries

MGS hi-res dataset

topography, thermal inertia, albedo
prescribed dust scenario

Grid spacing $\sim 100 - 10$ m



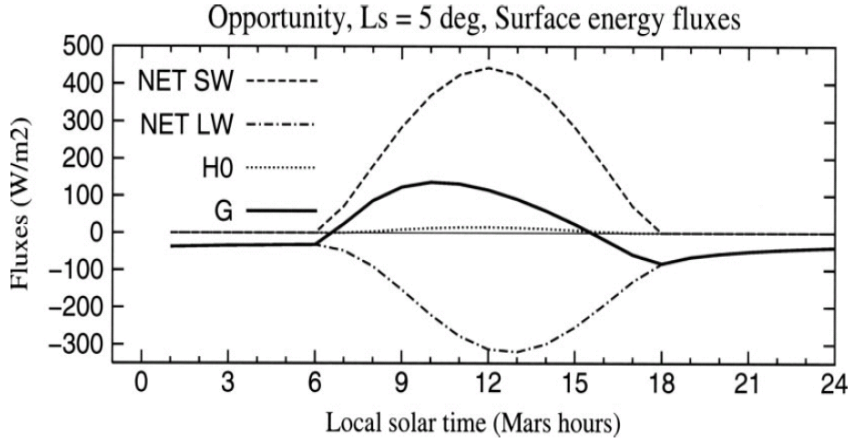
[Spiga et al., QJRMS 2010]

Outline

Energy budget for Martian surface

Surface energy budget

$$F_{\mathrm{LW}} + F_{\mathrm{SW}} = G + H_{\mathrm{s}} + LE$$



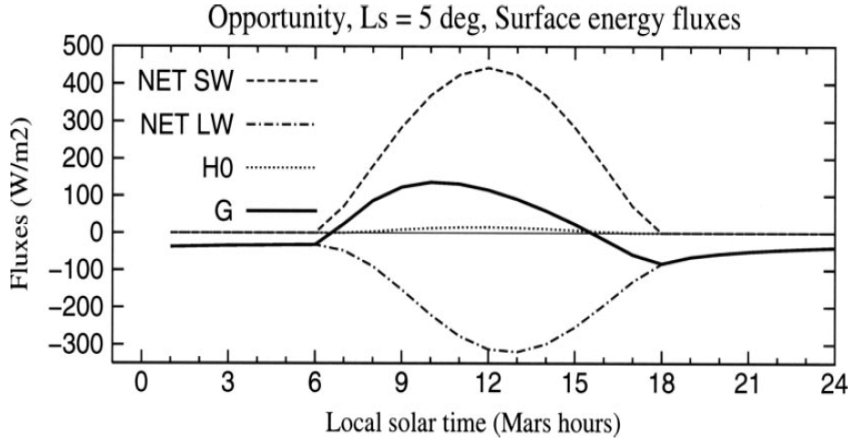
[Savijärvi and Kauhanen, QJRMS 2008]

Energy budget for Martian surface

Surface energy budget

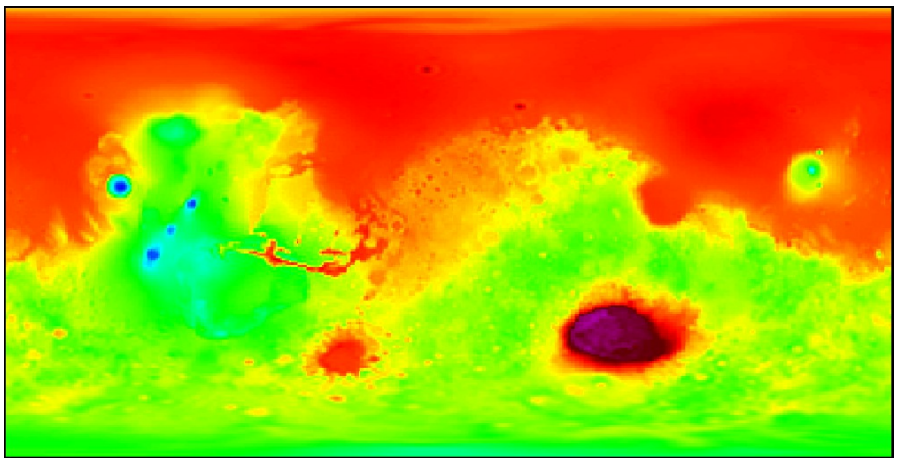
$$F_{LW} + F_{SW} = G + H_s + LE$$

$\rightarrow$ radiative equilibrium

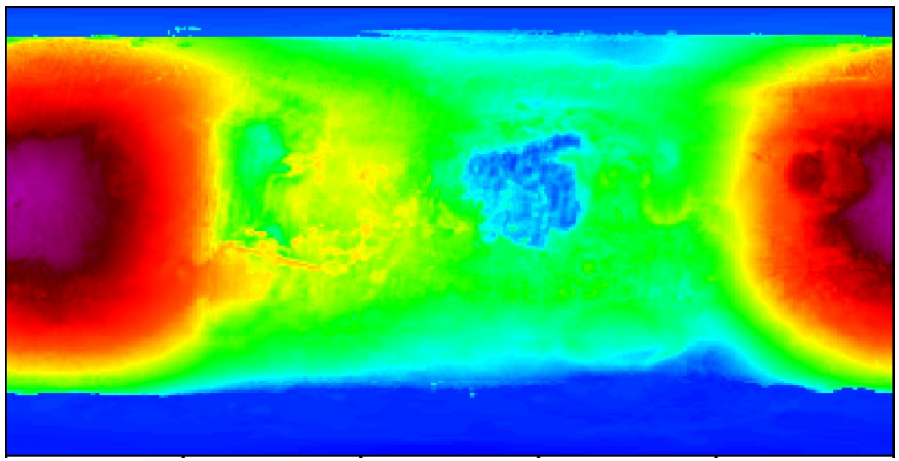


[Savijärvi and Kauhanen, QJRMS 2008]

Topography



Surface temperature



[outputs from the UK Mars GCM]

Thermal structure around a mountain on Earth

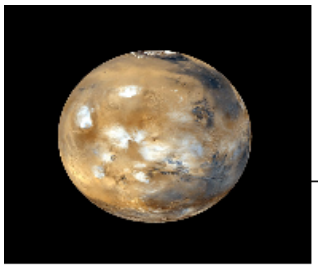
The surface influences the atmosphere only hundred meters above the surface

Moderate inversions near the surface

Terrestrial surface is in equilibrium with the atmosphere : sensible heat flux, latent heat flux

Temperature

Thermal structure around a mountain on Mars



The surface influences the atmosphere in the first kilometers thanks to CO_2 absorption

Strong inversions near the surface

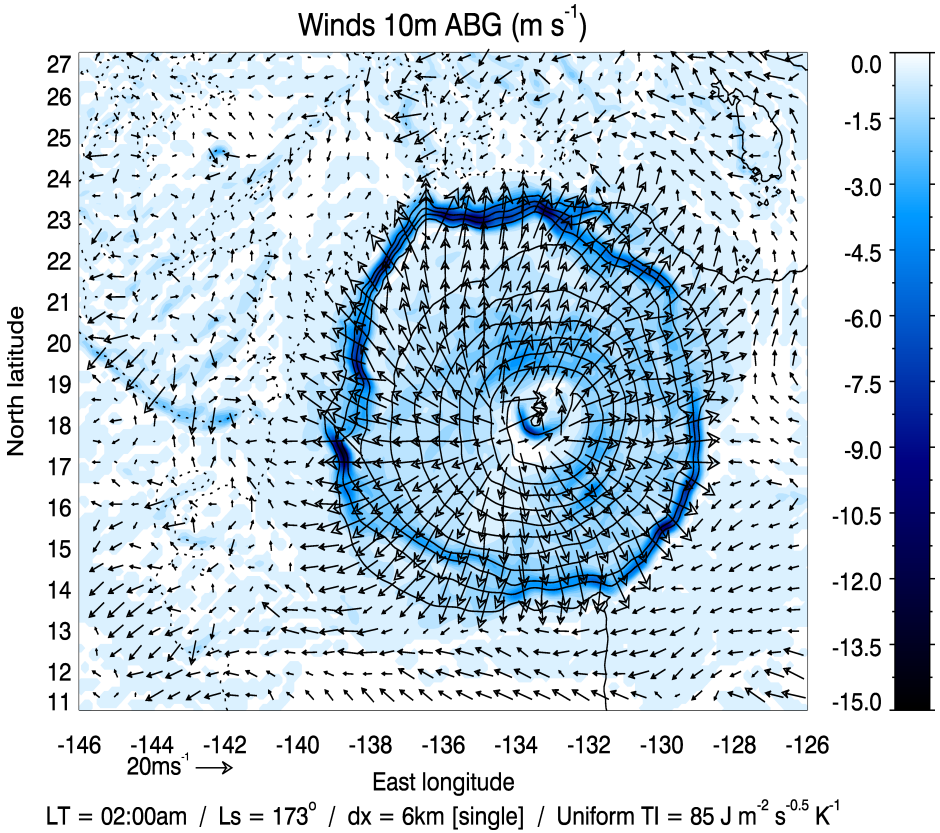
Martian surface is close to radiative equilibirum

Temperature

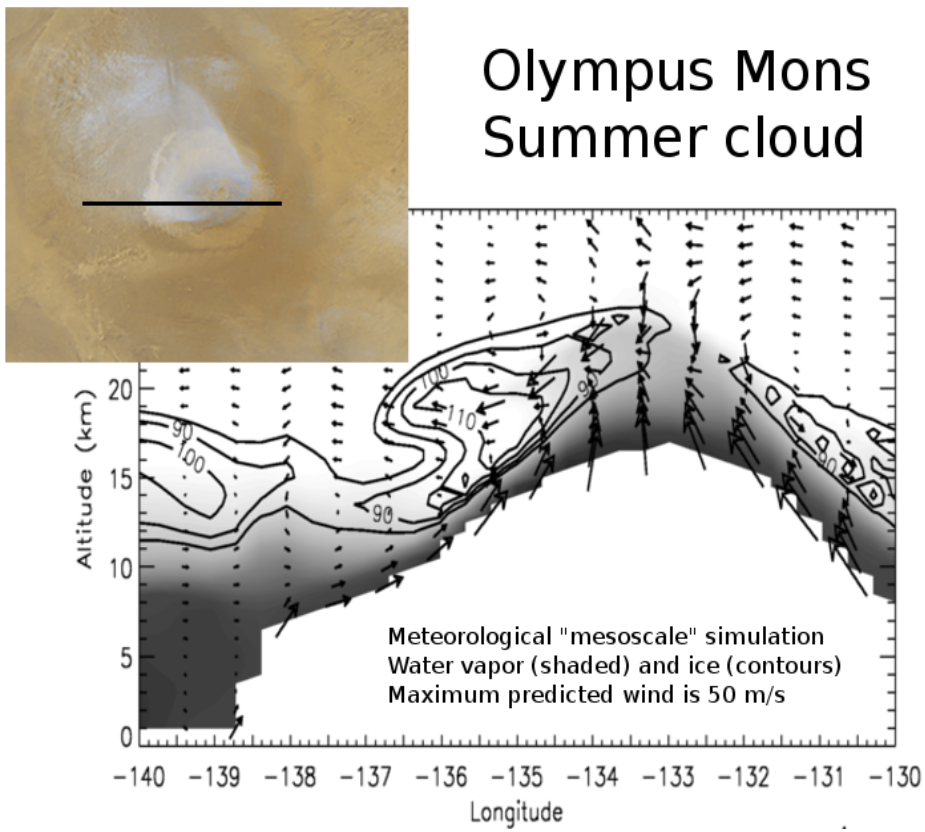
Outline

Katabatic and anabatic winds

Nighttime downslope

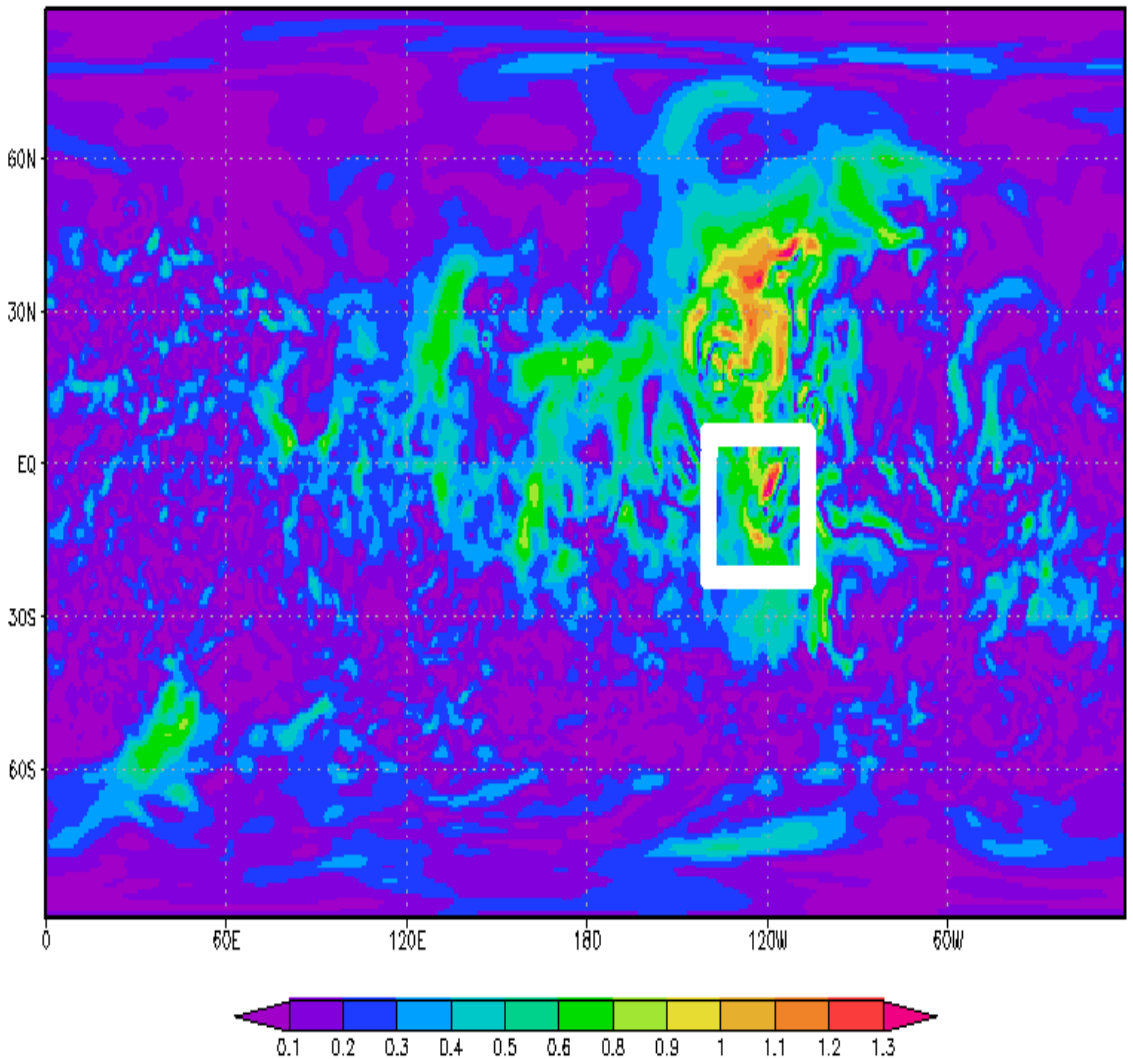


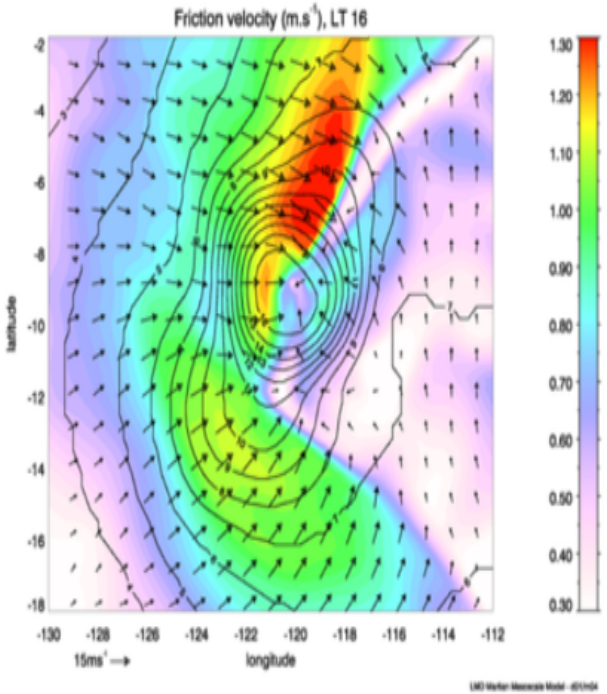
Daytime upslope



[Spiga and Forget JGR 2009; Spiga et al. Icarus 2011]

Anabatic winds: hi-res GCM vs. mesoscale

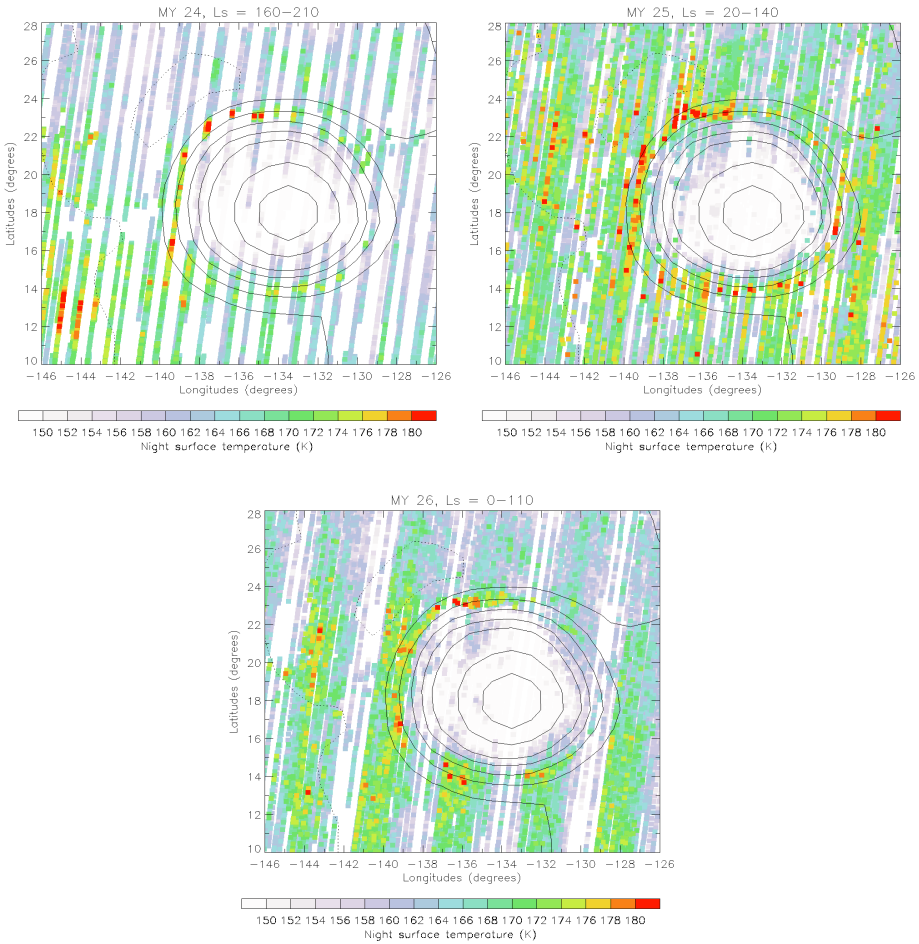




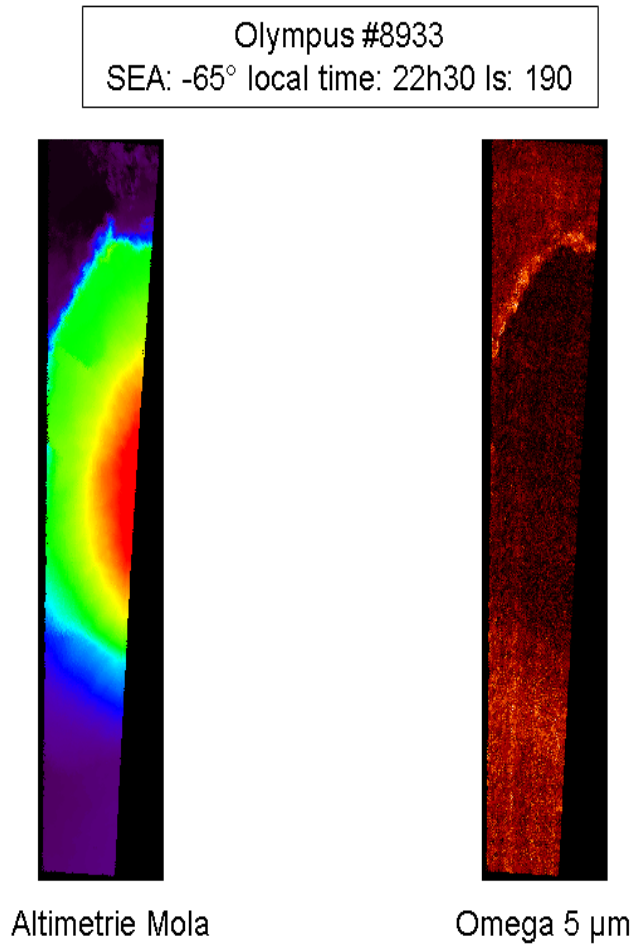
[Spiga and Lewis 2010]

Surface temperature at night, Olympus Mons

MGS / TES

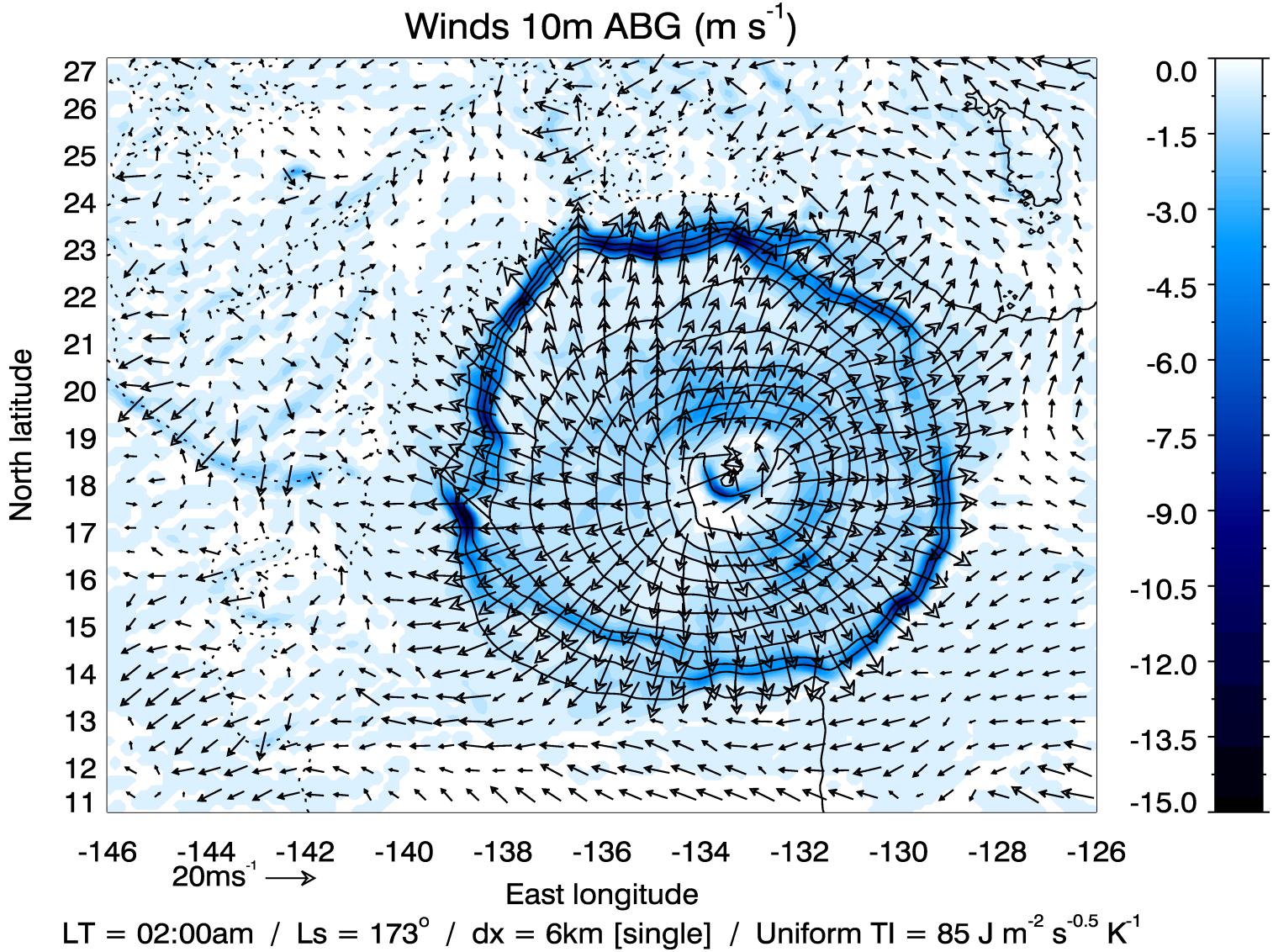


OMEGA



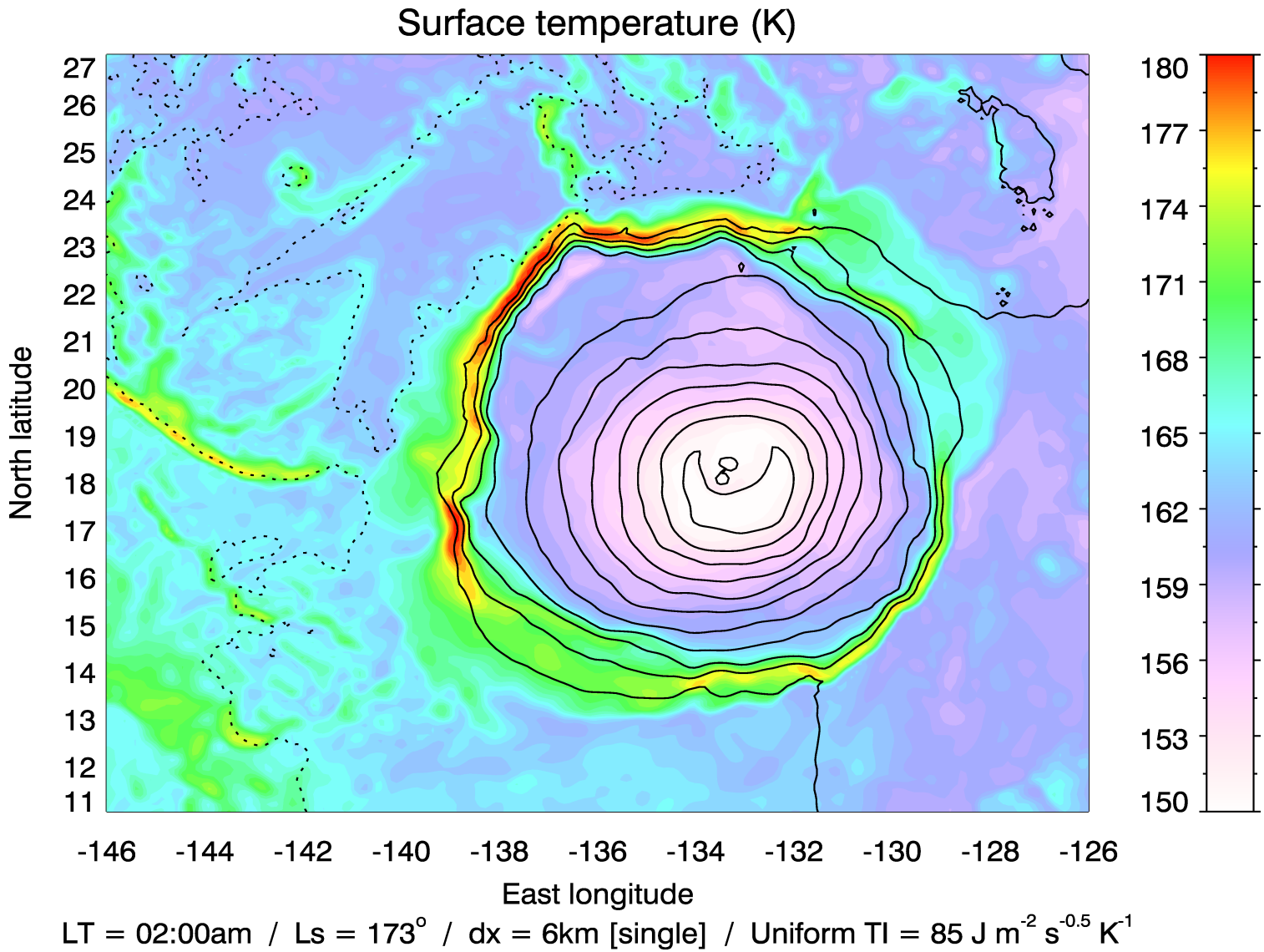
[Spiga et al., Icarus 2011; Gondet and Langevin, pers. comm.]

Katabatic winds in Olympus Mons and Lycus Sulci



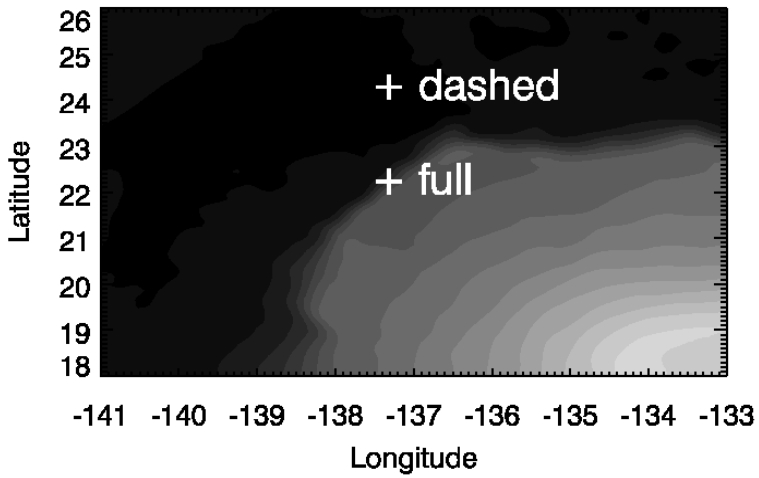
[Spiga and Forget, JGR 2009; Spiga et al., Icarus 2011]

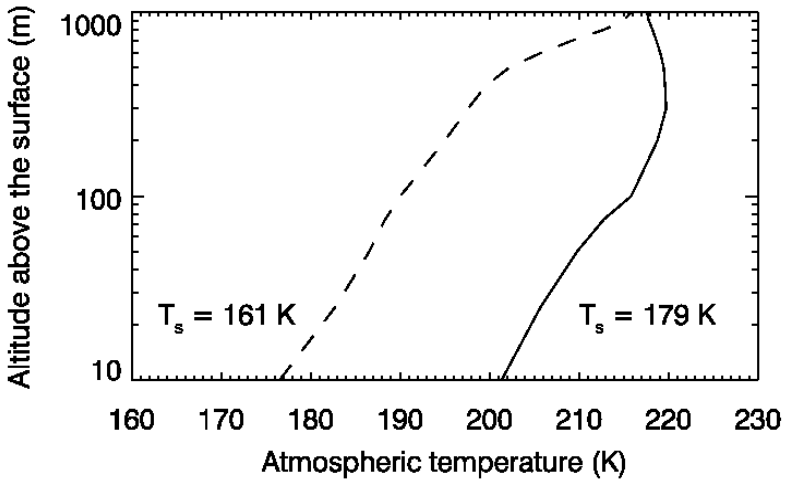
Nighttime “warm katabatic ring”

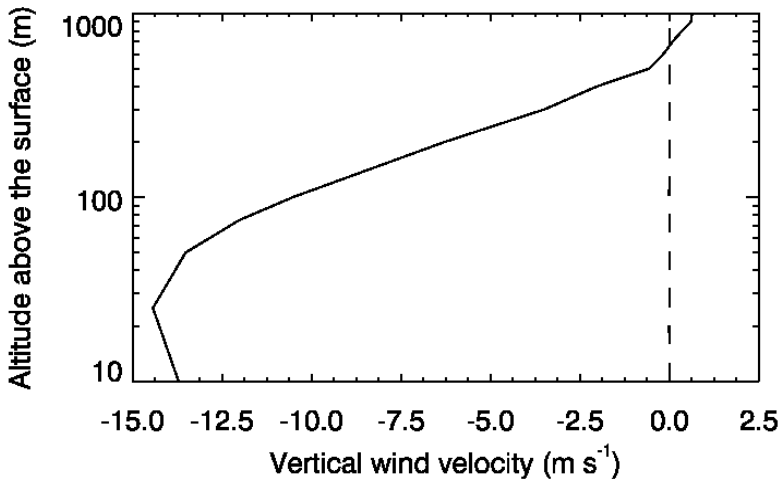


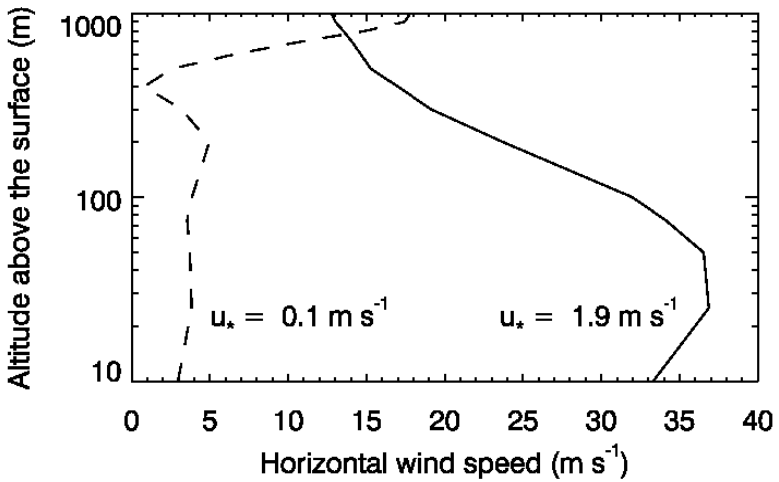
[Spiga et al., Icarus 2011]

Plain vs. steep slopes: typical near-surface profiles





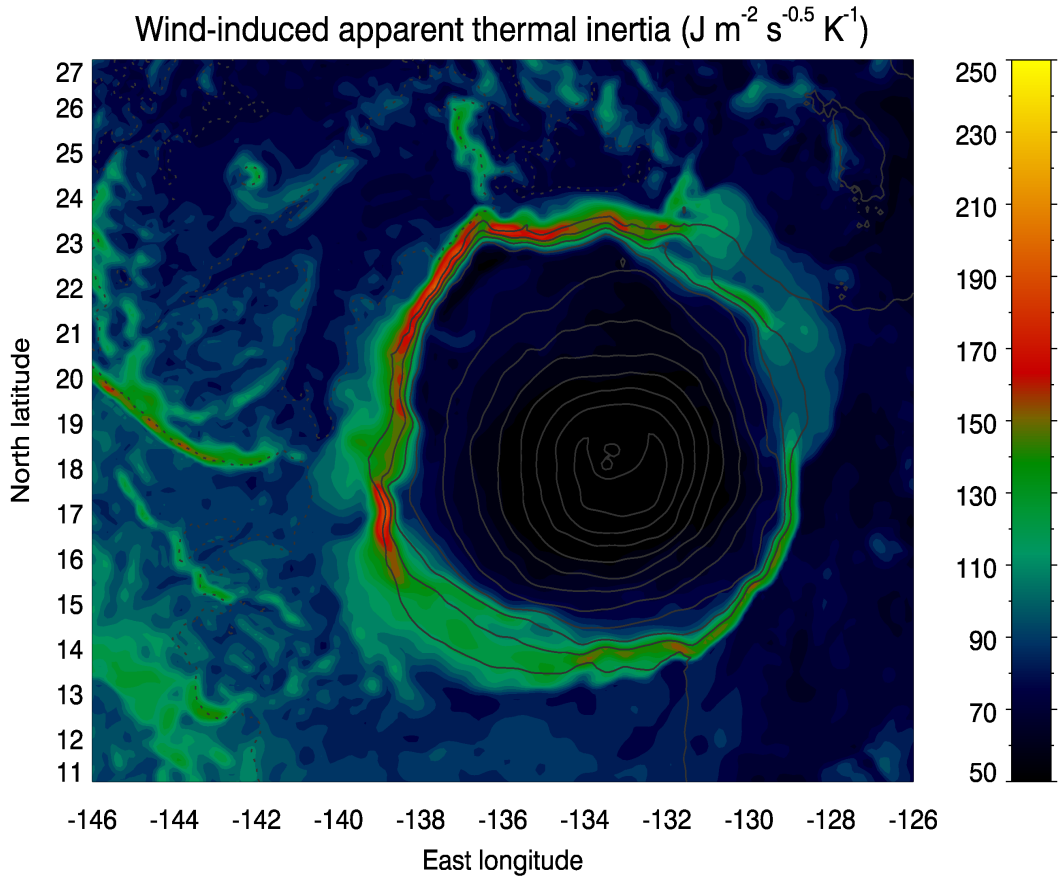




[Spiga et al., Icarus 2011]

Artefacts of thermal inertia

$$\epsilon\,\sigma\,T_{\rm S}^4 = I\sqrt{\frac{\pi}{\tau}}\left.\frac{\partial T_{\rm g}}{\partial\zeta}\right|_{\zeta=0} + \mathcal{F}_{\rm IR} - H_{\rm S}$$



[Spiga et al., Icarus 2011]

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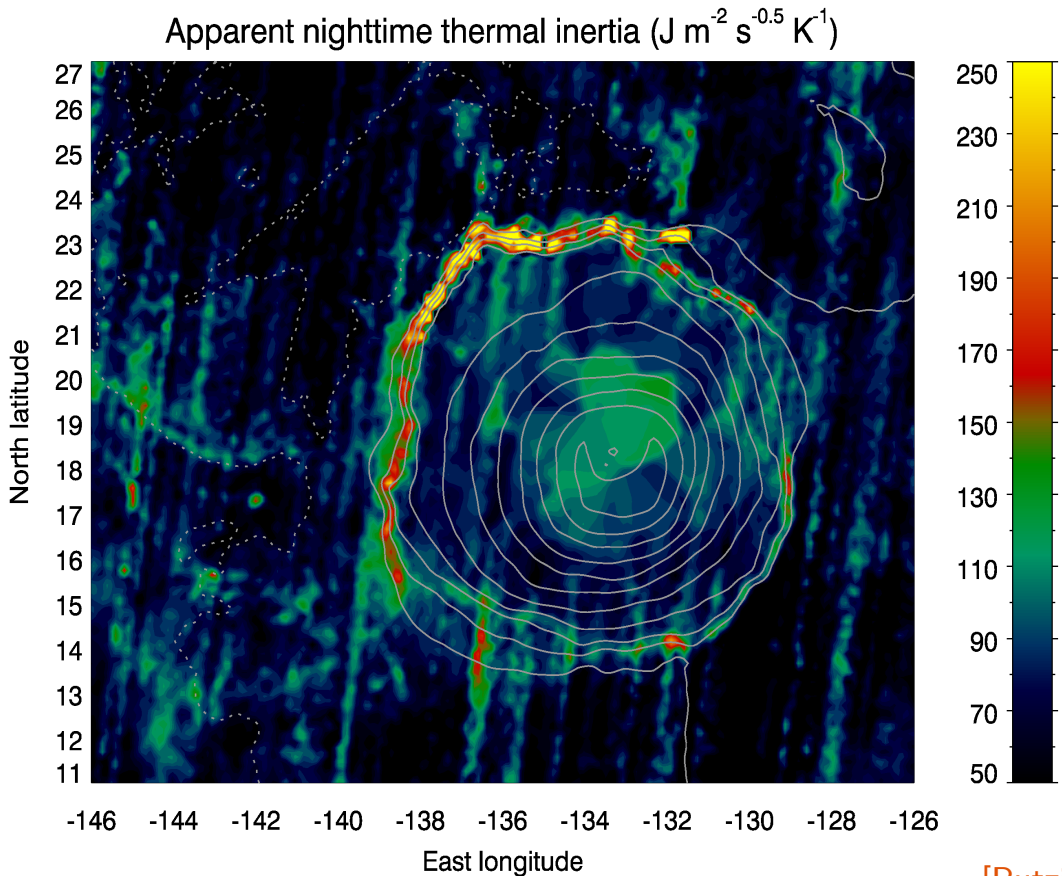
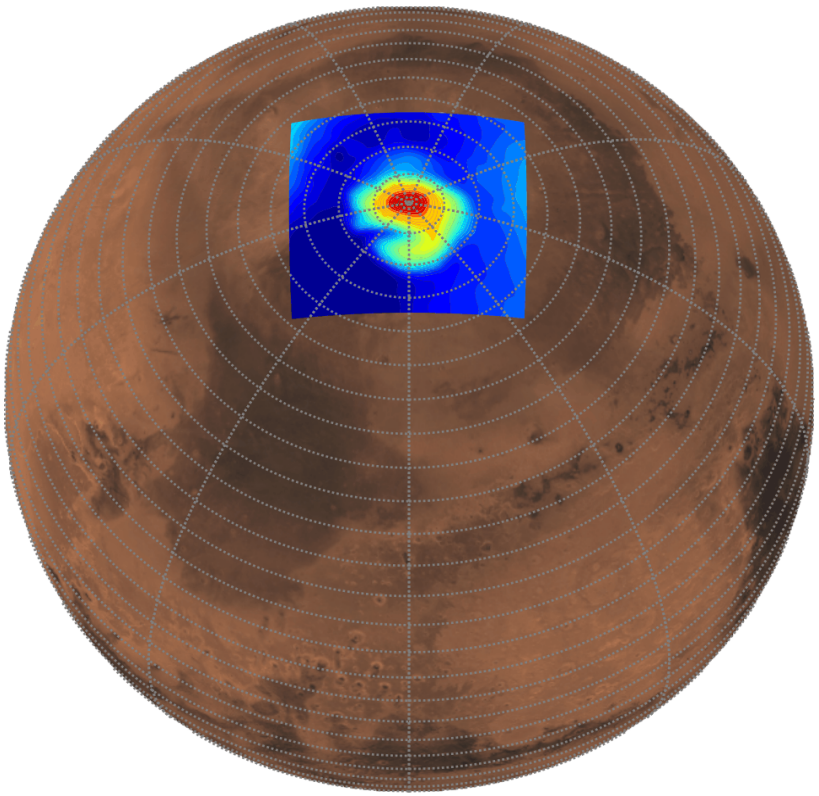
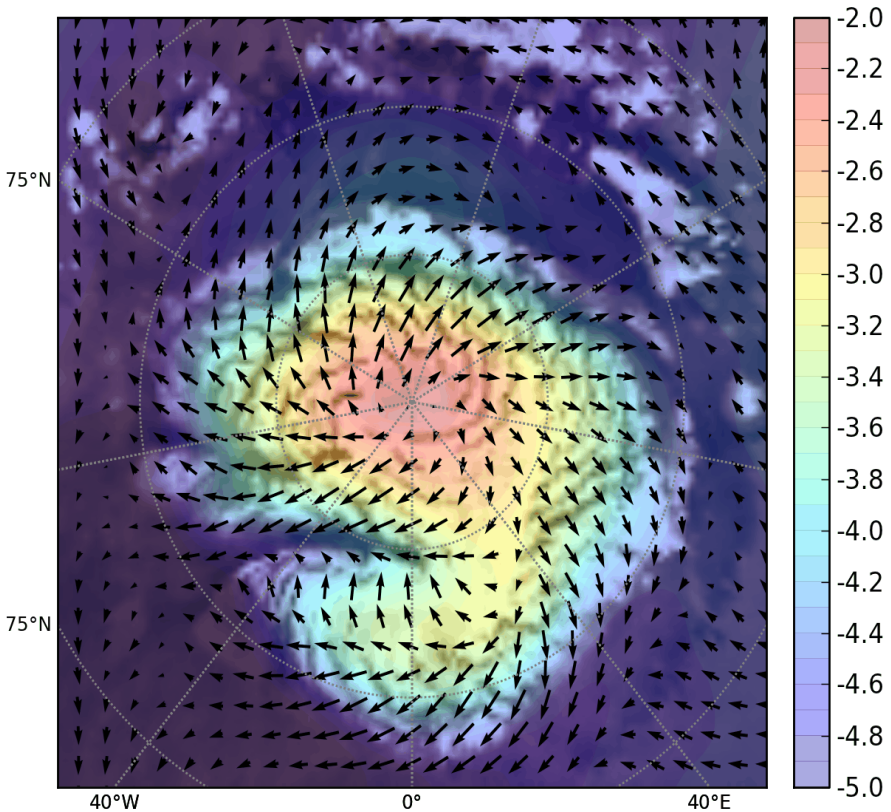


[Putzig and Mellon, Icarus 2007]

Outline

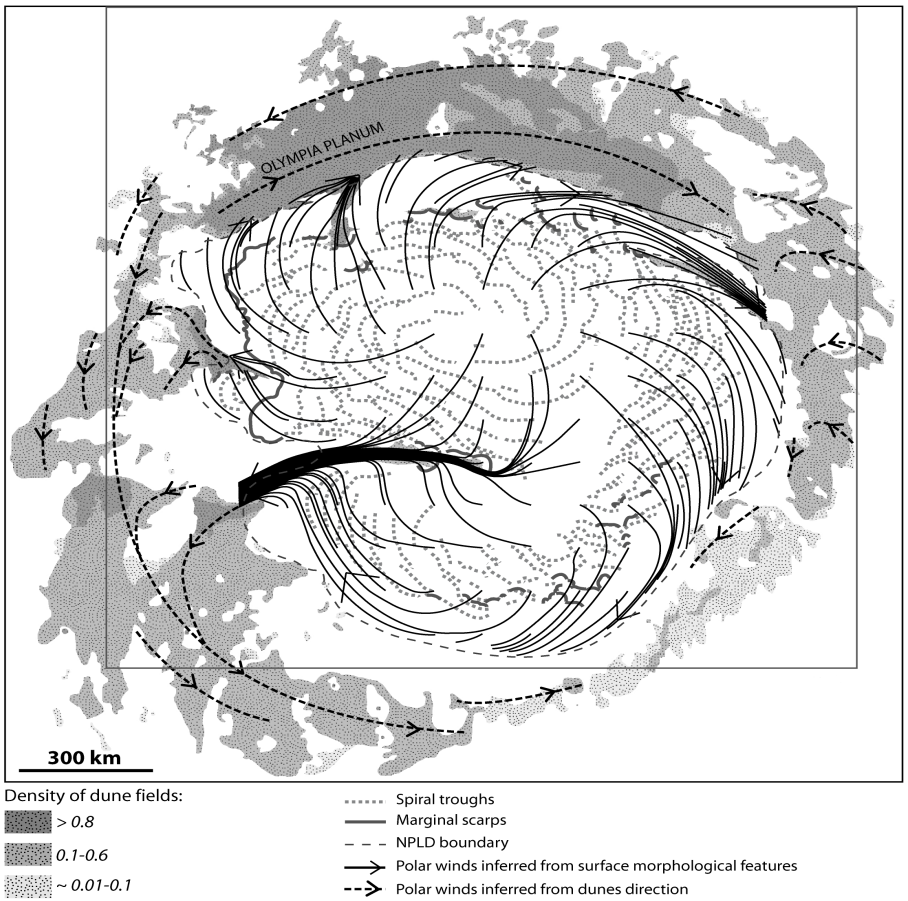
Near-surface regional winds: northern polar cap



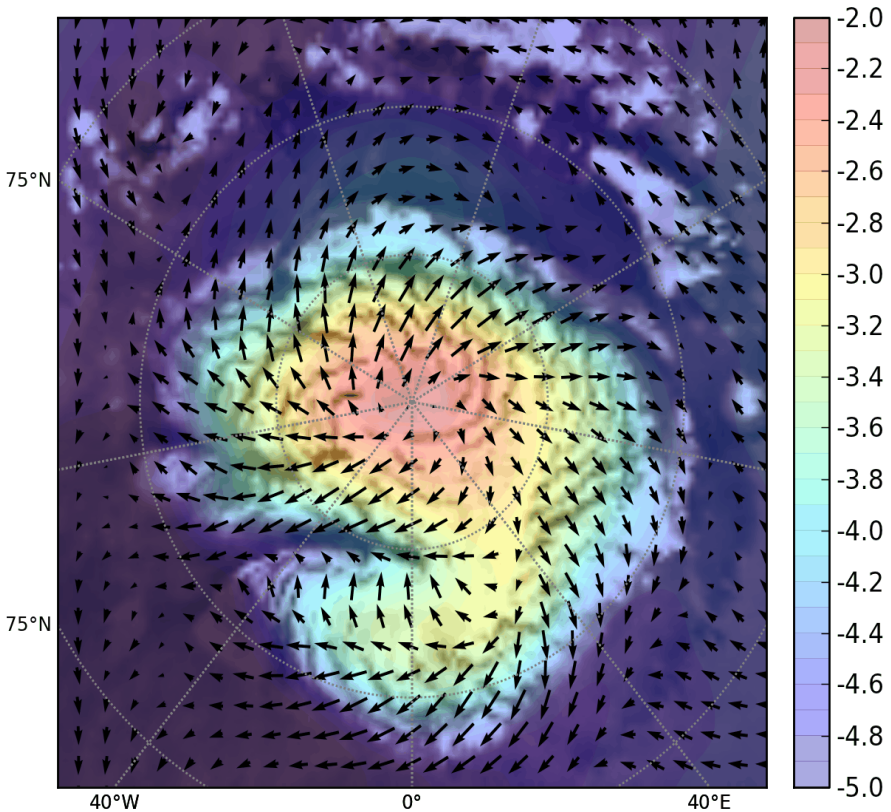


Near-surface regional winds: northern polar cap

Frost streak and dune mapping



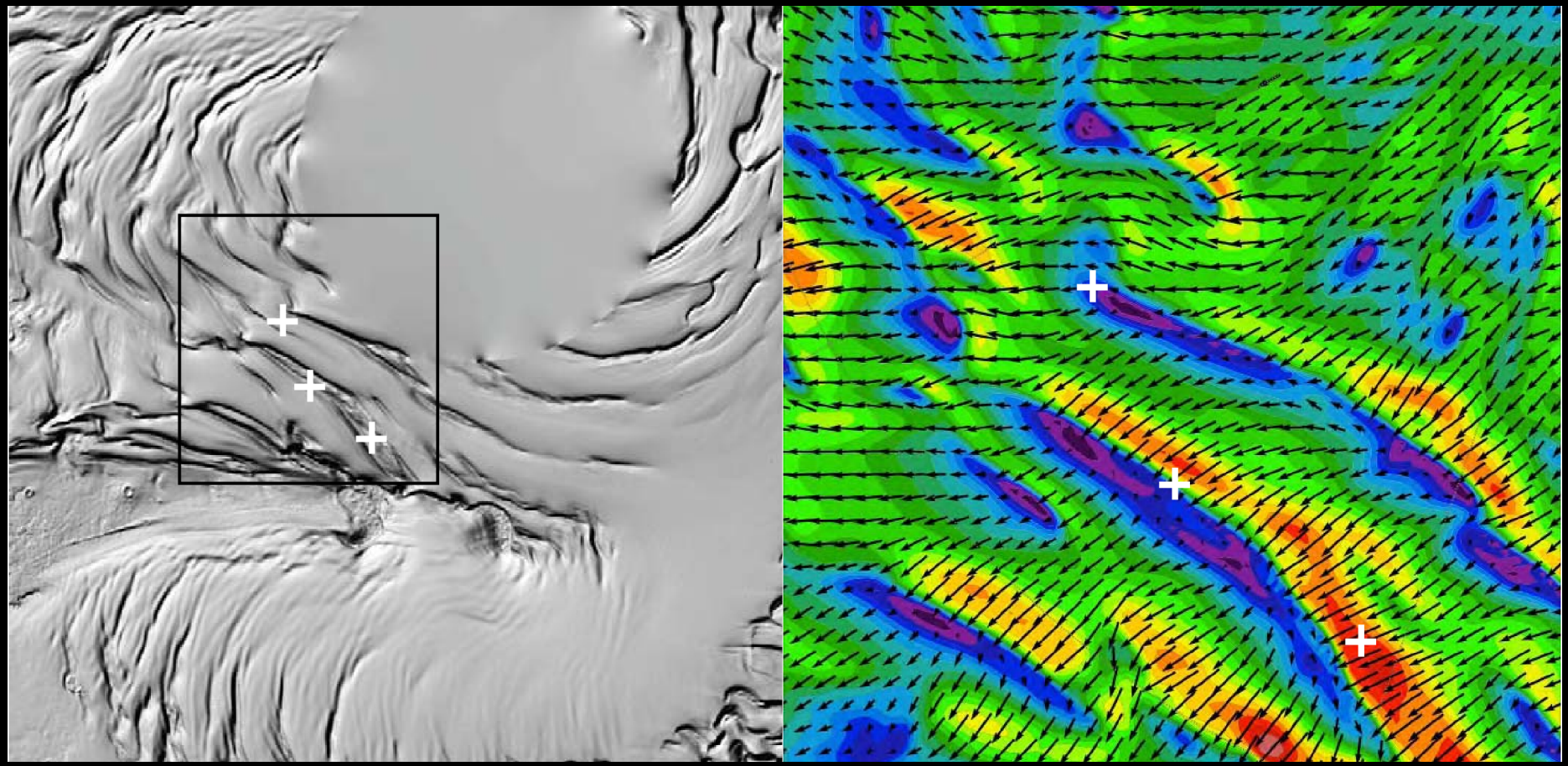
Mesoscale modeling



[Data: Howard Icarus 2000 and Massé et al. EPSL 2012]

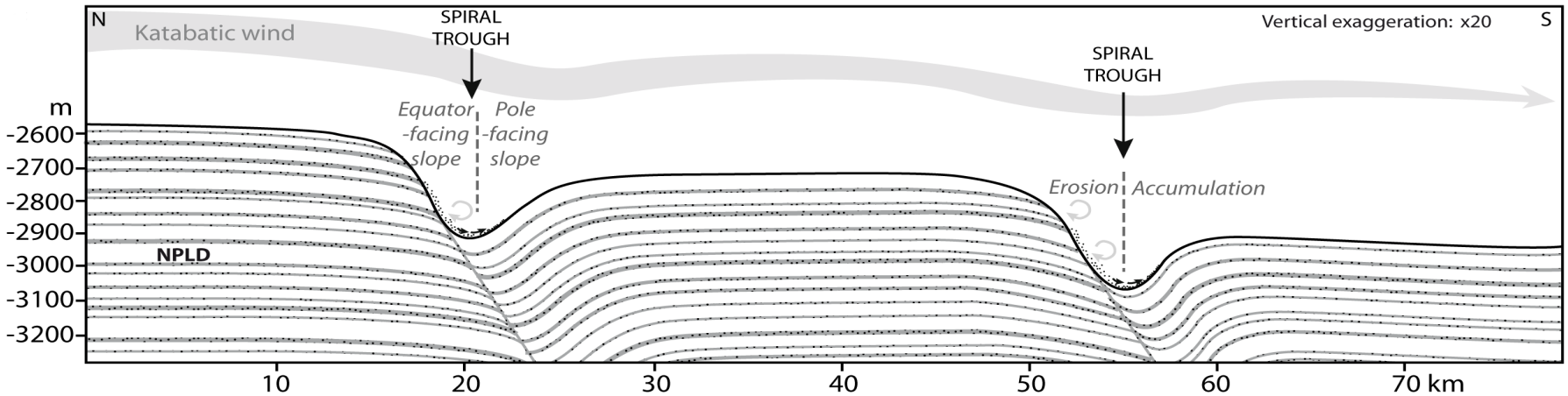
Troughs influence katabatic winds

Results from LMD mesoscale modeling with resolution 2 km

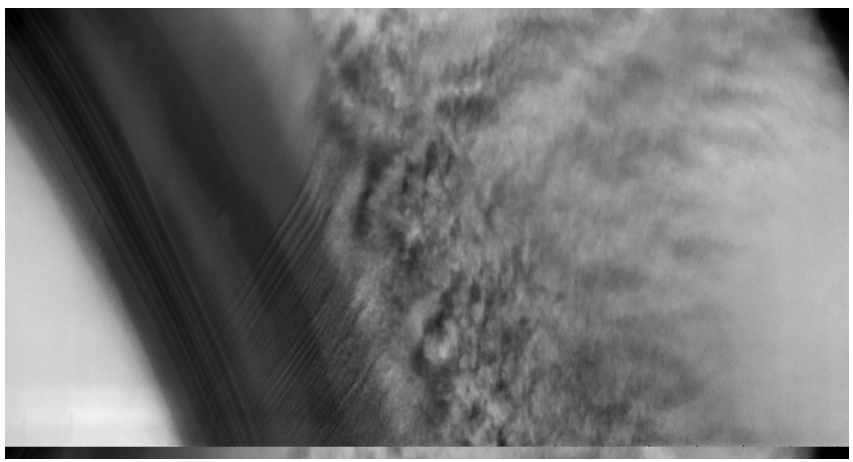


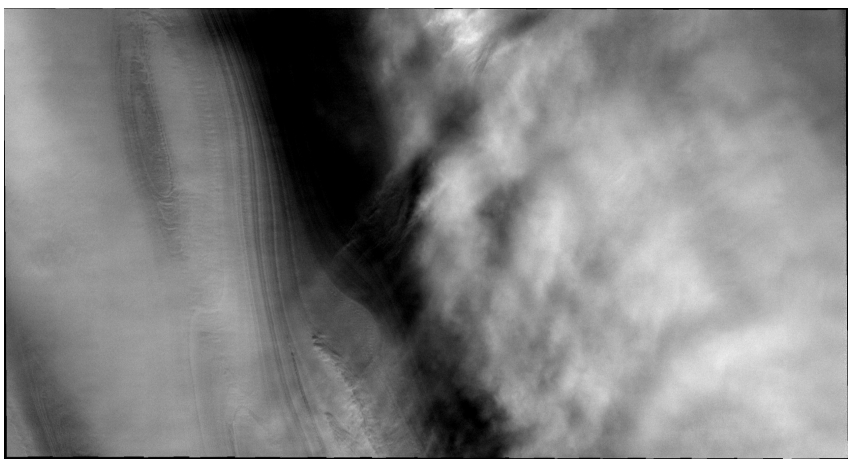
[Smith et al. submitted to JGR]

Trough migration & katabatic winds



[Massé et al., EPSL, accepted]





[Smith and Holt Nature 2010]

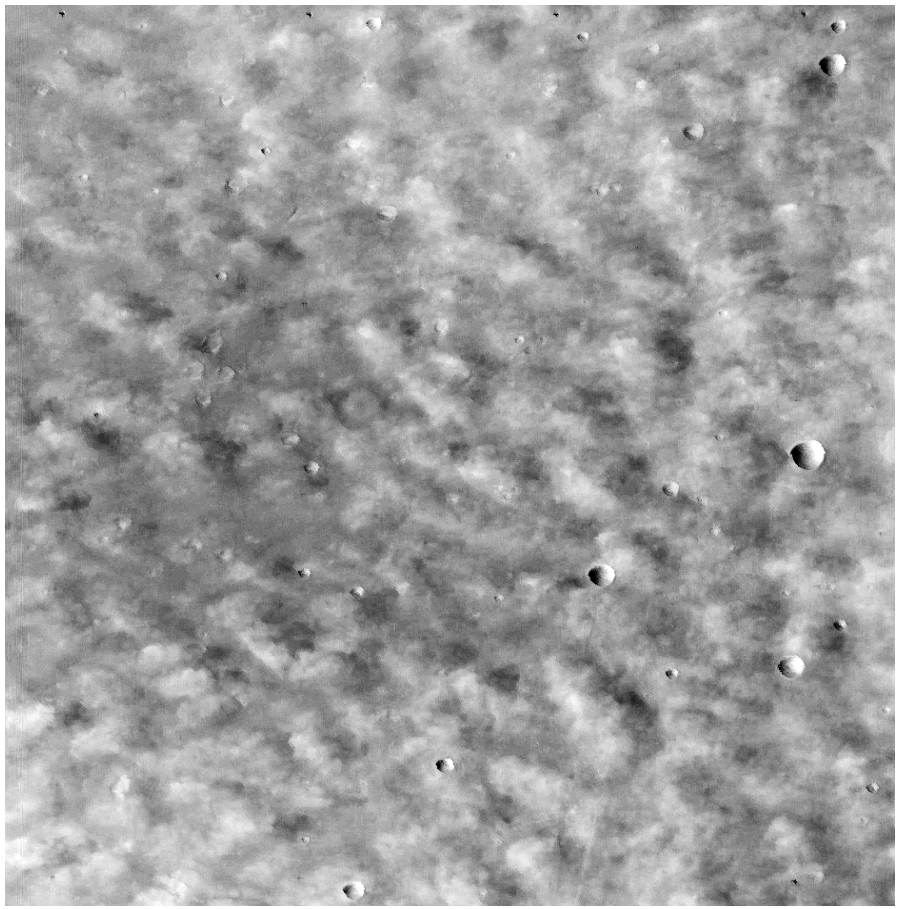
Outline

Mars PBL phenomena: Imagery

Dust devils

[Pancam on Spirit Rover]

Cloud streets

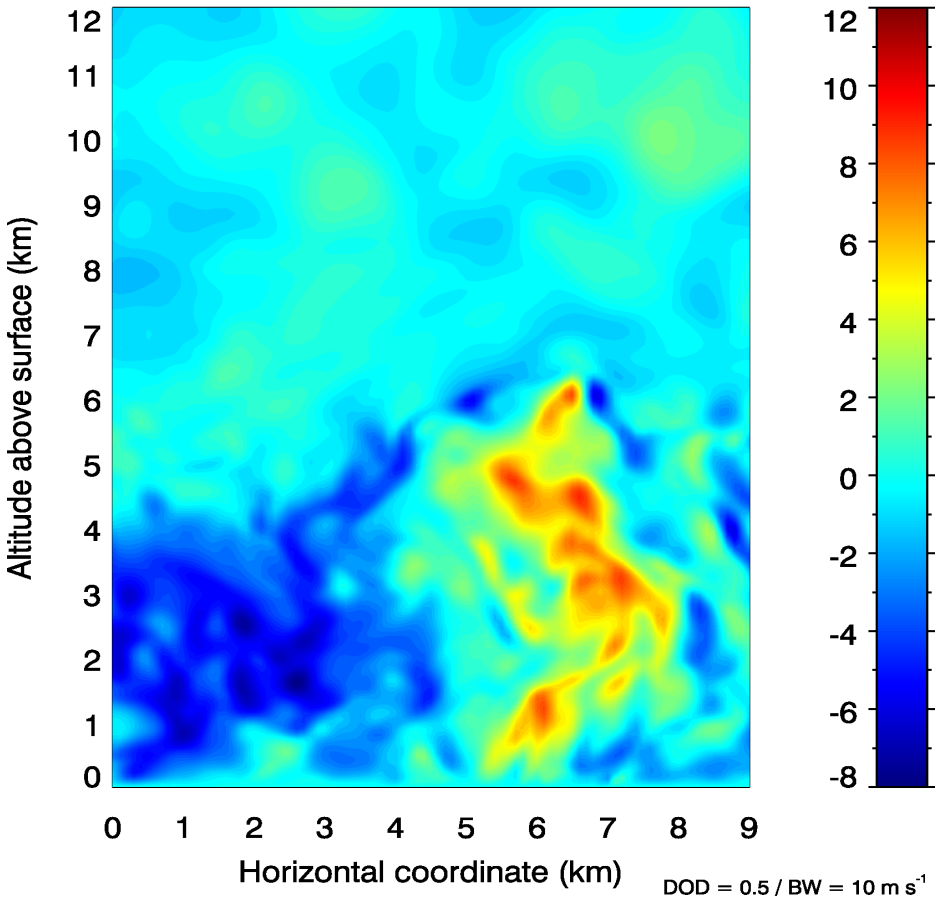


[Mars Orbital Camera on Mars Global Surveyor]

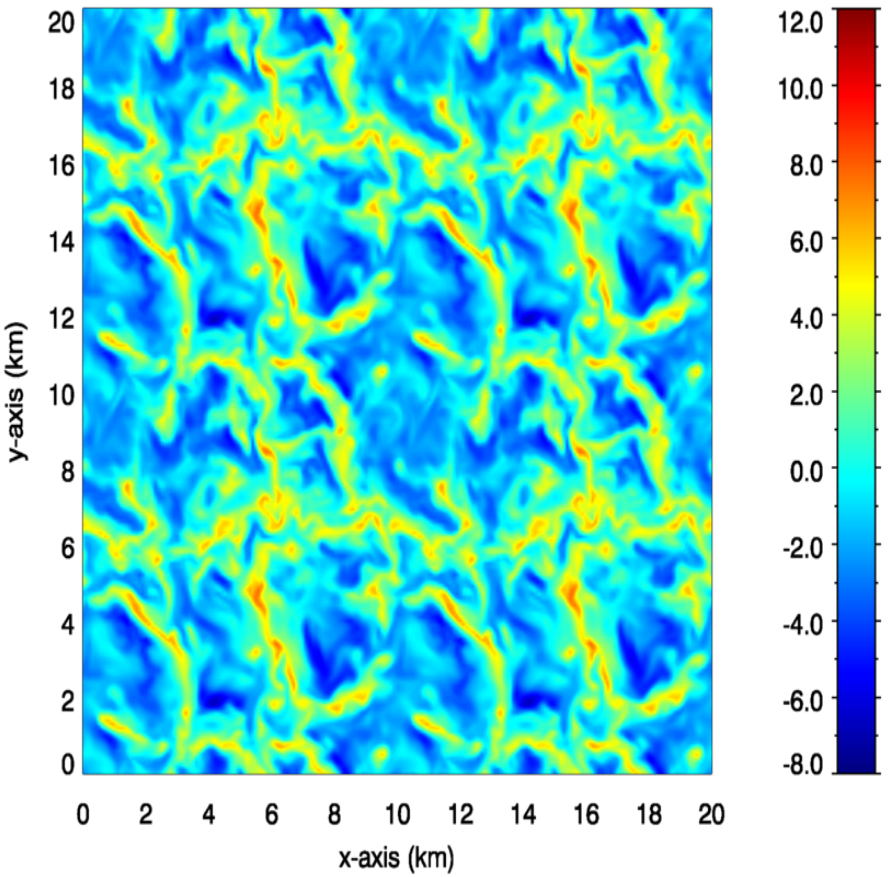
Turbulent convection in daytime boundary layer

Simulated through Large-Eddy Simulations [LES]

↓ Vertical ↑



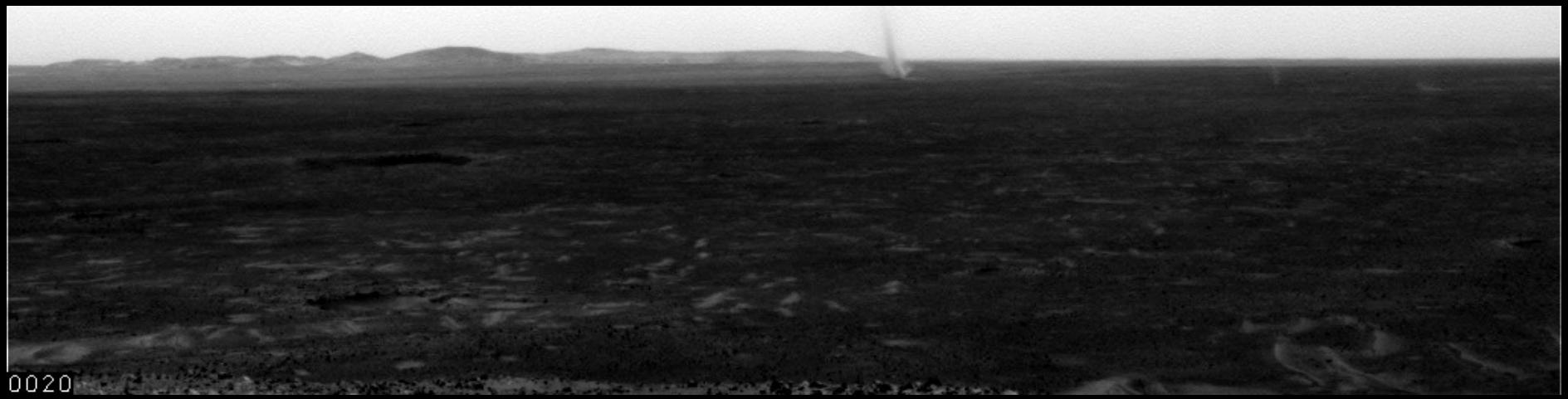
← Horizontal →



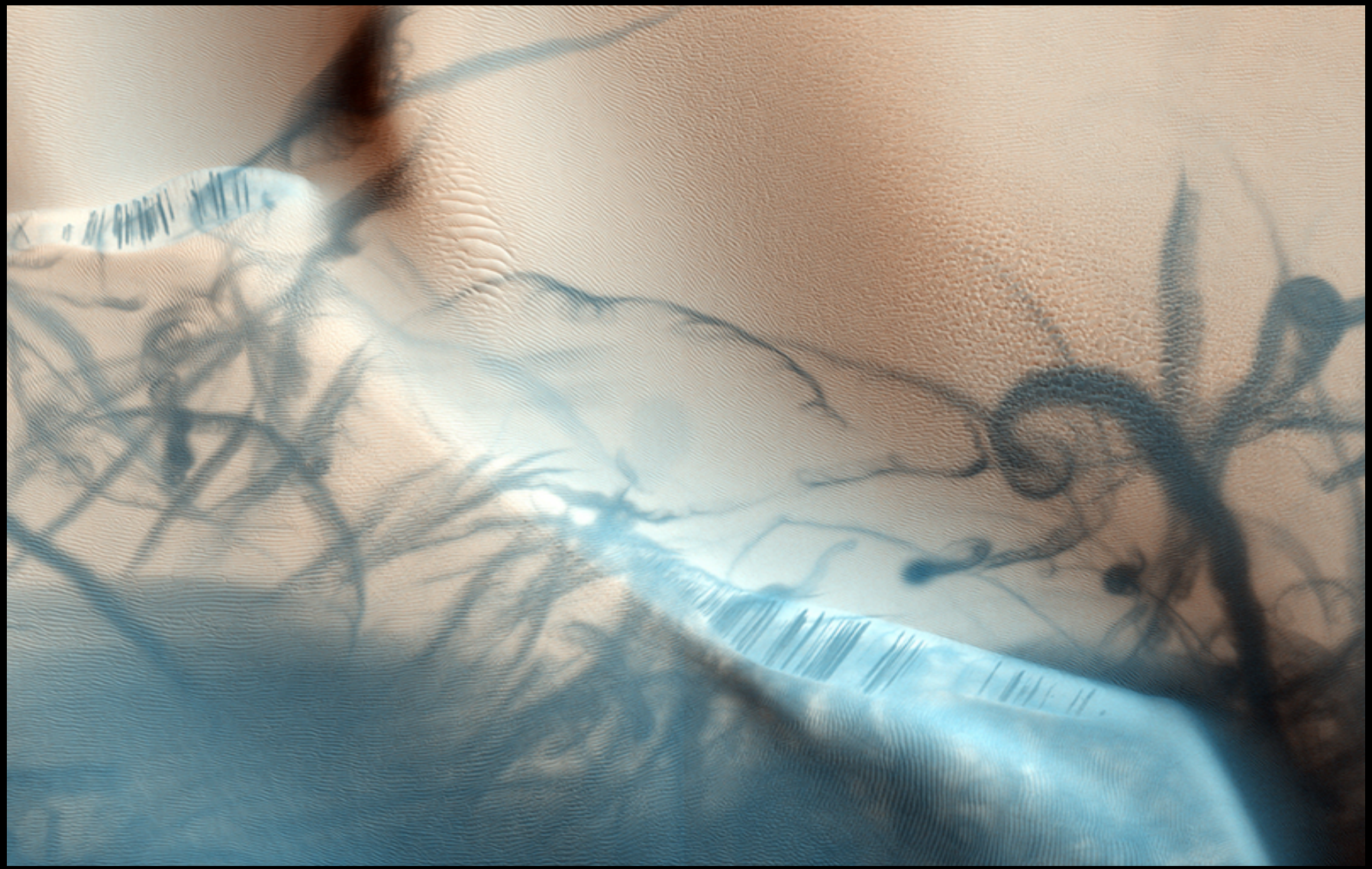
[Meridiani simulation for Exomars risk assessment]

Outline

Dust devils observed by Spirit

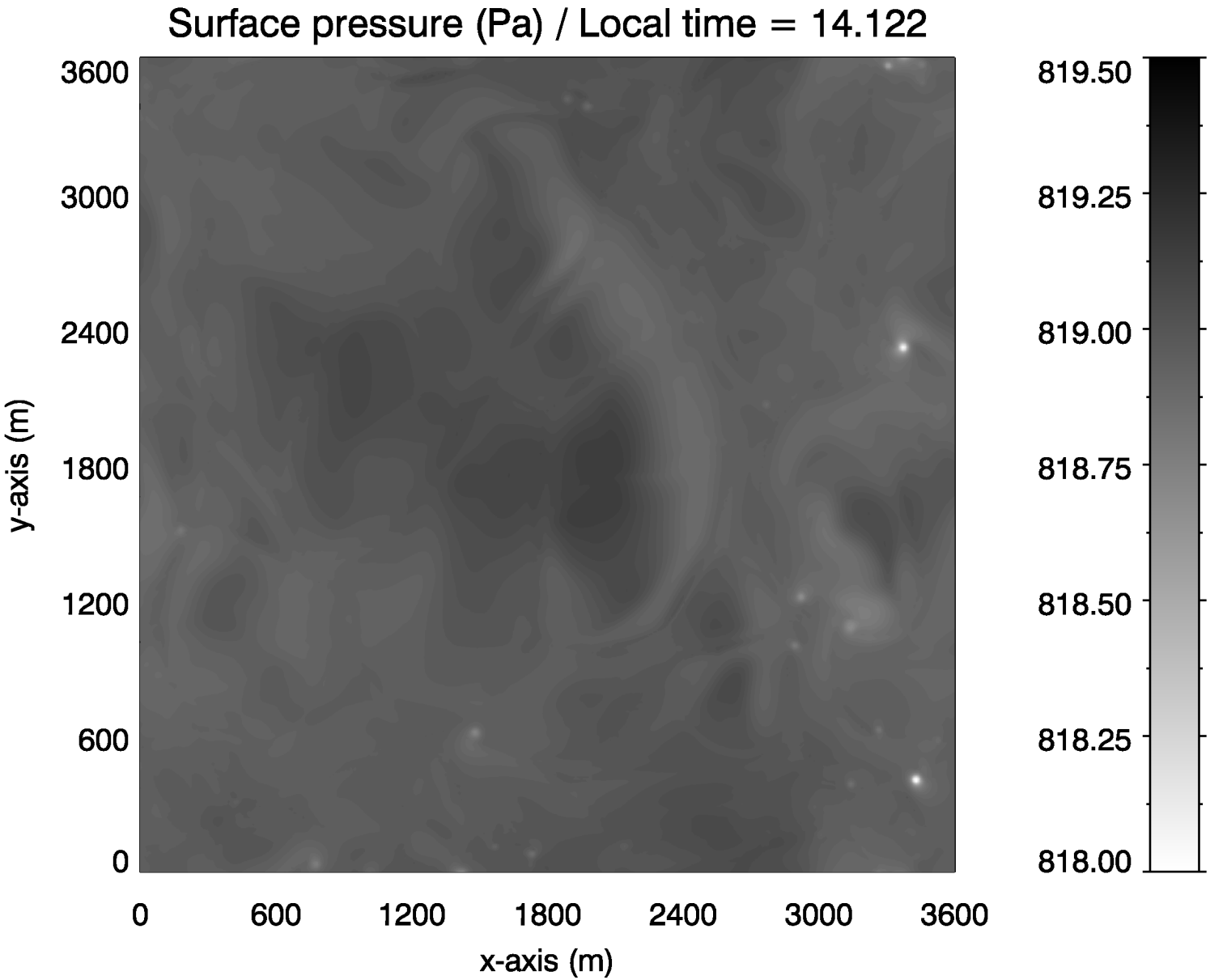


Graffitis martiens ! Champ de dunes Arabia Terra



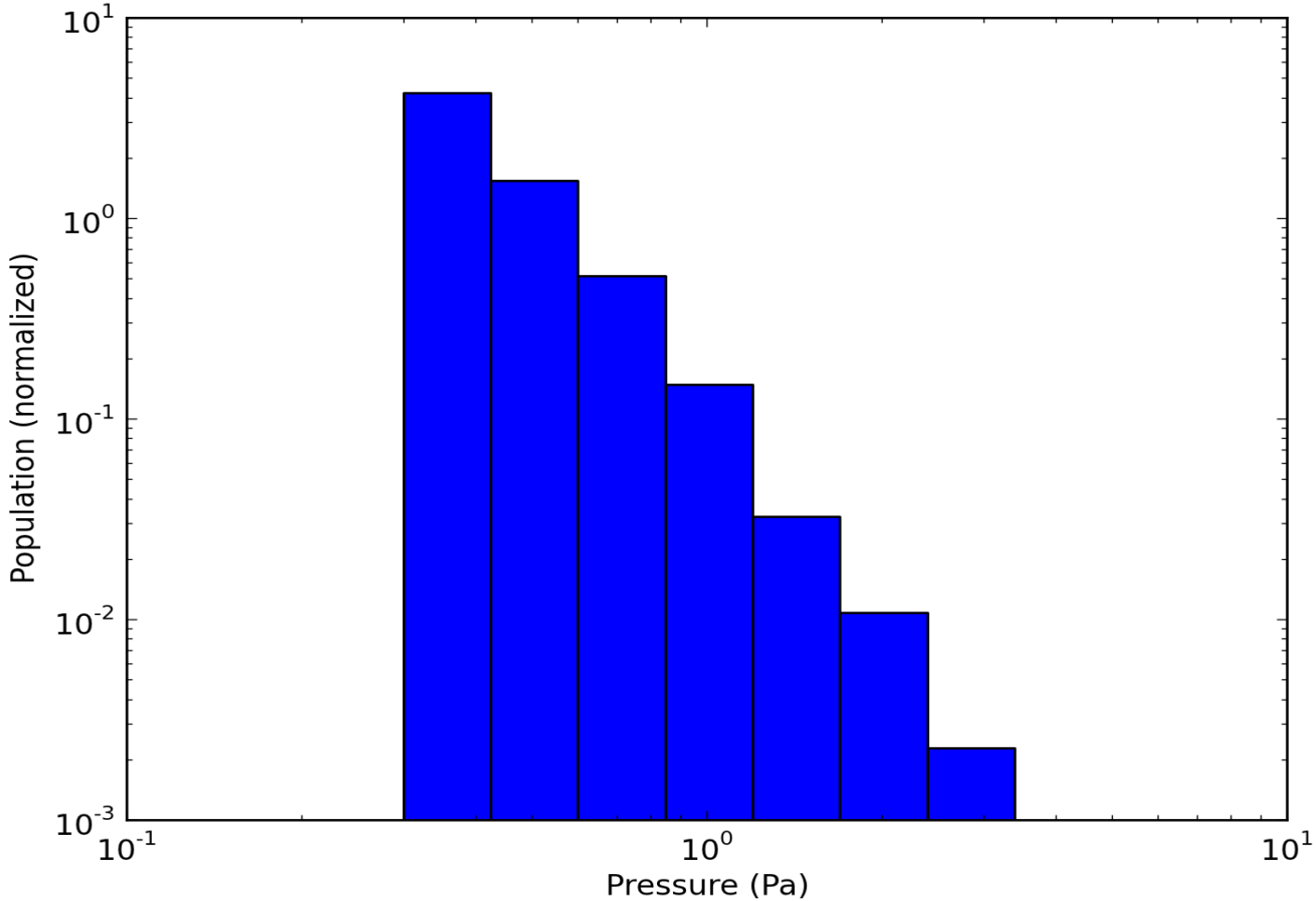
[HiRISE, Mars Reconnaissance Orbiter, 2009]

Convective vortices in LES



Distribution of pressure drop in 10 m LES

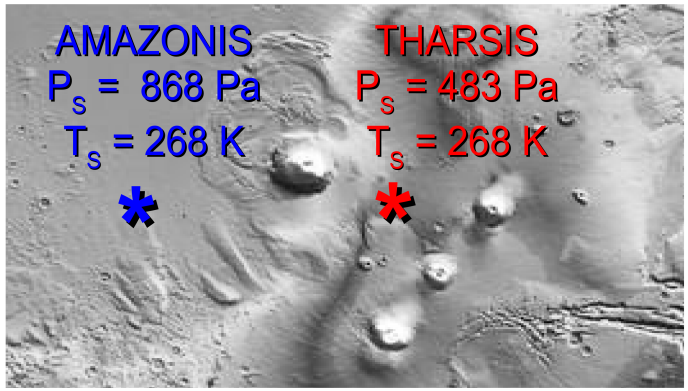
Histogram with logarithmic axes and bins

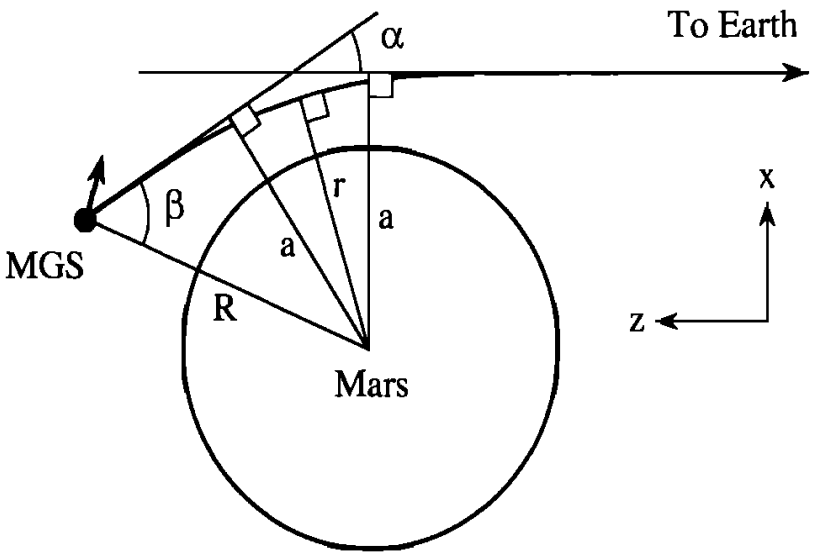


Note: nice power law fit with exponent 3.3

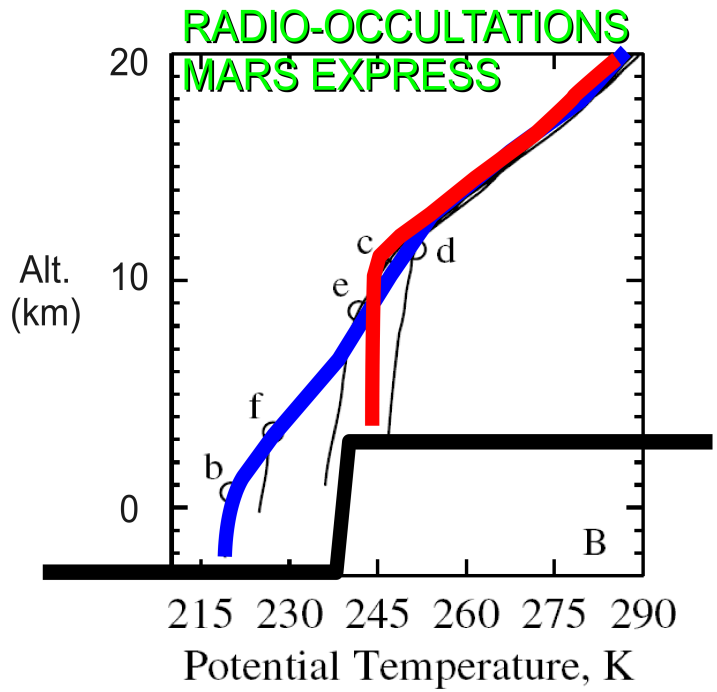
Outline

Mars Express radio-occultations



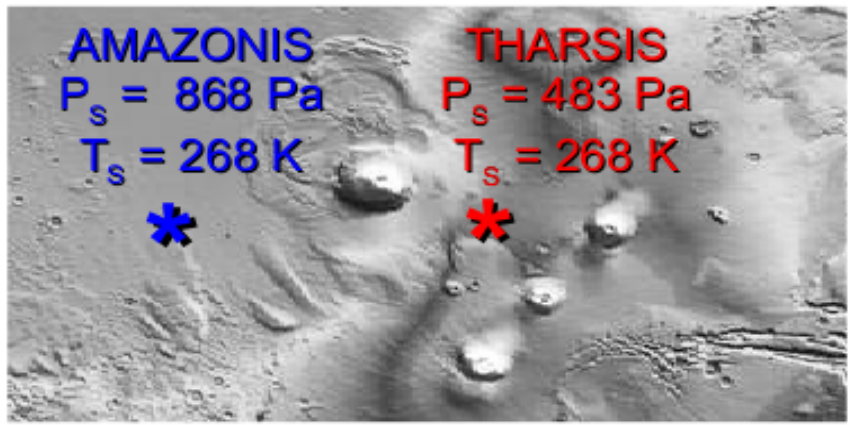


[Hinson et al., 1999]

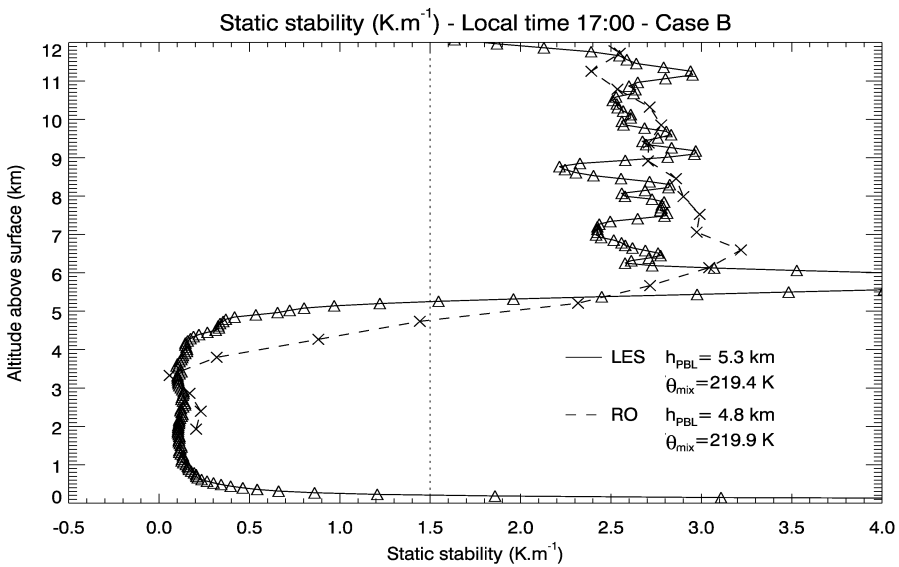


[Hinson et al., 2008]

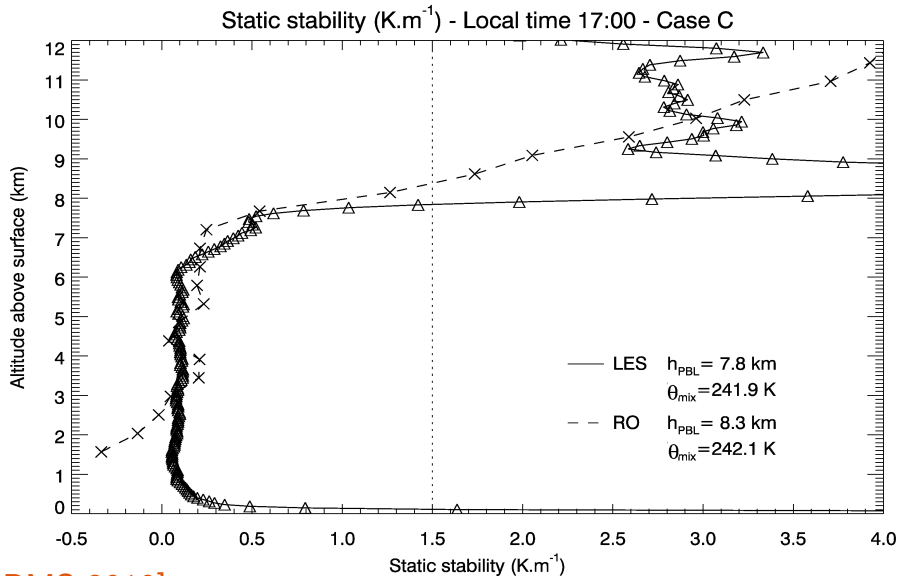
BL depth variability: observations vs. models



Lower plains [Amazonis]



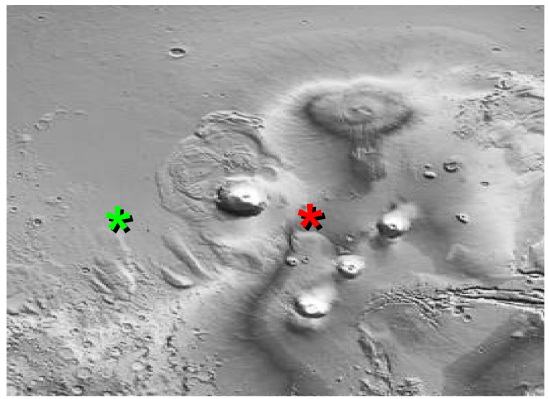
Higher plateaus [Tharsis]



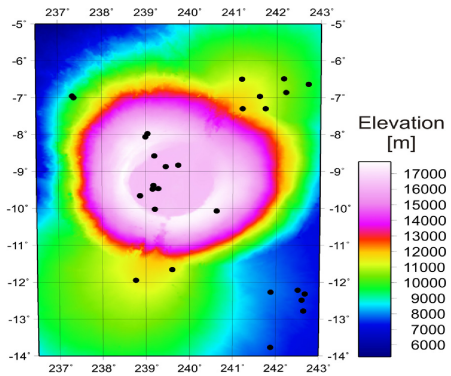
[Spiga et al., QJRMS 2010]

Existence of dust devils in high-altitude plateaus

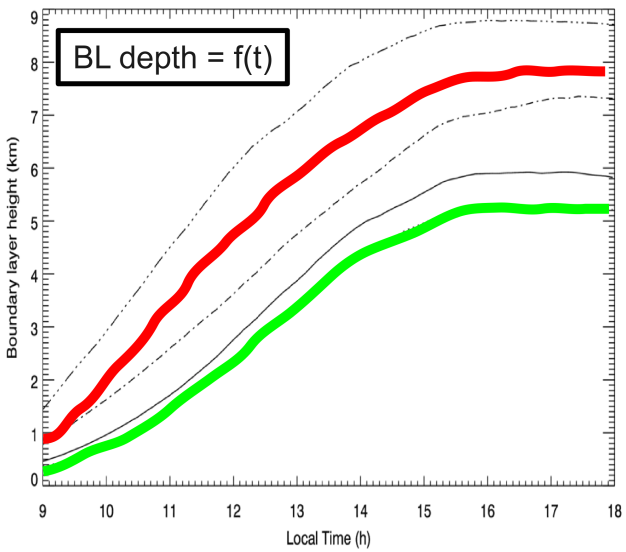
AMAZONIS
TI = 50 tiu / A = 0.3
855 Pa

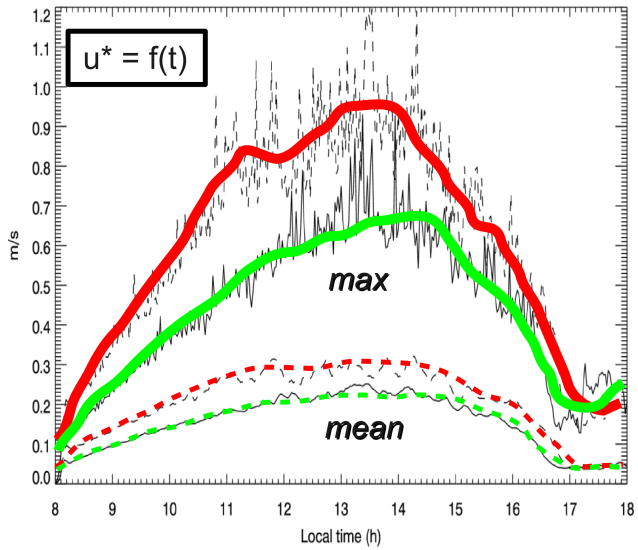


THARSIS
TI = 60 tiu / A = 0.3
483 Pa



[Reiss et al., LPSC 2009]





[Spiga and Lewis, Mars Journal 2010]

Energy budget, bottom of mixed layer

(free convection conditions)

$$c_p \frac{\partial \theta}{\partial t} = \left(\frac{p_0}{p} \right)^{R/c_p} \left[\mathcal{J}_{\mathrm{LH}} + \mathcal{J}_{\mathrm{LW}} + \mathcal{J}_{\mathrm{SW}} \right] - c_p \frac{\partial \langle w' \theta' \rangle}{\partial z}$$

Mars

$$\frac{\partial \theta}{\partial t} \sim \left(\frac{p_0}{p} \right)^{R/c_p} \frac{\mathcal{J}_{\mathrm{LW}}}{c_p}$$

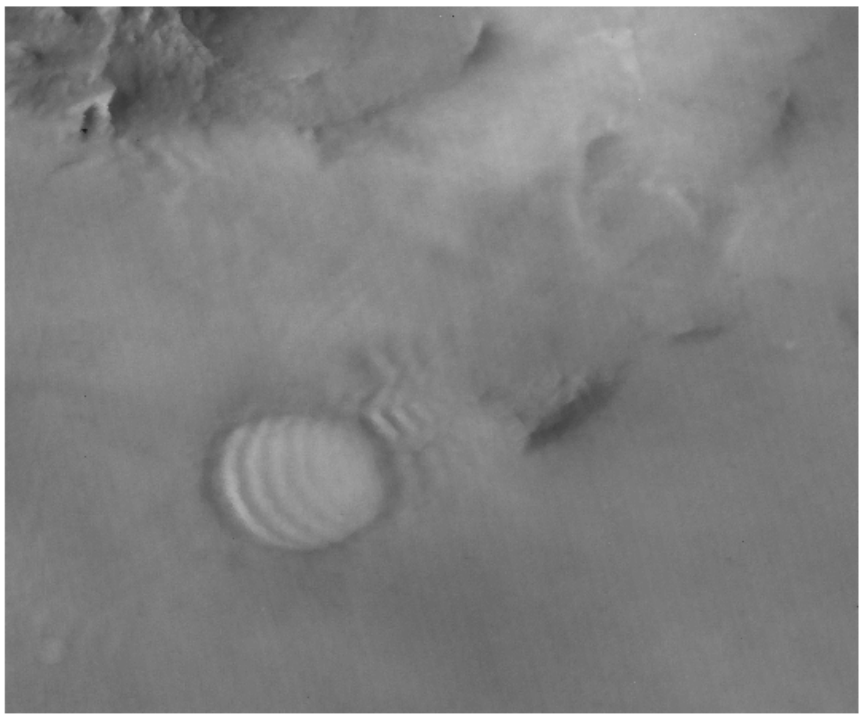
Earth (arid terrains)

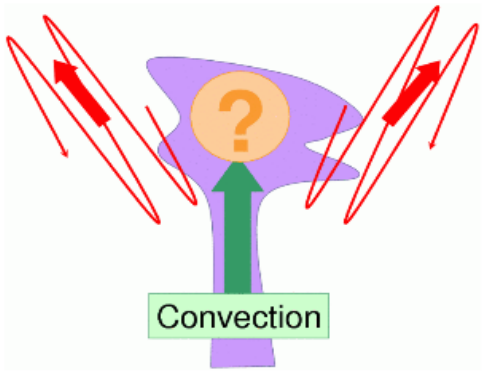
$$\frac{\partial \theta}{\partial t} \sim - \frac{\partial \langle w' \theta' \rangle}{\partial z}$$

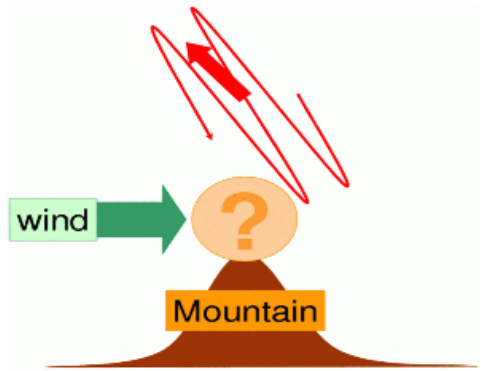
[Spiga et al., QJRMS 2010]

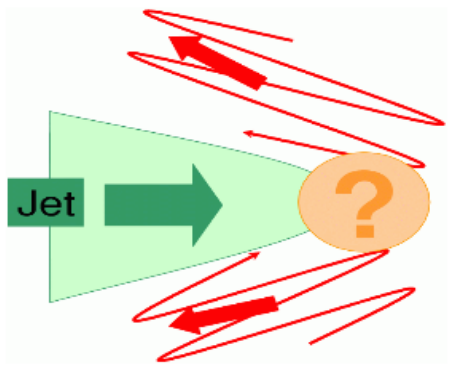
Outline

Gravity Waves [GWs] and their sources







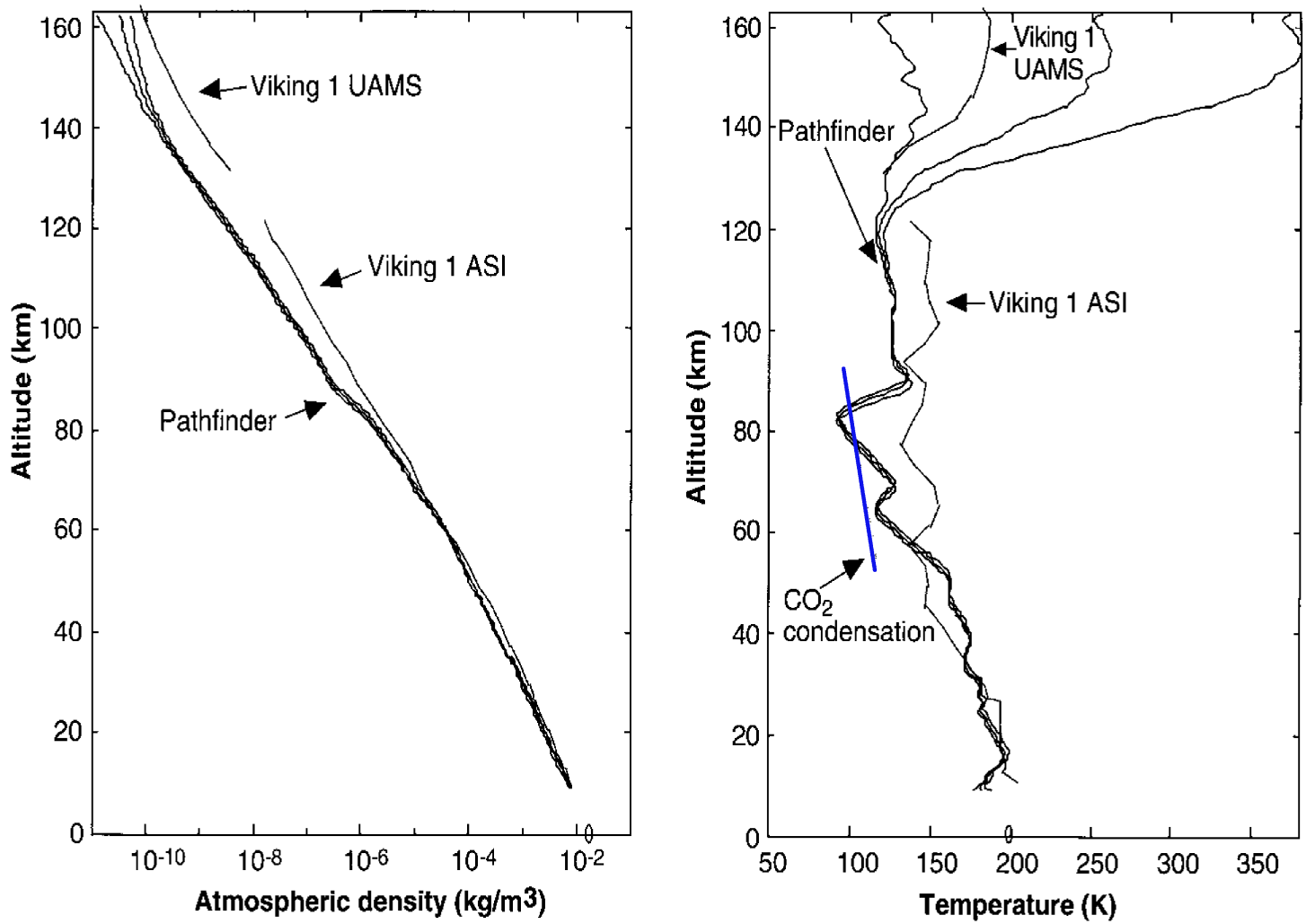


[MGS/MOC Image]

Outline

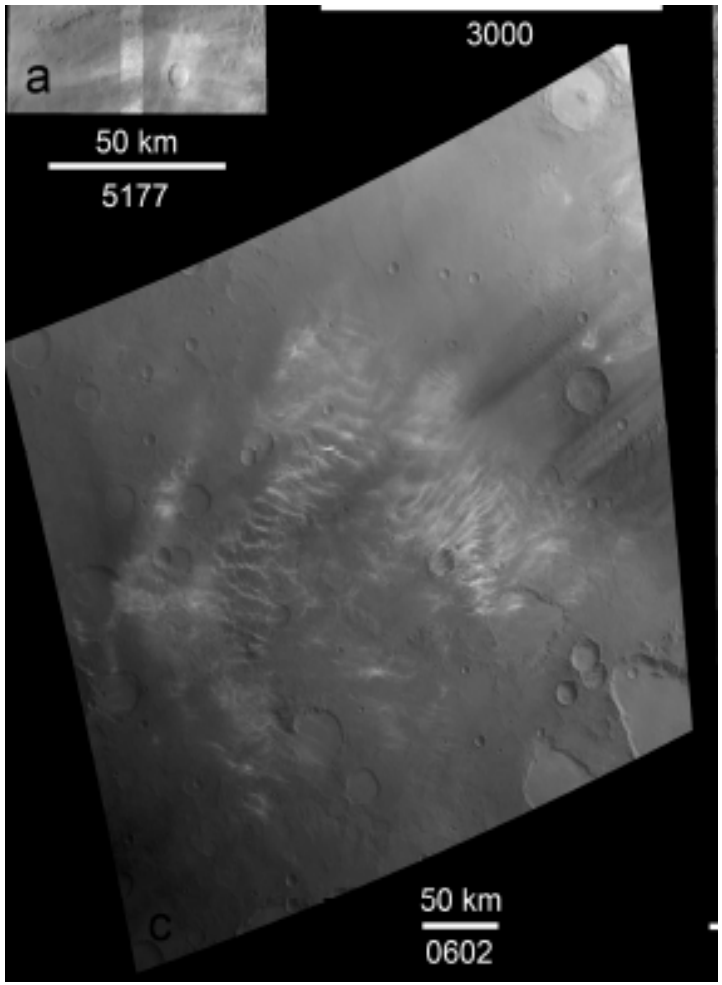
GW events observed in entry profiles

Viking [Seiff and Kirk 1977] Pathfinder [below] MGS and ODY [Fritts et al. 2006]
MERs [Withers and Smith 2006] Phoenix [Withers and Catling 2010]

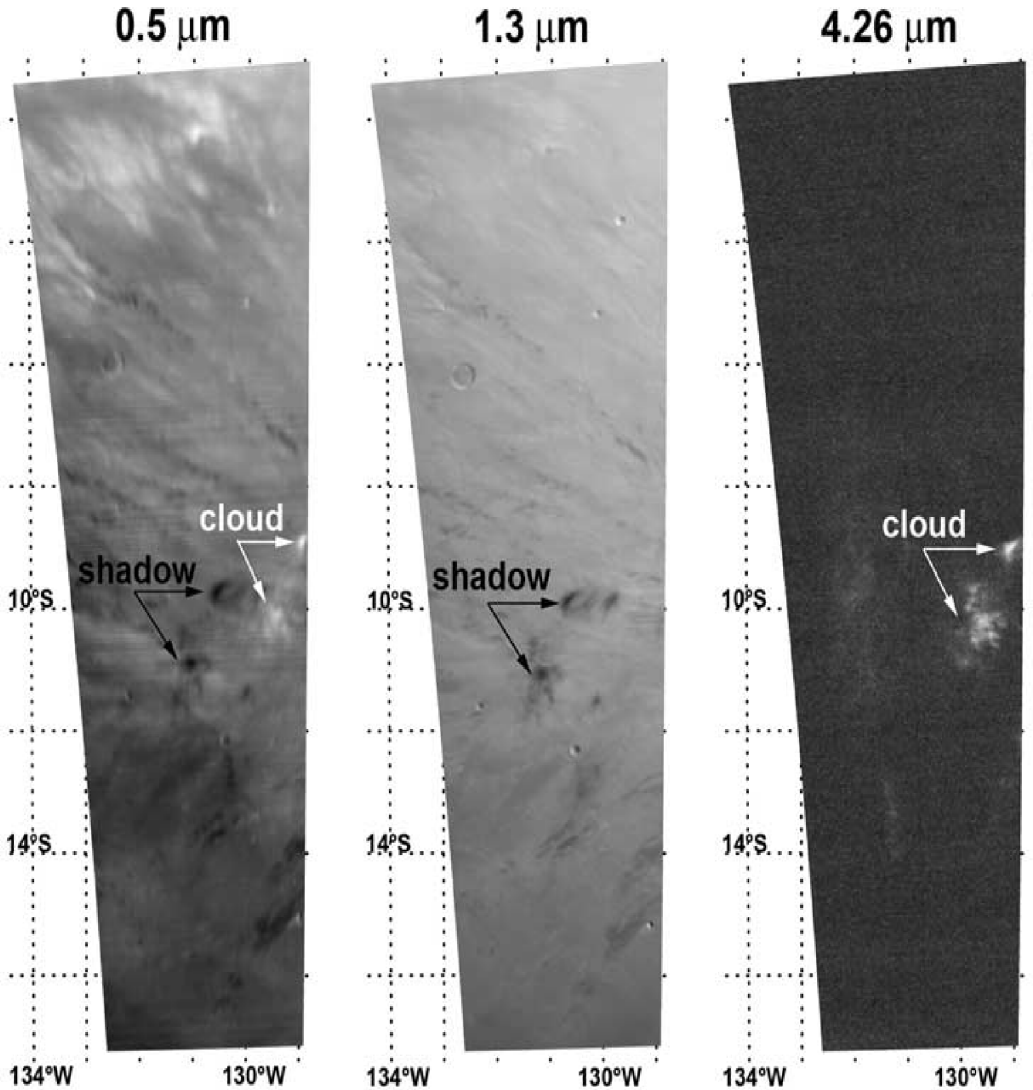


[Schofield, Science 1997; Magalhaes et al. JGR 1999]

Mesospheric CO_2 clouds



[MEx HRSC, Määttänen et al. Icarus 2010]

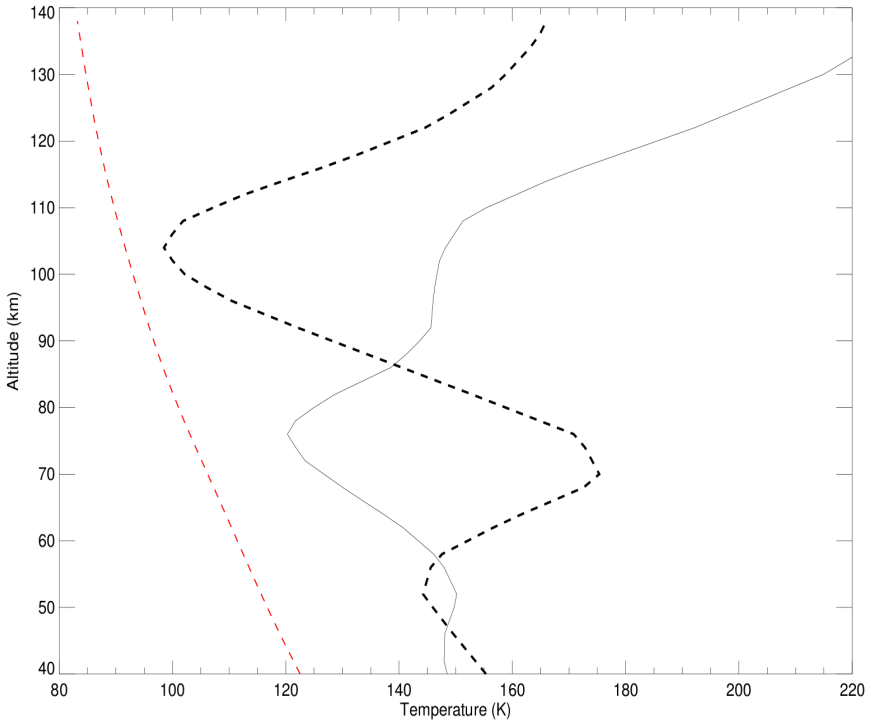


[MEx OMEGA, Montmessin et al. JGR 2007]

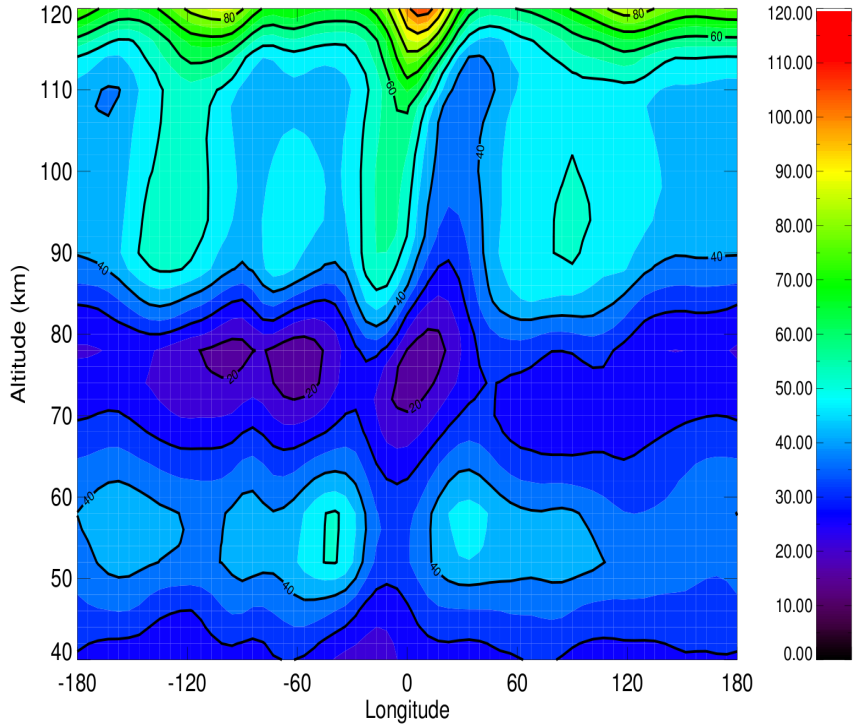
Global Circulation Modeling

Role of thermal tides in the formation of cold pockets propitious to CO_2 clouds

T profiles night (dash) / day (full)



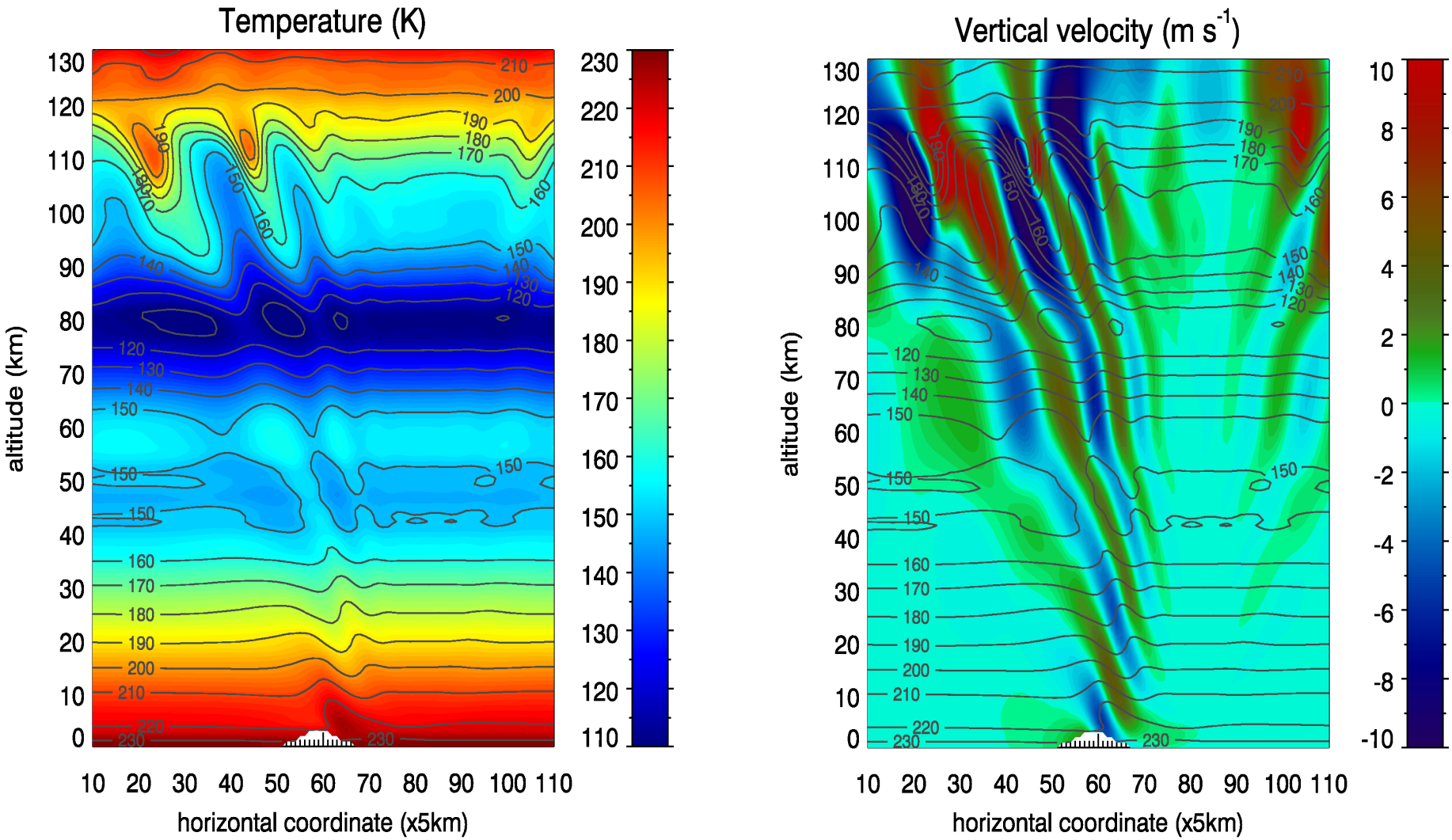
Spatial variations T - Tsat



[L_s is $0 - 30^{\circ}$, latitude and longitude 0°. Gonzalez-Galindo et al. Icarus 2011]

3D GW simulation with 30 m s^{-1} rightward wind

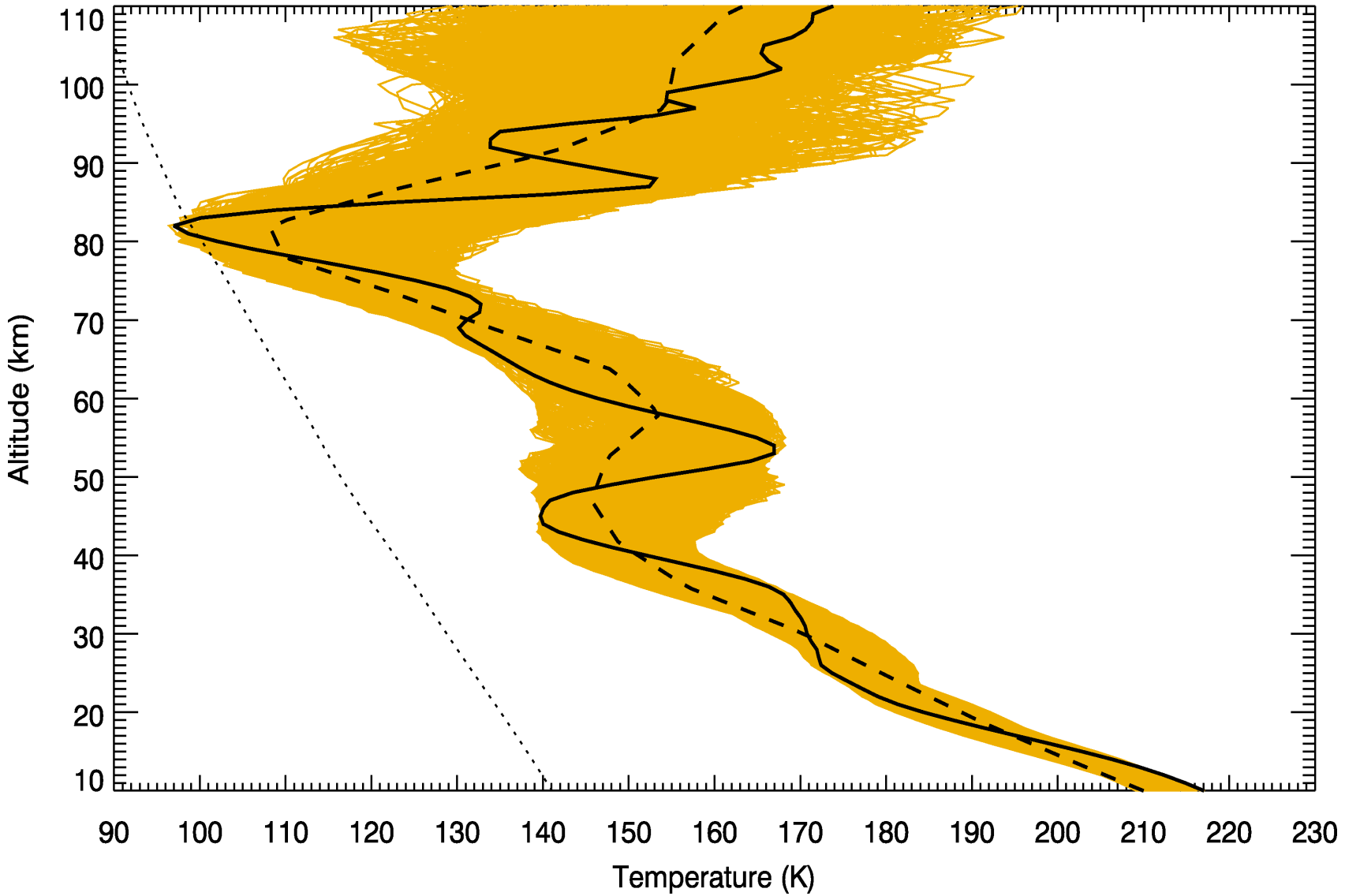
$\delta x = 5km$, $\delta z \sim 1km$, model top 180 km with 50-km sponge layer



[Spiga et al. GRL 2012]

Gravity waves & subcondensation pockets

Full: Large-scale profile. Dashed and envelope: + resolved mesoscale waves

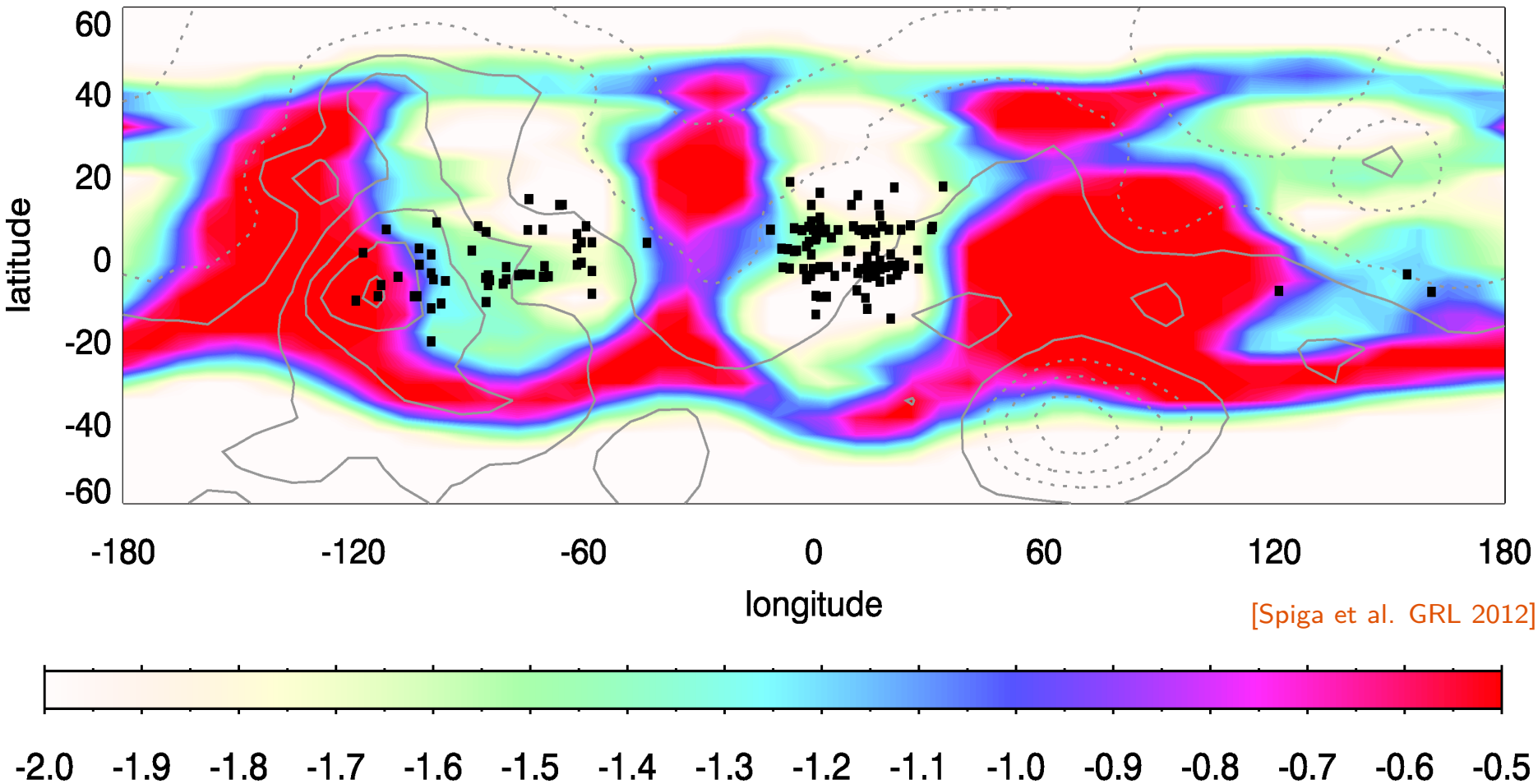


[Spiga et al. GRL 2012]

Spatial variations of GW filtering $\rightarrow \mathcal{S}$ maps

Northern spring CO_2 clouds

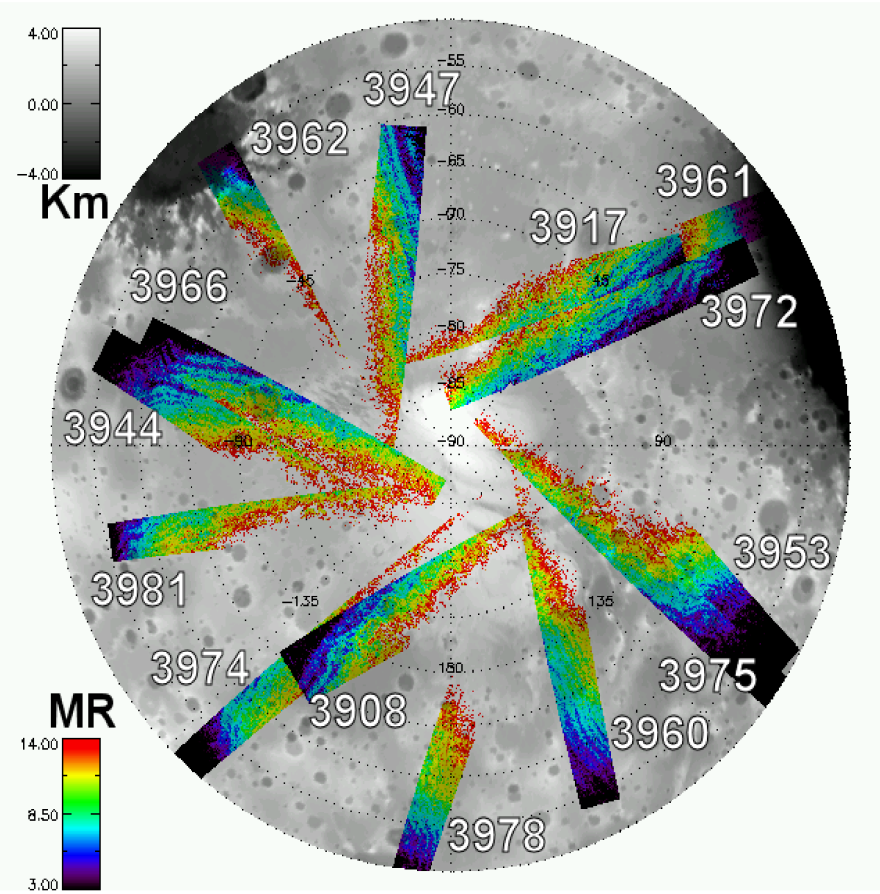
Regions/seasons with observed mesospheric CO_2 clouds feature propitious atmospheric conditions for GW propagation.



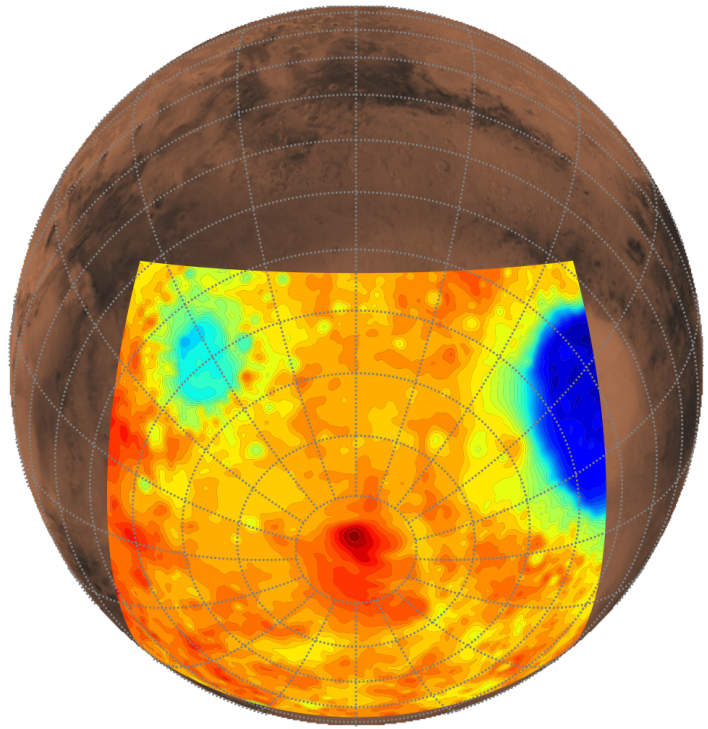
Outline

Mapping of gravity waves by O_2 airglow

OMEGA airglow observations



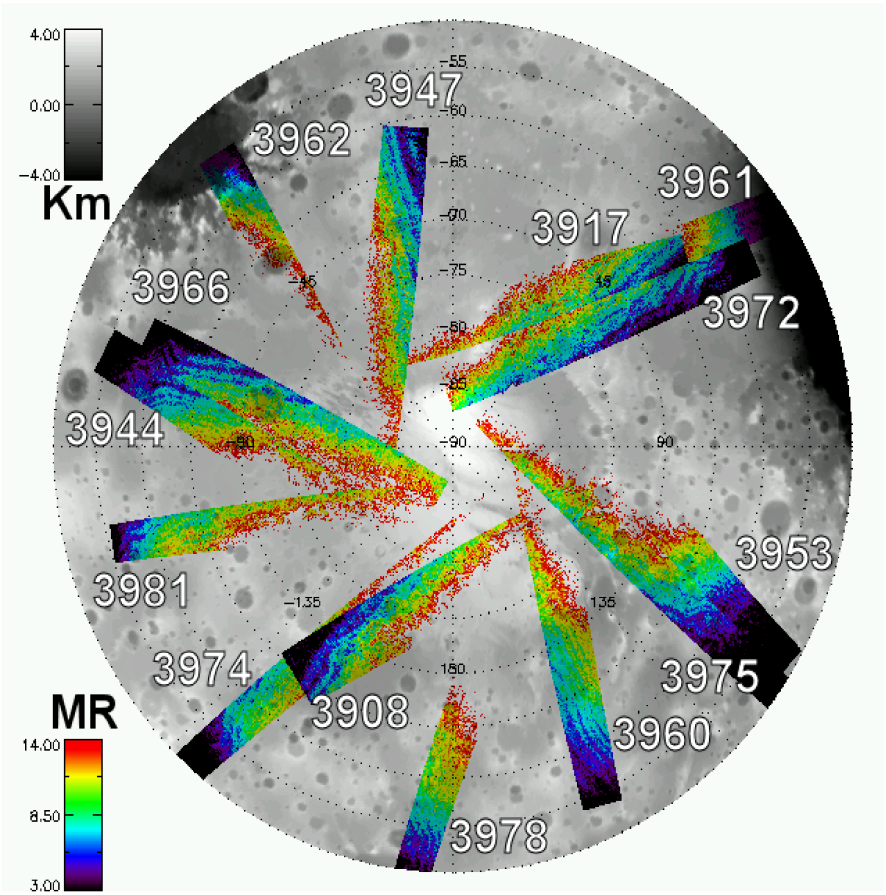
Mesoscale polar modeling



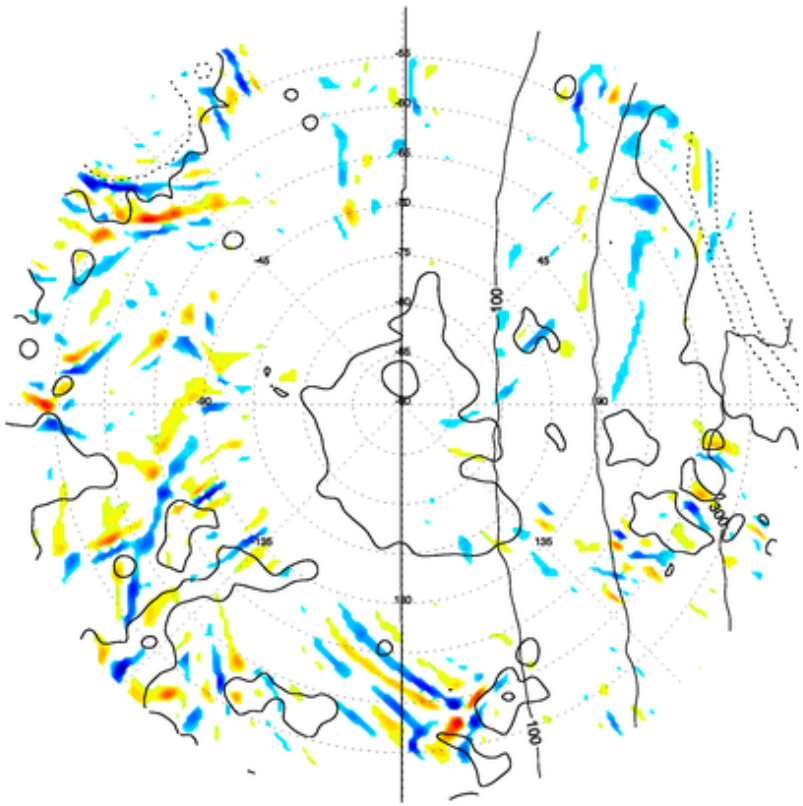
[Altieri et al. JGR 2012]

Mapping of gravity waves by O_2 airglow

OMEGA airglow observations

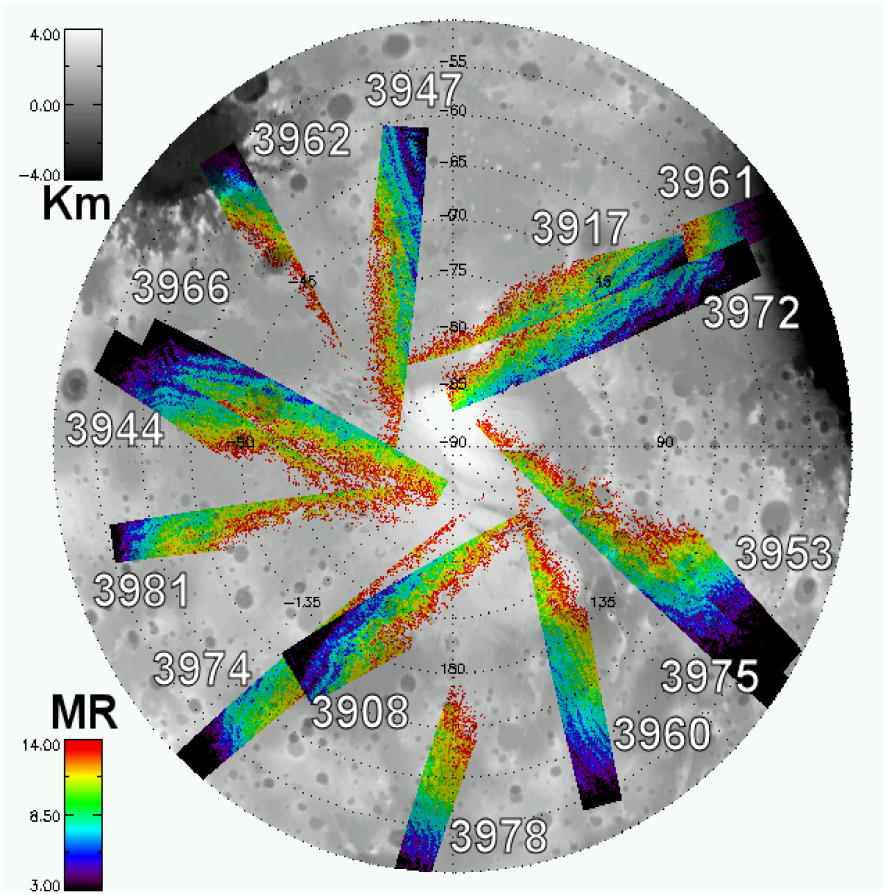


Mesoscale polar modeling

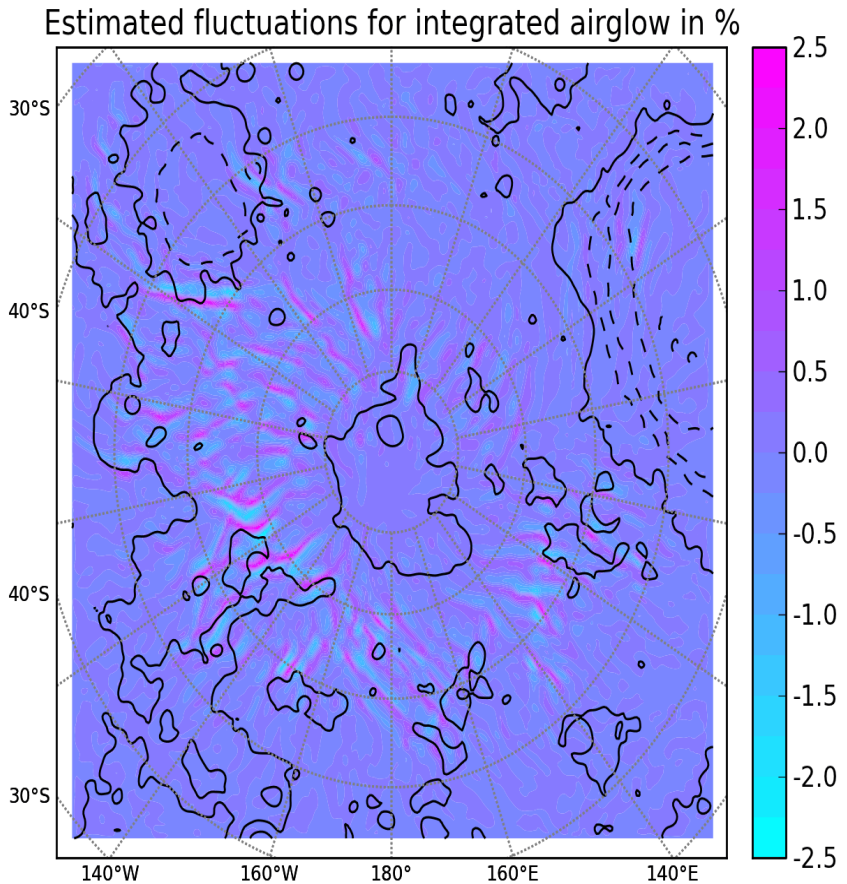


Mapping of gravity waves by O_2 airglow

OMEGA airglow observations



Mesoscale polar modeling

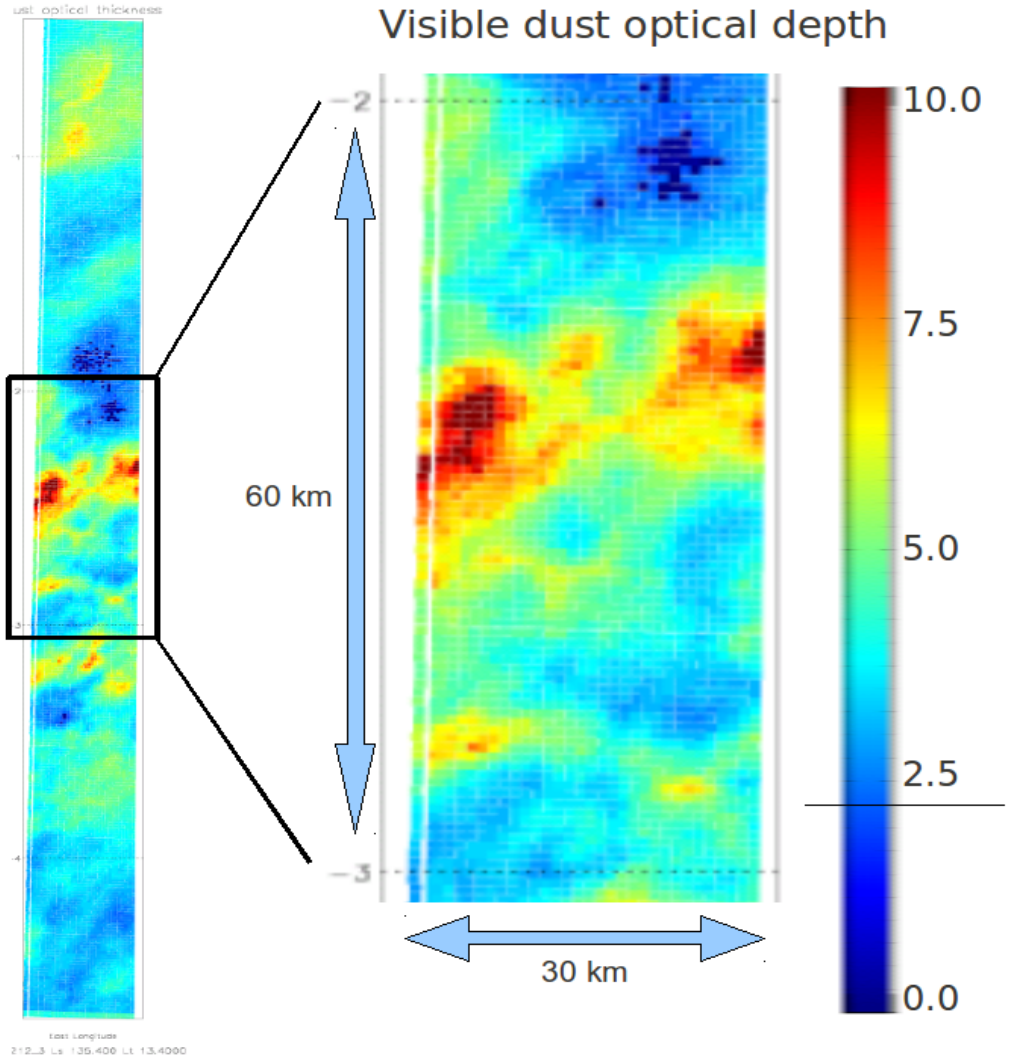


[Altieri et al. JGR 2012]

Outline

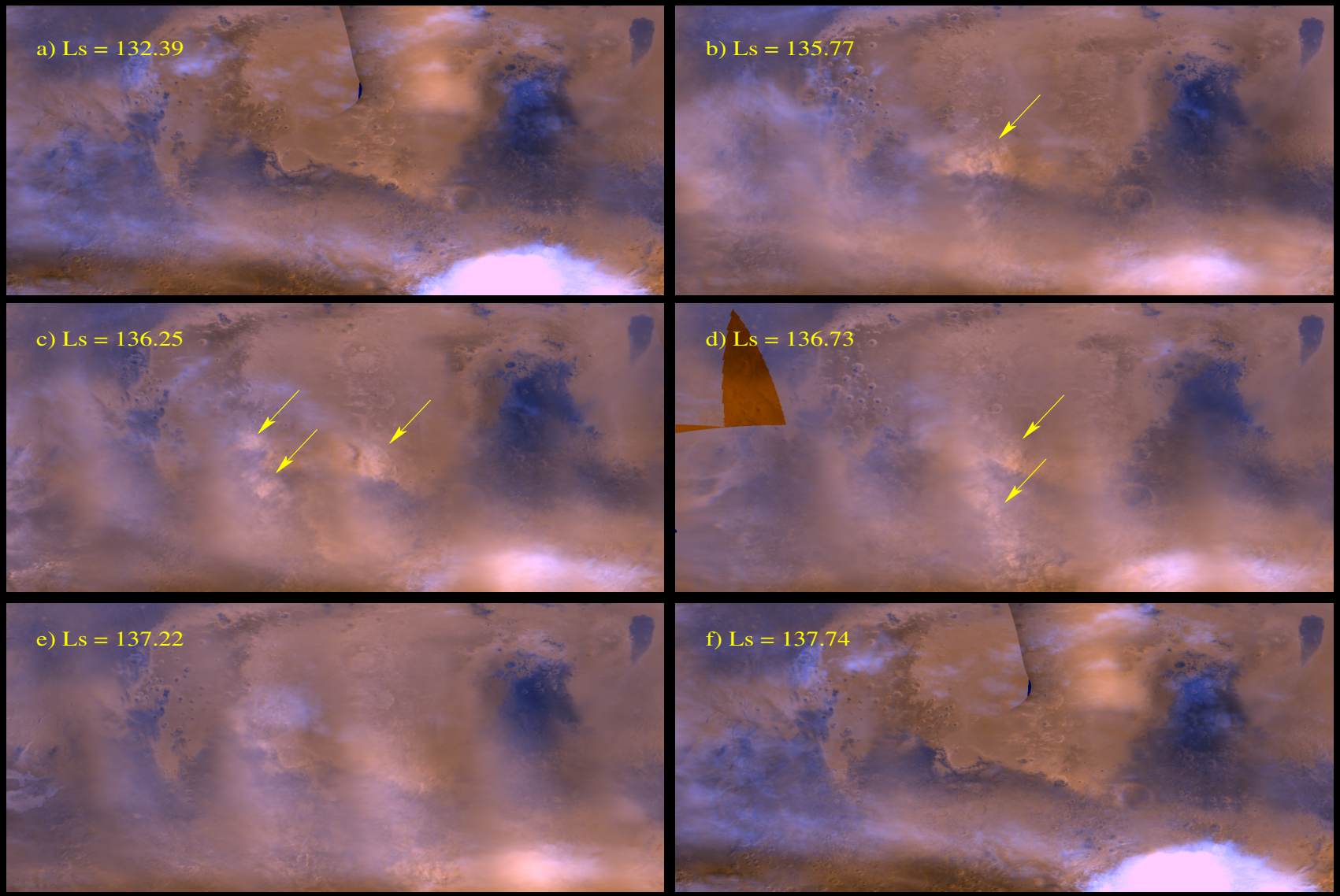
The "OMEGA storm" witnessed by Mars Express

A complex, cumuliform, dust storm in Terra Meridiani at $L_s = 135°$



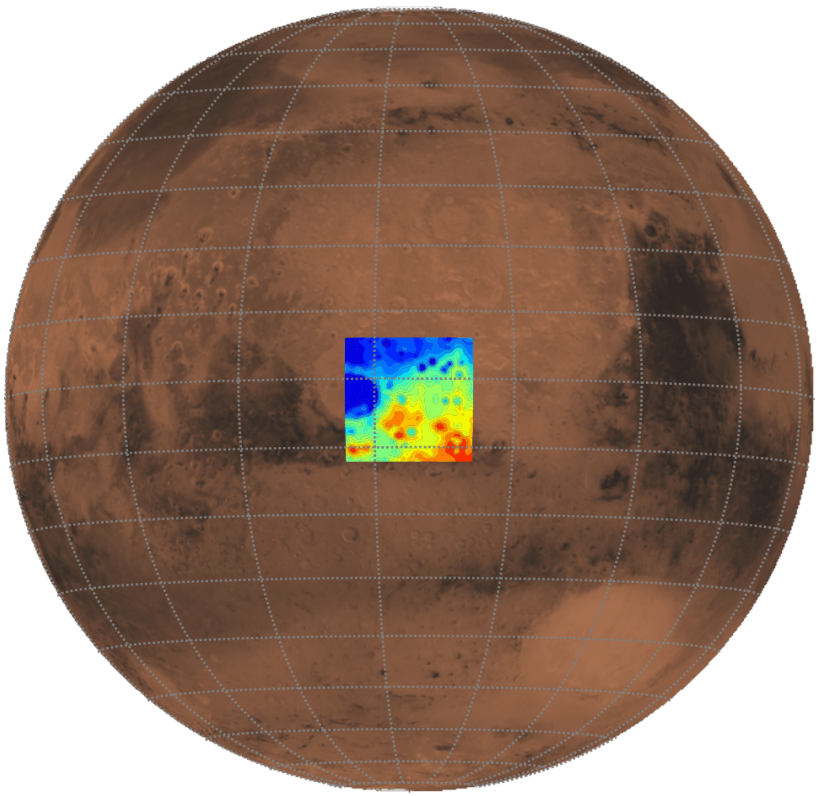
[Adapted from Määttänen et al. Icarus 2009]

MOC images before, during, after "OMEGA" storm



[Image built from Mars daily global images downloaded in the "Mars Climate Center" website hosted by Ashima Research]

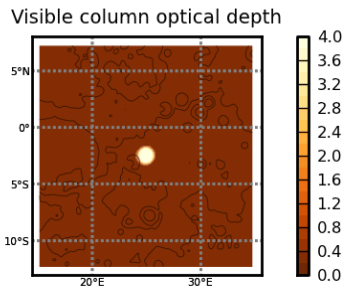
Mesoscale simulation

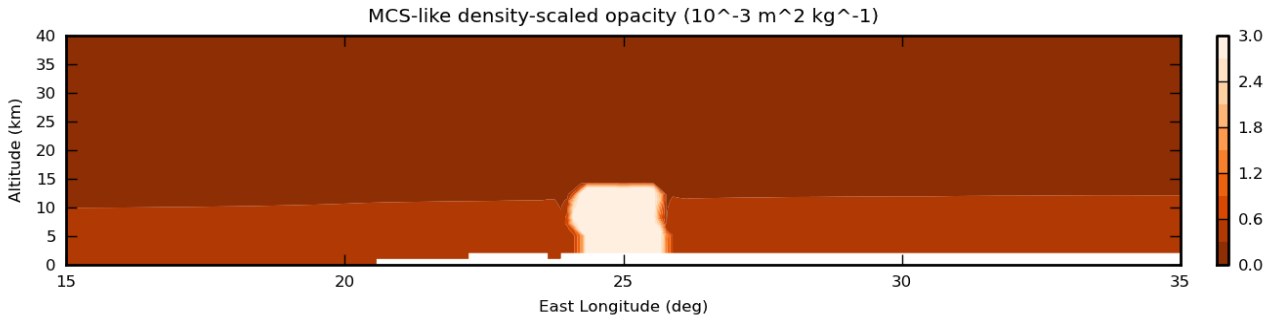


- LMD-MMM with tracers [*Spiga & Forget* JGR 2009]
- Dust radiative transfer and 2-moment transport scheme [*Madeleine et al.* JGR 2011]
- Recent dust optical indices [*Wolff et al.* JGR 2009]

- Terra Meridiani site [OMEGA]
- $181 \times 181 \times 101$ grid points
- 7 km horizontal grid spacing
- $\sim$ 700 m vertical grid spacing with model top at 1 Pa

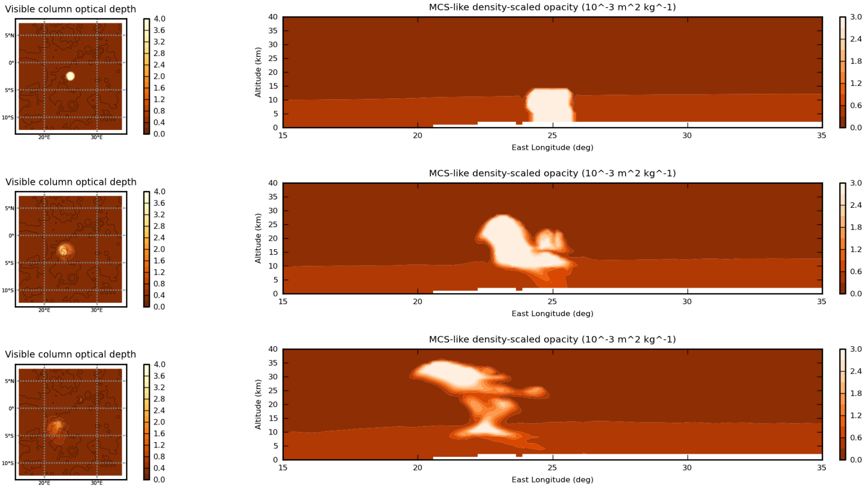
Afternoon. Local time 1400





[Spiga et al. JGR 2012, arxiv 1208.5030]

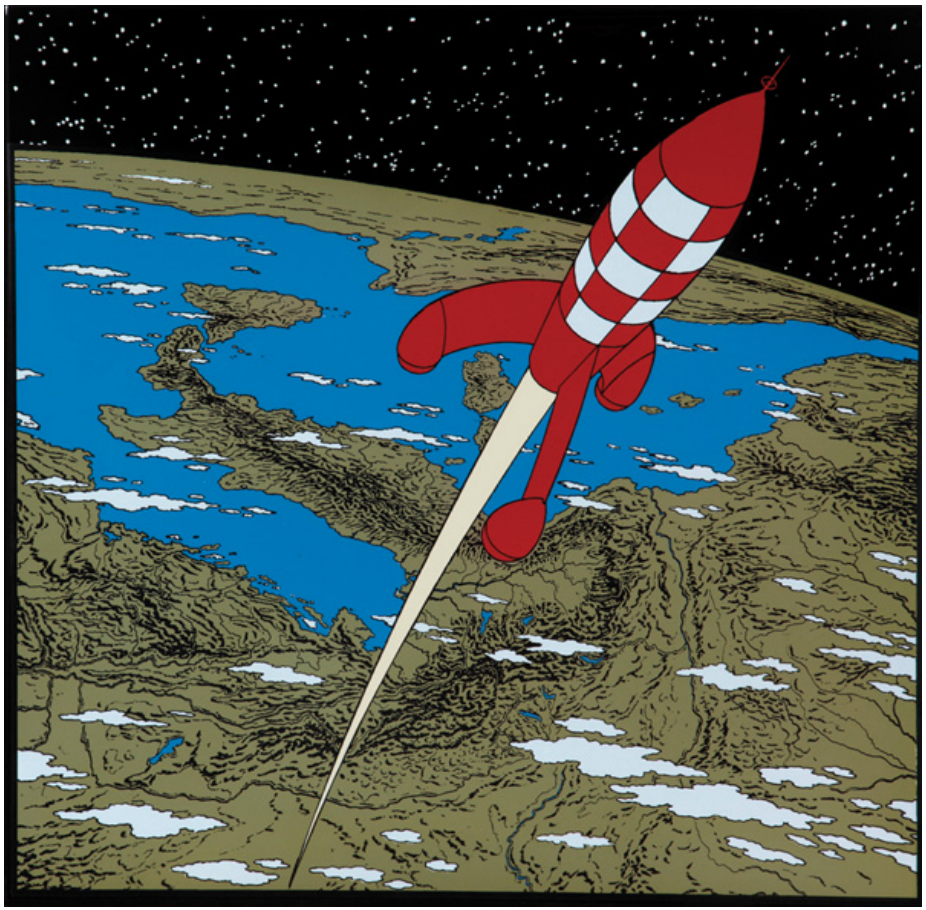
Afternoon. Local times 1400, 1600, 1800

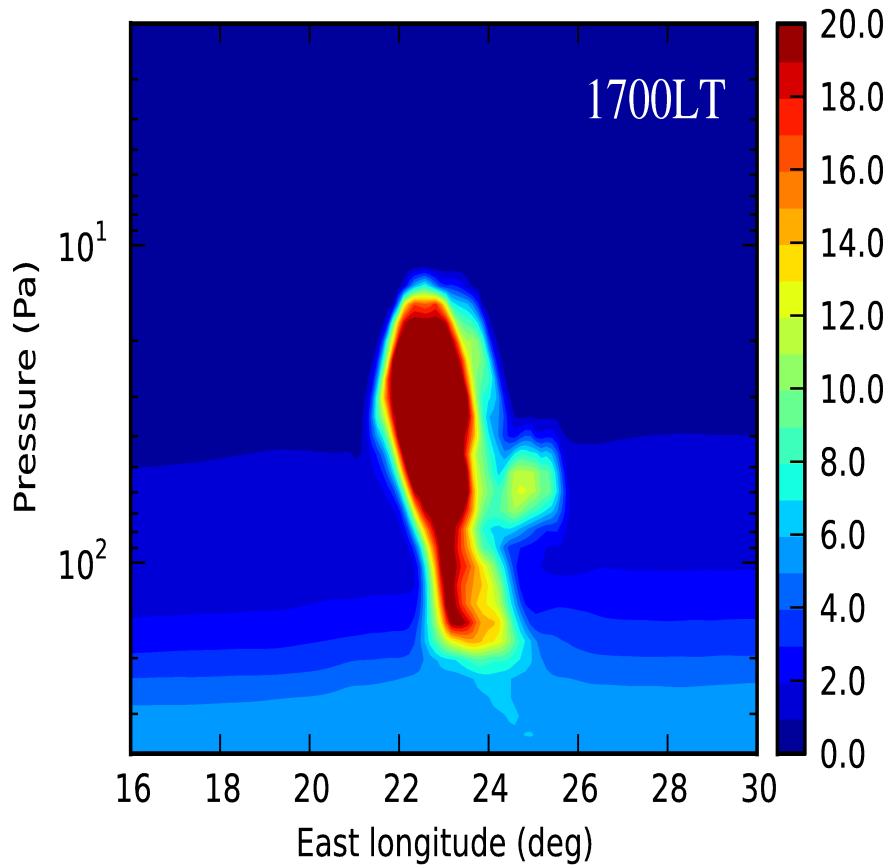


[Spiga et al. JGR 2012, arxiv 1208.5030]

“Rocket dust storms”!

Rapid and powerful vertical transport of dust particles

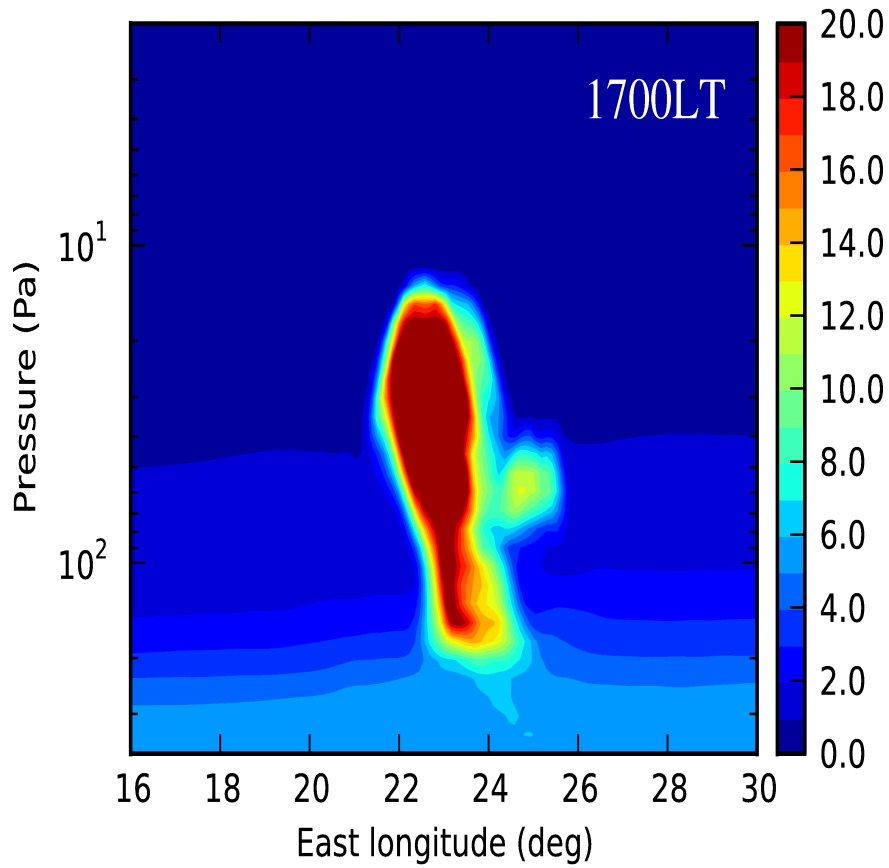




[Left picture extracted from Hergé Casterman 1954]

... or: "conio-cumulonimbus"

Dust-driven deep convection on Mars

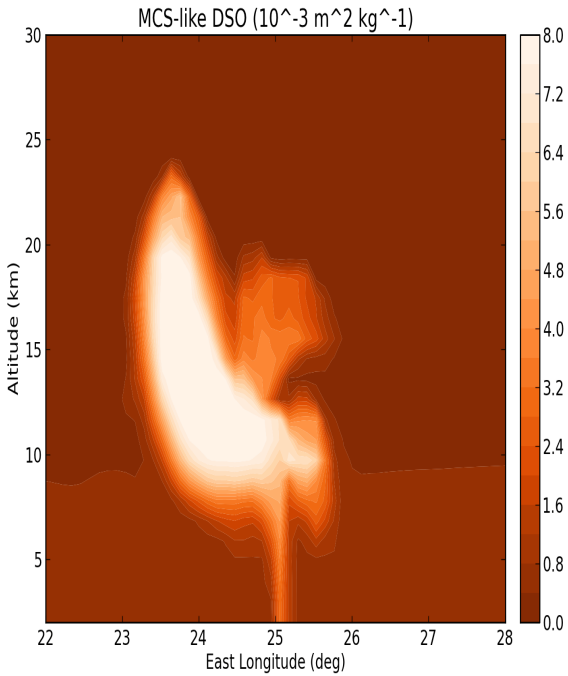


[Left picture downloaded from NOAA website]

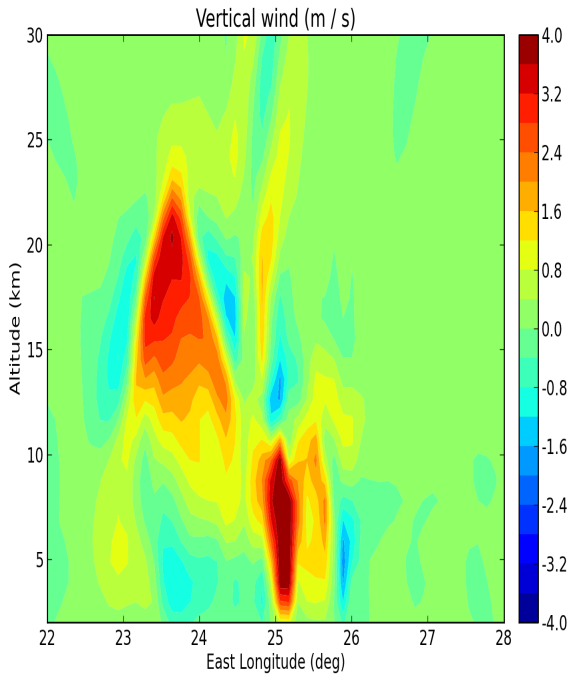
Rocket dust storm [a.k.a. conio-cumulonimbus]

Dust-driven deep convection on Mars

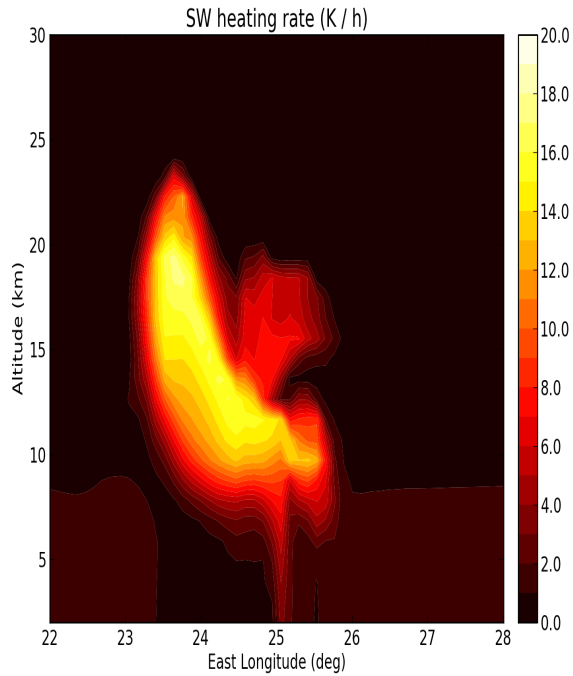
(DS) Optical depth



Vertical wind

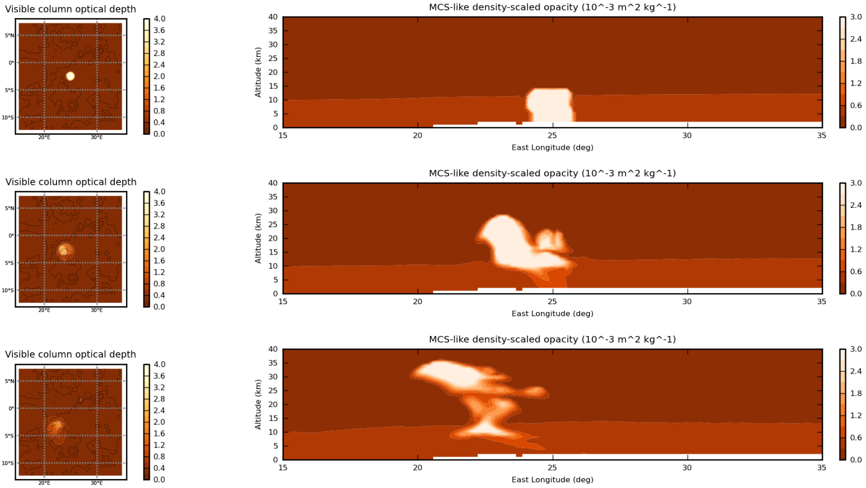


SW heating rate



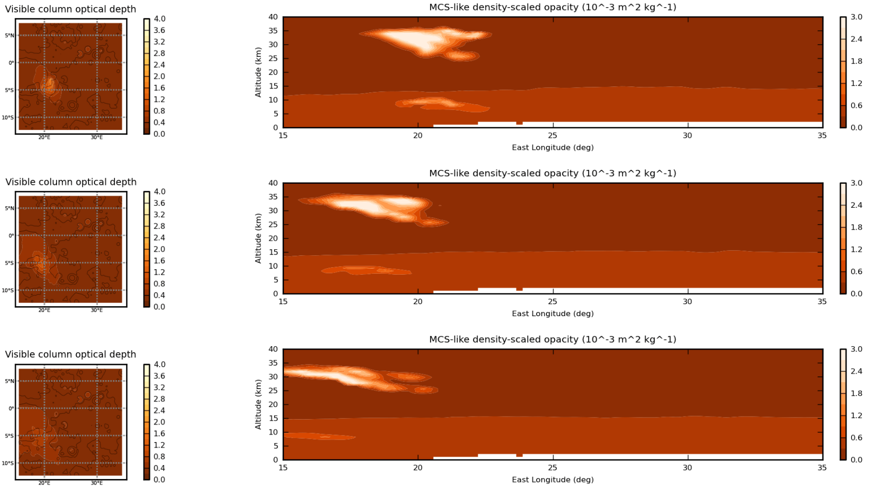
[Spiga et al. JGR 2012, arxiv 1208.5030]

Afternoon. Local times 1400, 1600, 1800



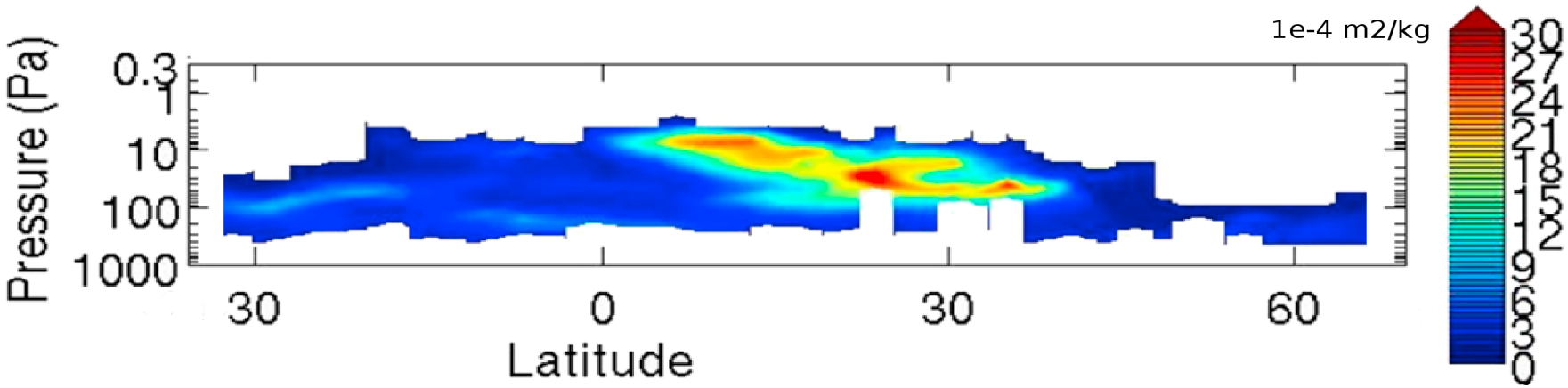
[Spiga et al. JGR 2012, arxiv 1208.5030]

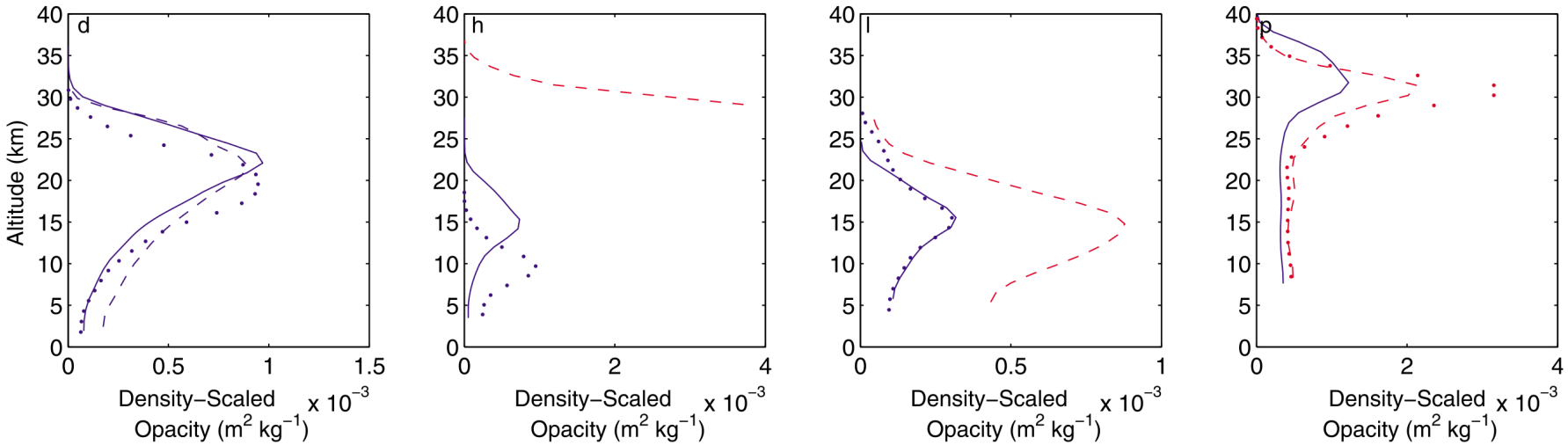
Evening. Local times 2000, 2200, 0000



[Spiga et al. JGR 2012, arxiv 1208.5030]

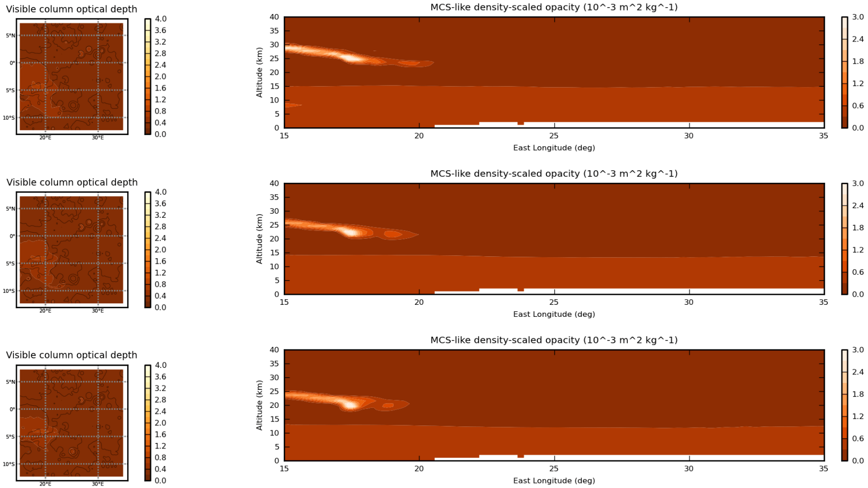
Detached layers of dust: MCS observations





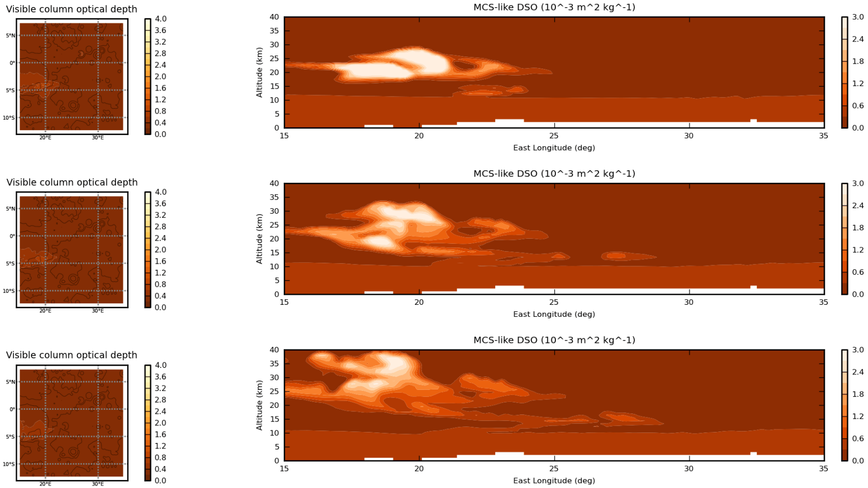
[Heavens et al. JGR 2011 (part 1 & 2)]

Nighttime. Local times 0200, 0400, 0600



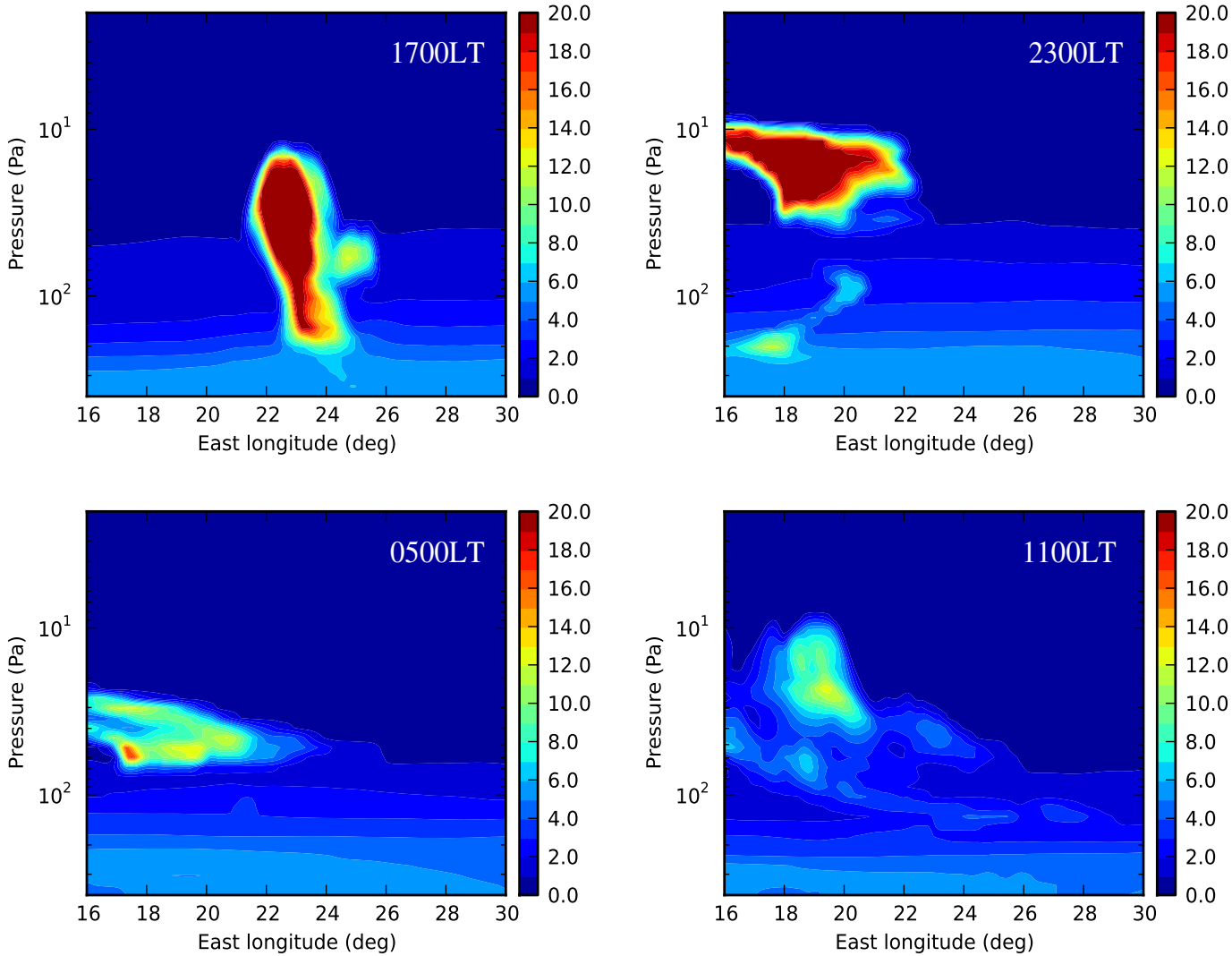
[Spiga et al. JGR 2012, arxiv 1208.5030]

Morning. Local times 0800, 1000, 1200



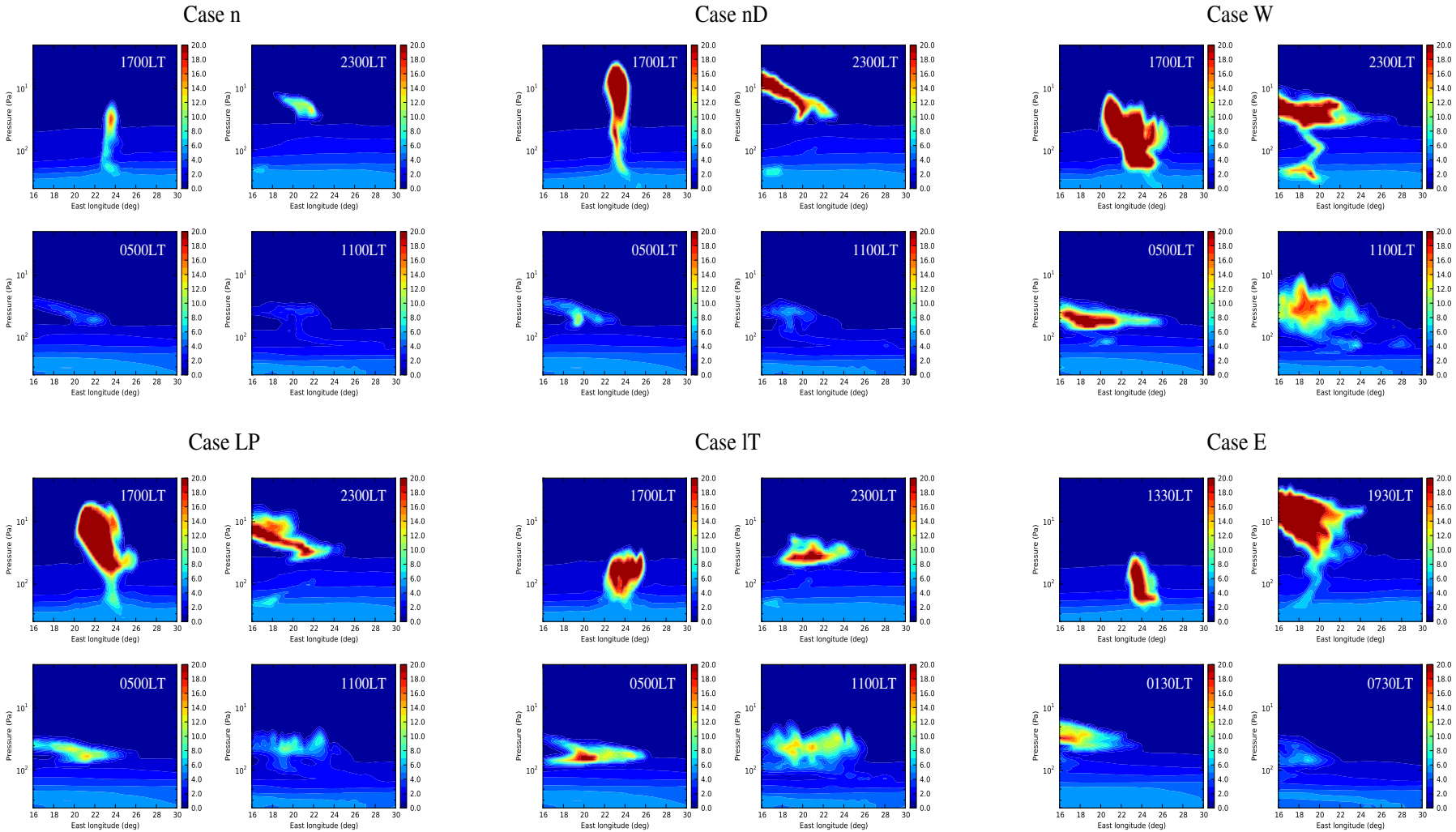
[Spiga et al. JGR 2012, arxiv 1208.5030]

From rocket dust storm to detached dust layers



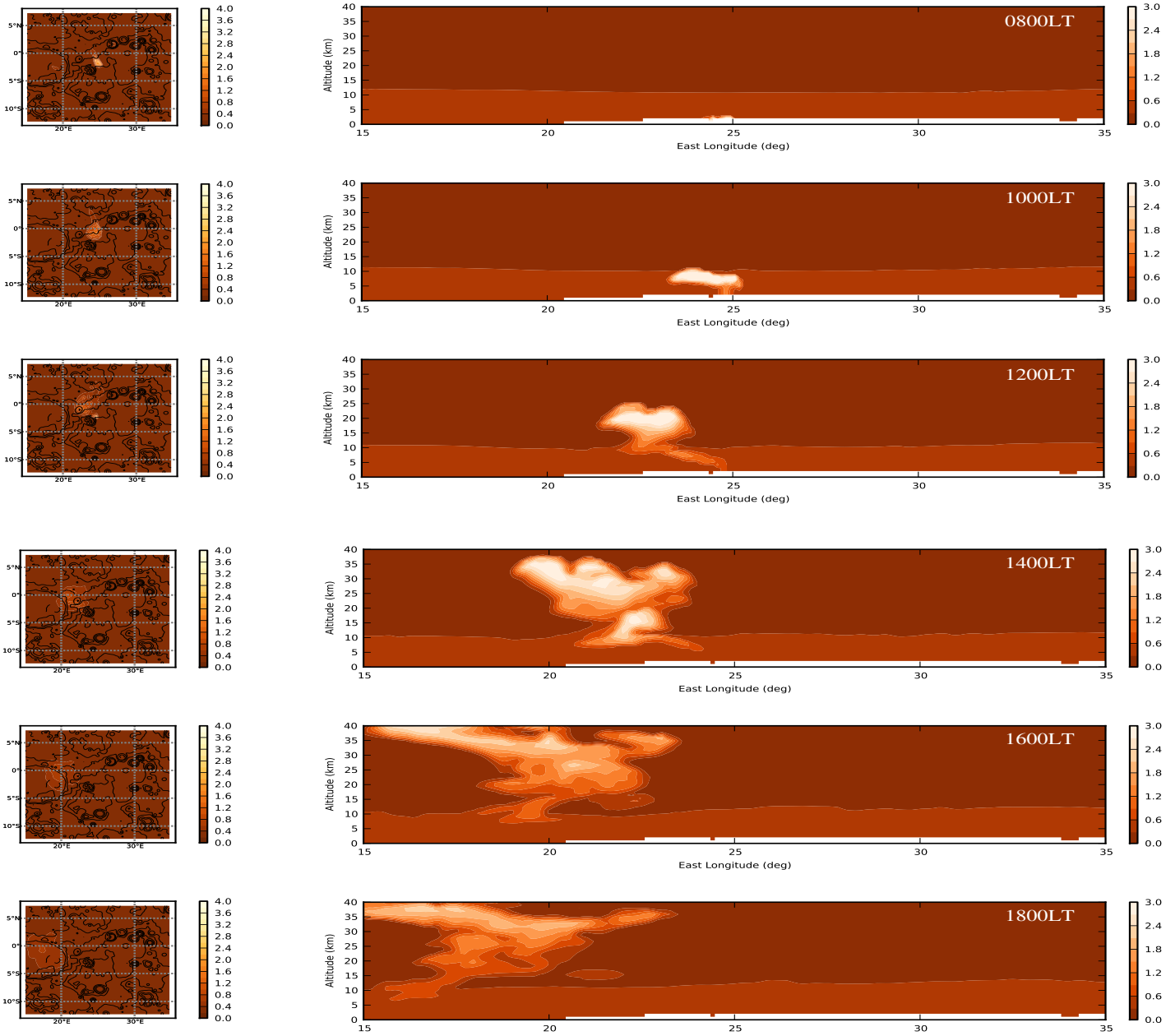
[Spiga et al. JGR 2012, arxiv 1208.5030]

Sensitivity study: results



[Spiga et al. JGR 2012, arxiv 1208.5030]

With simplified lifting (storm area only, $\sigma_t = 5$ mN m^{-2}, $\alpha = 2 \times 10^{-3}$ m^{-1})



Factor of variability for rocket dust storms

Major

- Incoming solar radiation: the further the dust disturbance from subsolar latitudes, the weaker the convection.
- Background dustiness: the less dusty the atmosphere, the lower the environmental temperature, the stronger the convection.

Less crucial

- Atmospheric lapse rate: A more stable profile would tend to inhibit convective ascent of rocket dust storms.
- Wind shear: strong vertical shear impact vertical extent.

Necessary conditions

- Dust particles available for lifting.
- Lifting threshold reached.

Variability of subsequent detached layers of dust

High-altitude detached dust layers by rocket dust storms would

- ☞ be particularly discernible in low-latitudes from late N winter to late N summer ("high-altitude tropical dust maximum")
- ☞ correlate with interannual variability of "early dust storm season"
- ☞ yield significant longitudinal variability (fast mesoscale processes)
- ☞ create enriched layers within background dust layer in dusty season, instead of "truly detached" layers in clear seasons

$\Rightarrow$ scenario consistent with MCS measurements

[McCleese et al. JGR 2011, Heavens et al. JGR 2011 part 1 & 2]

Implications of dusty deep convection on Mars

In addition to the impact on dust distribution:

- ☞ importance of mesoscale processes
- ☞ impact on global circulations (heat & momentum budget, predictability, planetary waves); GCM parameterization needed!
- ☞ impact on regional/global dust storms and their dynamics;
- ☞ vertical transport of water vapor and chemical species;
- ☞ generation of strong electric fields;
- ☞ source of gravity waves;
- ☞ atmospheric hazard for robotic and human exploration;
- ☞ comparative planetology perspectives.

Outline

Rich mesoscale and microscale meteorology!

- ☞ Powerful slope winds $\Rightarrow$ surface budget: heat, volatiles, ...
- ☞ PBL convection: not-so-shallow, radiatively controlled ($\neq$ Earth)
- ☞ Gravity waves: troposphere and mesosphere ($\Rightarrow$ CO_2 clouds)
- ☞ Rocket dust storms: radiatively-induced deep convection

Selected references and contact

- ☞ JGR 2009, QJRMS 2010, Icarus 2011, GRL 2012, JGR 2013
- ☞ PDFs available `http://www.lmd.jussieu.fr/~aslmd`
- ☞ E-Mail `aymeric.spiga@upmc.fr`
- ☞ Twitter `@aymeric_spiga`