Mesoscale and microscale modeling for Mars (and a bit of Venus)

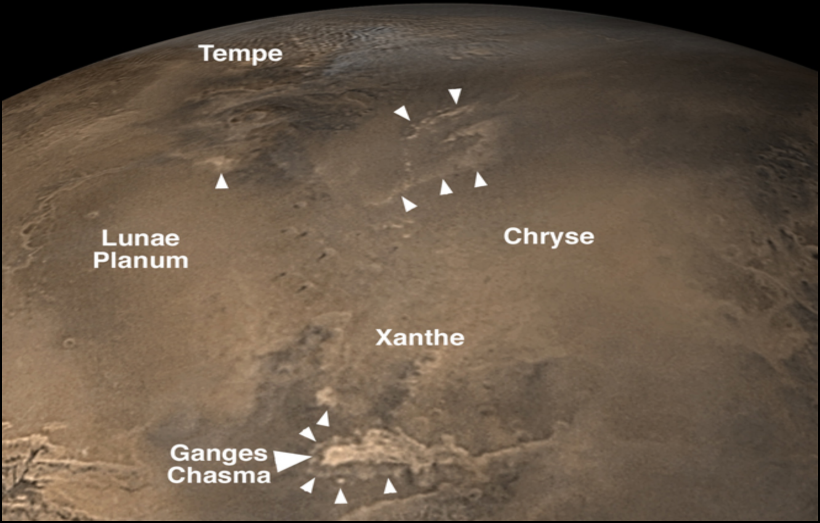
A. Spiga
and many co-authors

Franco-japanese workshop on modeling planetary atmospheres
May 12, 2015

Outline

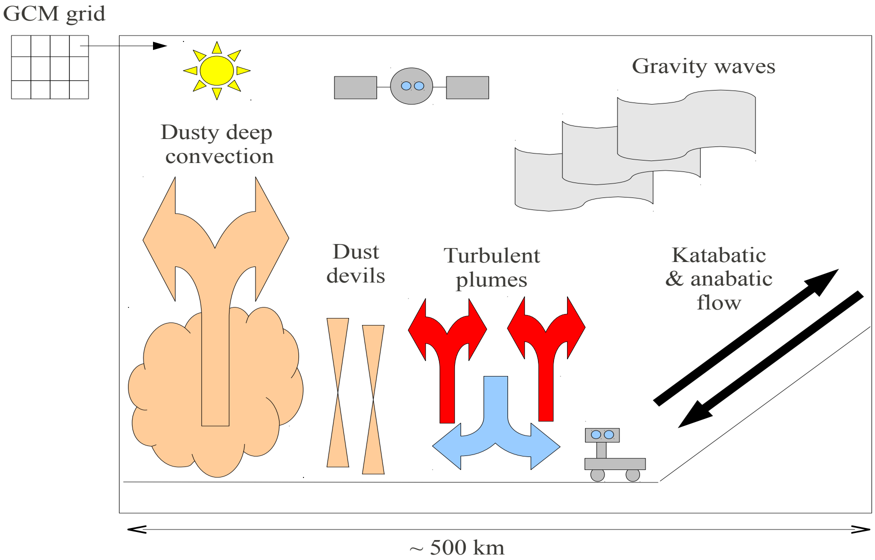
Outline

The Martian mesoscale "zoo"

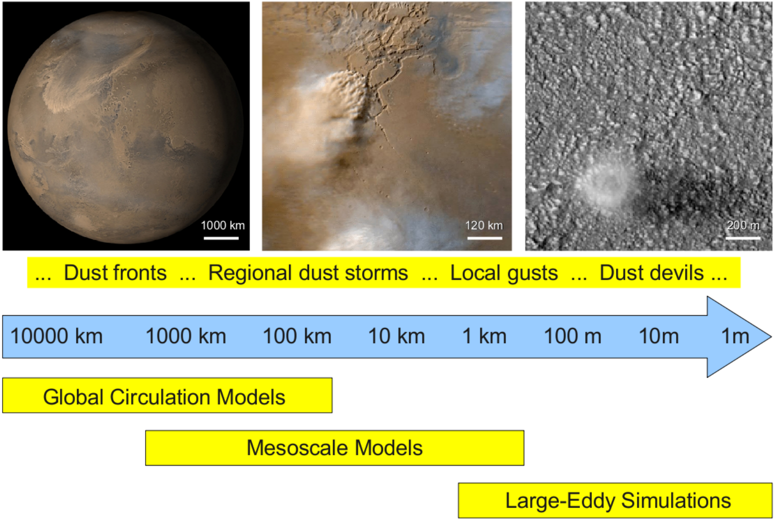


[MGS/MOC imagery, Malin Space Science Systems, 02/2002]

Processes left unresolved at GCM resolutions



Scales and Models



[Spiga and Lewis, Mars Journal 2010]

Mars Global Climate Model: LMD-MGCM

LMDz dynamical core

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

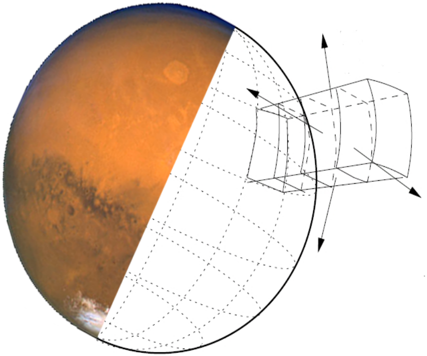
LMD Mars physics

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

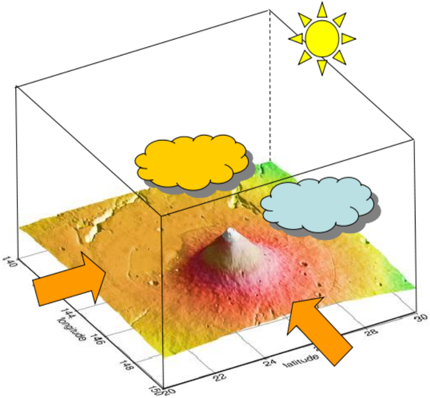
LMD Mars GCM fields

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]

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

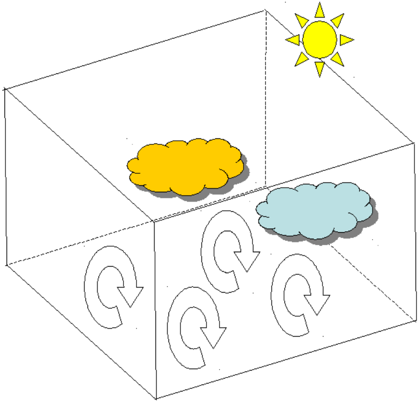
LMD Mars GCM fields

initial profiles only, periodic boundaries

MGS hi-res dataset

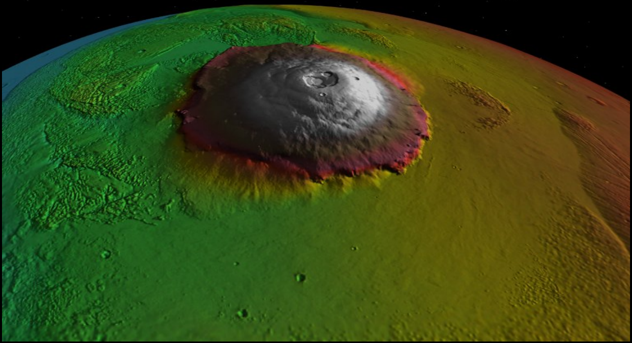
topography, thermal inertia, albedo
prescribed dust scenario

Grid spacing $\sim 100 - 10$ m



[Spiga et al., QJRMS 2010]

Outline

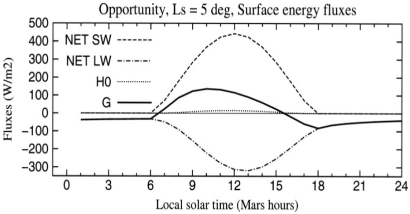


Olympus Mons

Energy budget for Martian surface

Surface energy budget

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



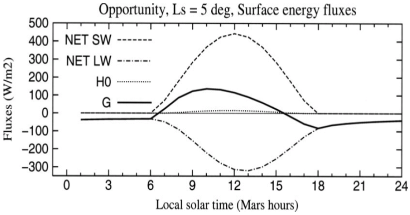
[Savijärvi and Kauhanen, QJRMS 2008]

Energy budget for Martian surface

Surface energy budget

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

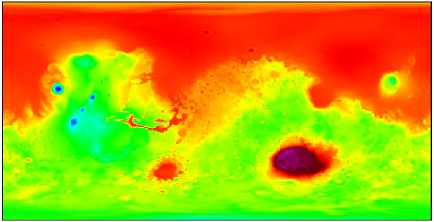
$\rightarrow$ radiative equilibrium

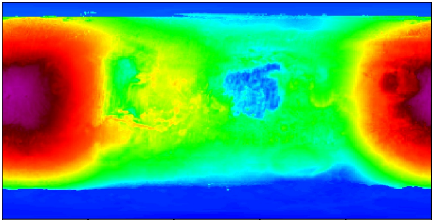


[Savijärvi and Kauhanen, QJRMS 2008]

Topography

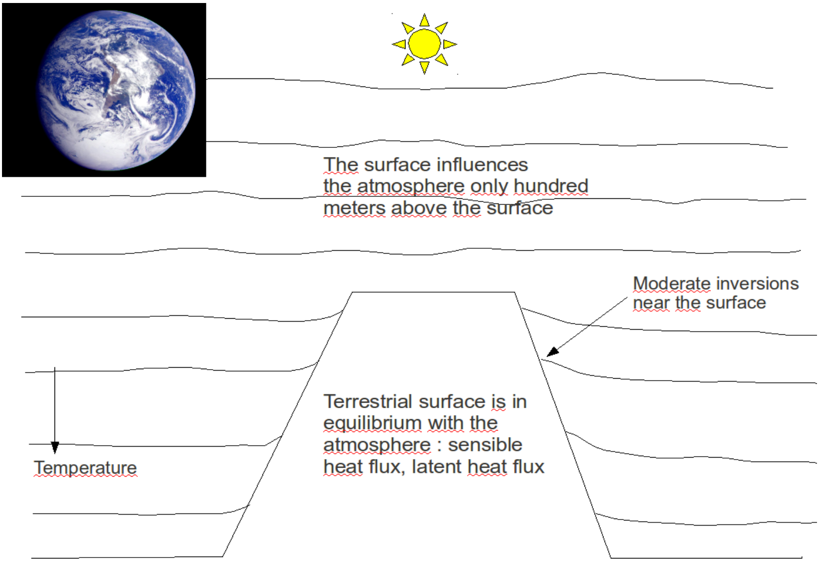
Surface temperature



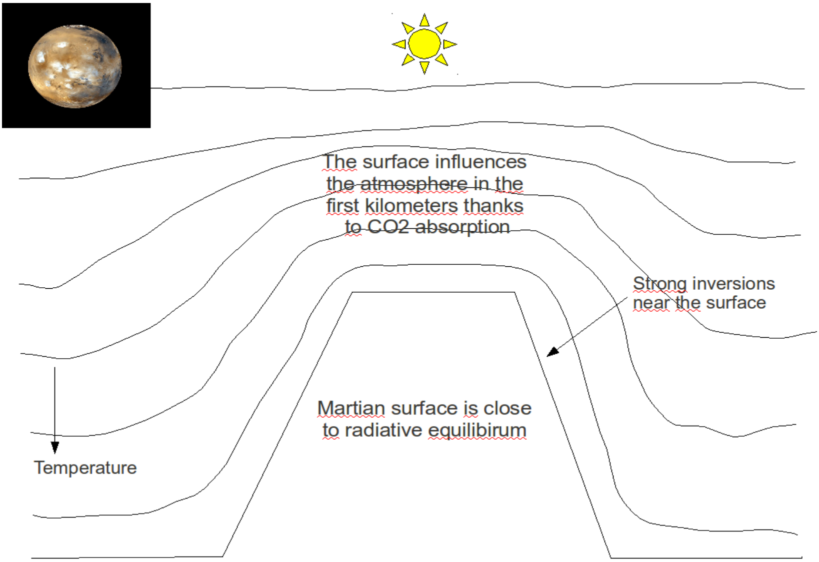


[outputs from the UK Mars GCM]

Thermal structure around a mountain on Earth

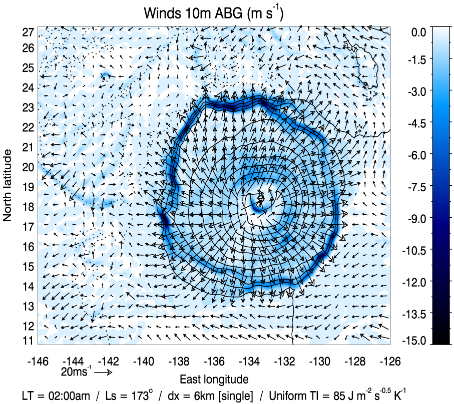


Thermal structure around a mountain on Mars

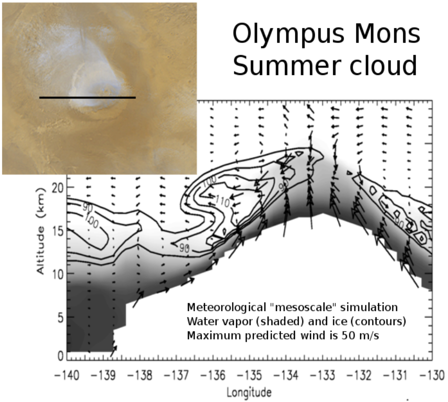


Katabatic and anabatic winds

Nighttime downslope

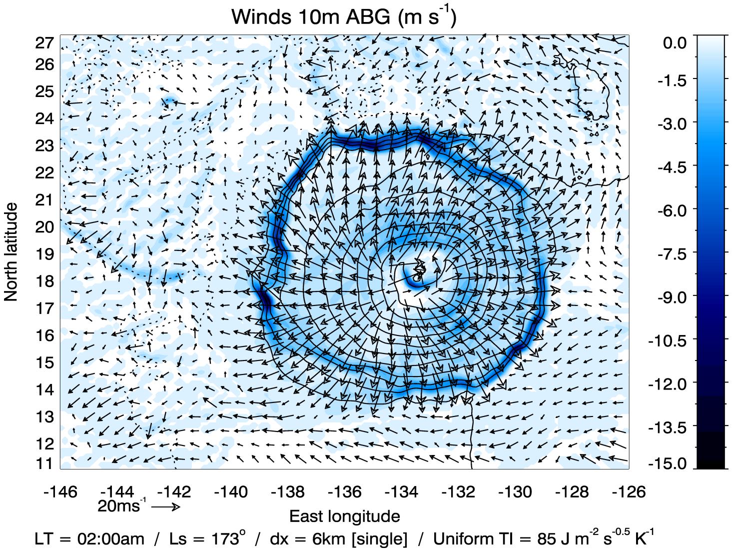


Daytime upslope



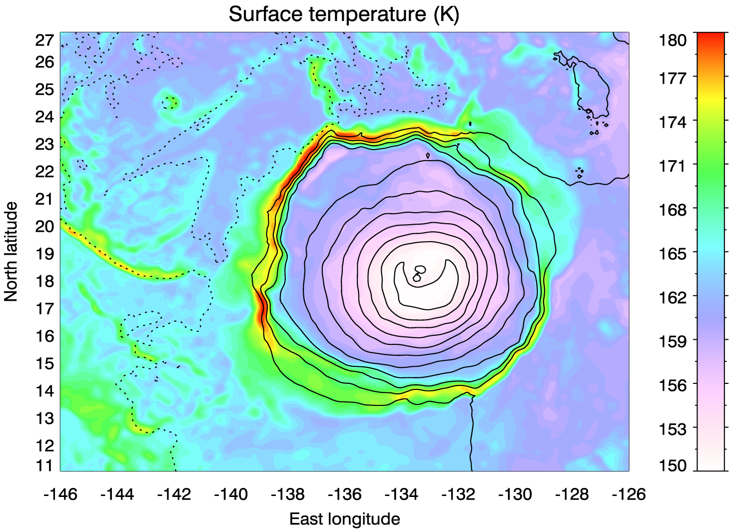
[Spiga and Forget JGR 2009; Spiga et al. Icarus 2011]

Katabatic winds over Olympus Mons



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

Nighttime "warm katabatic ring"

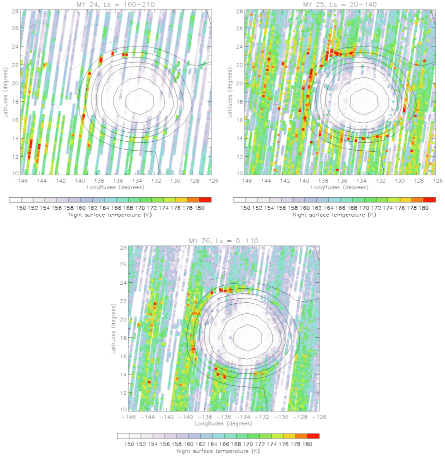


LT = 02:00am / Ls = 173^{o} / dx = 6km [single] / Uniform TI = 85 J m^{-2} s$^{-0.5}$ K^{-1}

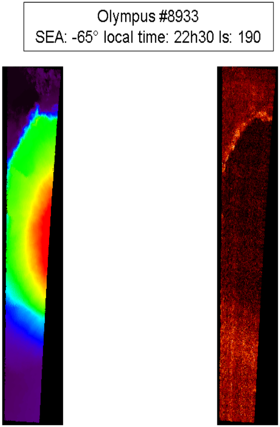
[Spiga et al., Icarus 2011]

Surface temperature at night, Olympus Mons

MGS / TES



OMEGA



Altimetrie Mola

Omega 5 µm

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

Katabatic wind over Antarctica

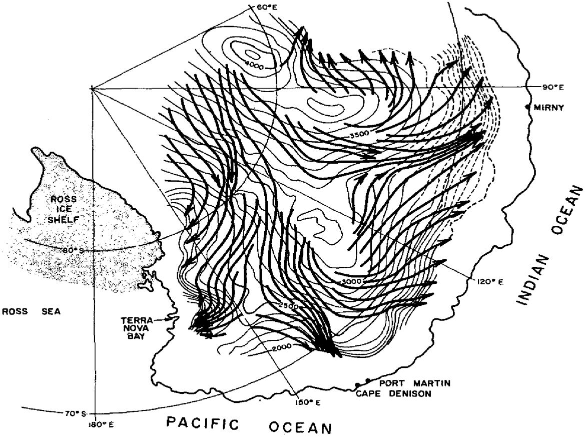
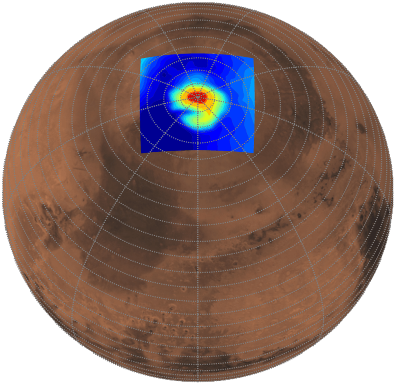
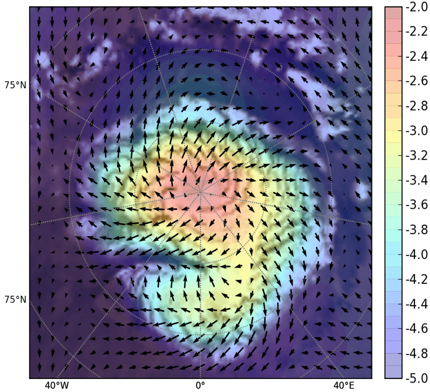


FIG. 2. Time-averaged winter flow pattern over the surface of the Antarctic based on model wind calculations of Parish (1982).

[Parish et al., 1983]

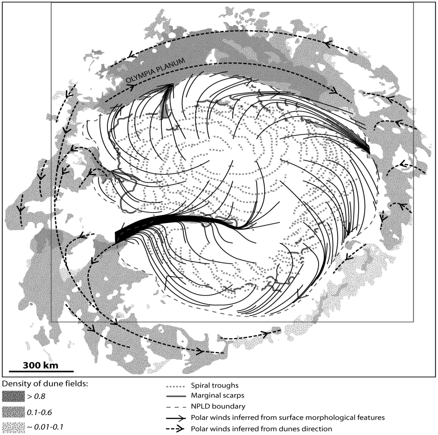
Near-surface regional winds: northern polar cap



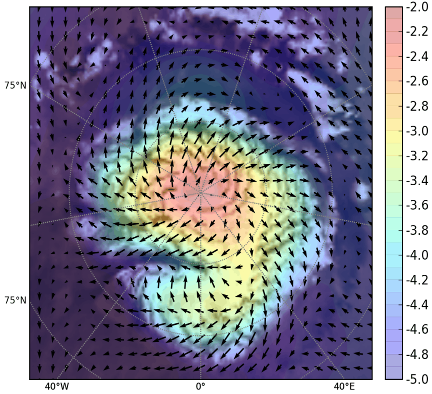


Near-surface regional winds: northern polar cap

Frost streak and dune mapping



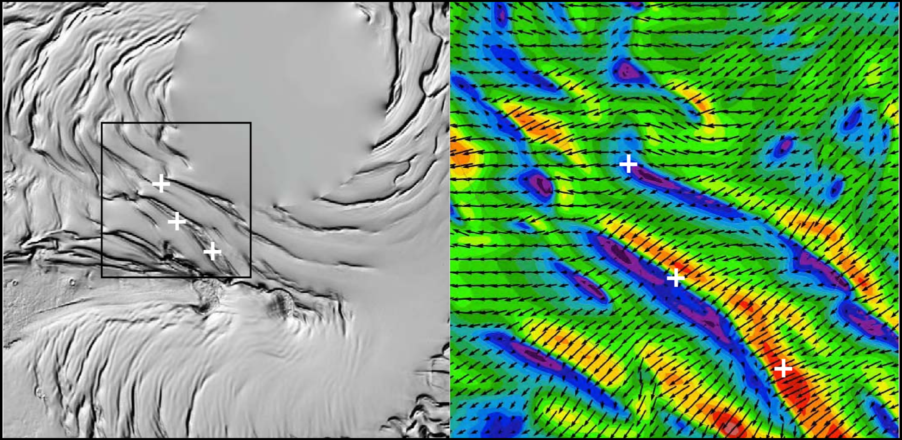
Mesoscale modeling



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

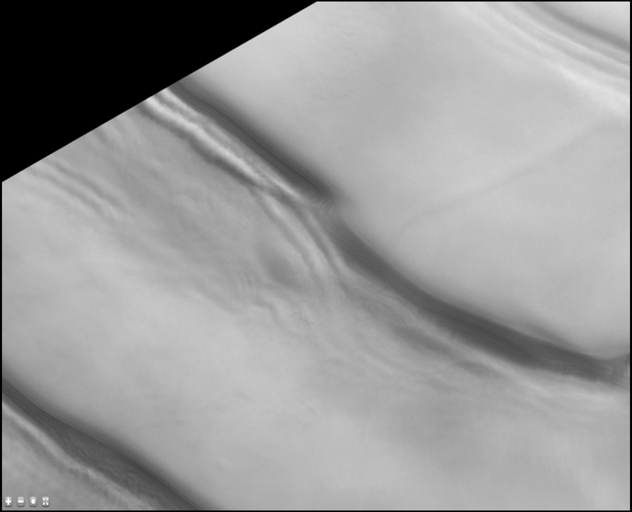
Troughs influence katabatic winds

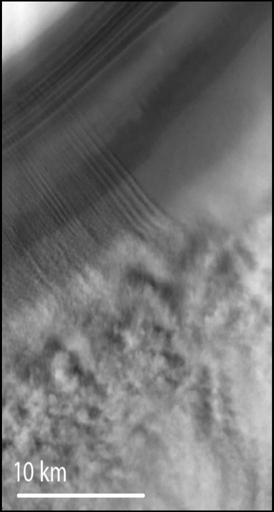
Results from LMD mesoscale modeling with resolution 2 km



[Smith et al. JGR 2013]

Polar trough clouds on Mars

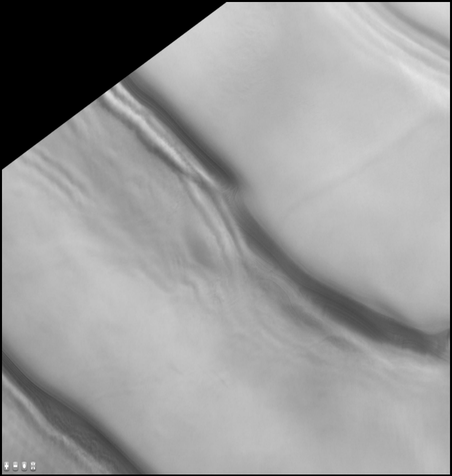




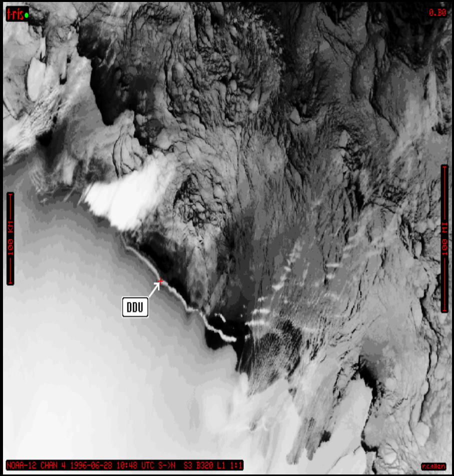
[Smith and Holt Nature 2010, Smith et al. JGR 2013]

Katabatic flow jumps [a.k.a. Loewe phenomena]

Mars NPLD troughs



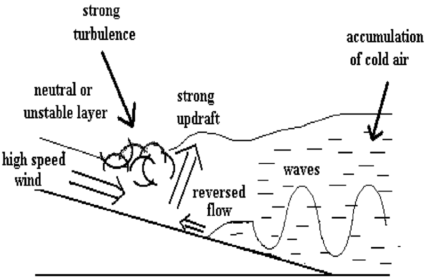
Earth Antarctica coasts



[Left: HRSC image from Smith et al. JGR 2013; Right: NOAA satellite image.]

Katabatic jumps [a.k.a. Loewe phenomena]

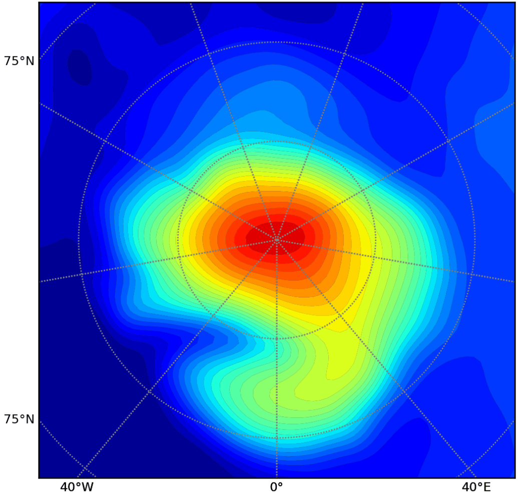
[Australian Antarctic Division website]



[Yu and Cai BLM 2006; see also Pettré and André JAS 1991]

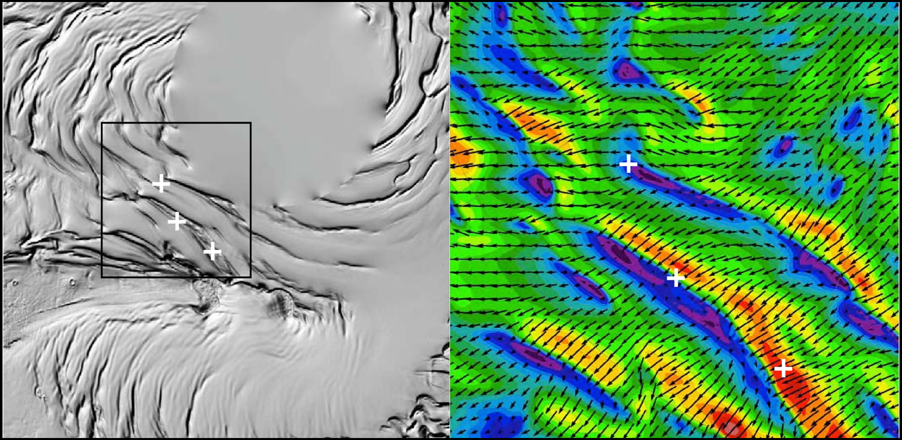
Five nested domain zooming in one polar trough!

Horizontal resolutions: 20 km / 6.7 km / 2.2 km / 740 m / 250 m



Troughs influence katabatic winds

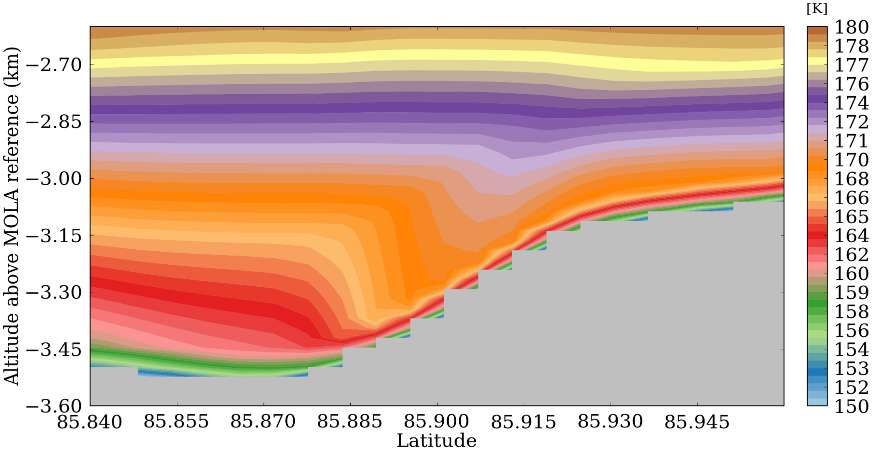
Results from LMD mesoscale modeling with resolution 2 km



[Smith et al. JGR 2013]

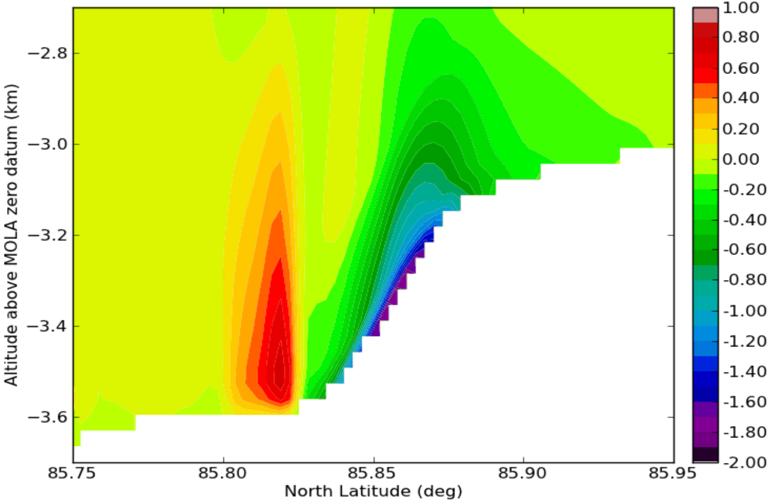
Hi-res modeling of katabatic jumps in troughs

Potential temperature (traces adiabatic motions)



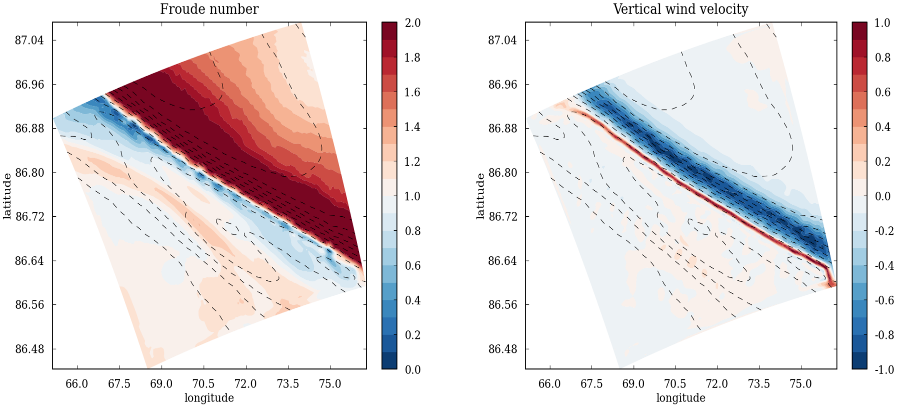
3D simulations of katabatic jumps in polar troughs

Vertical velocity at longitude -43°E in nest 5

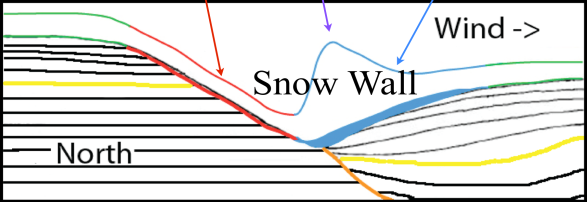


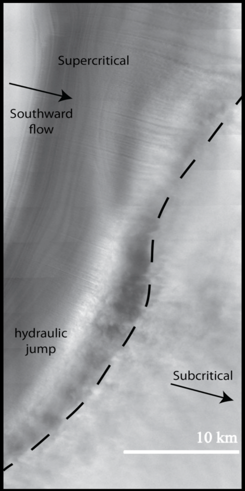
Hi-res modeling of katabatic jumps in troughs

maps are shown about 100m above local surface



Interpretation of trough clouds





V12295001

Red: Erosion, sublimation
Blue: Deposition, snowfall
Green: No change

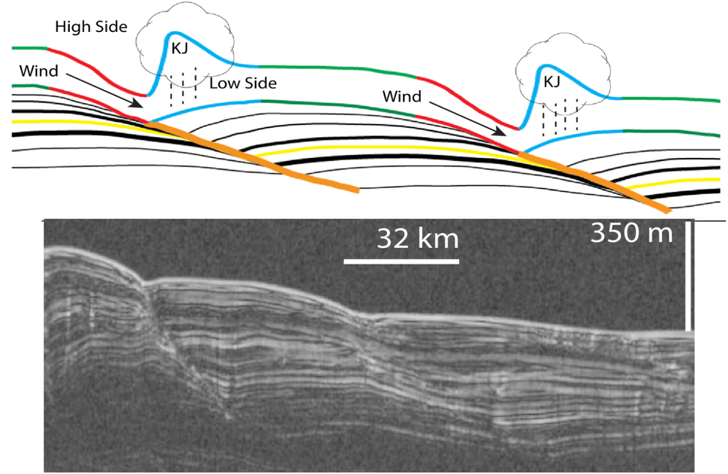
MY 27
$L_s = 90.6$

[Smith et al. JGR 2013; Smith and Holt Nature 2010]

A proposed scenario for the evolution of troughs

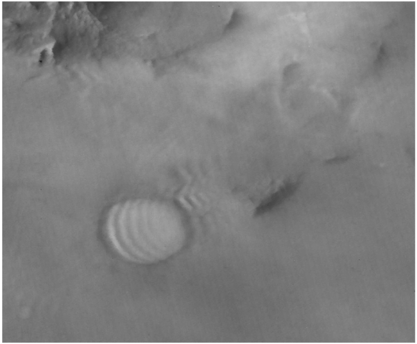
Spiral troughs analogous to terrestrial bedforms known as cyclic steps. Developed with the ice surface, not later or independently.

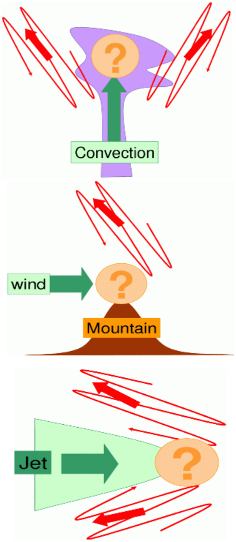
[Smith et al. JGR 2013]



Outline

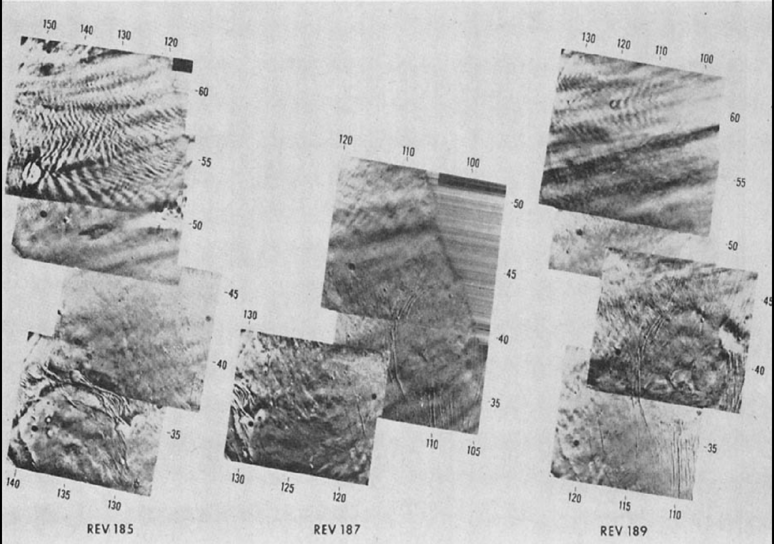
Gravity Waves [GWs] and their sources





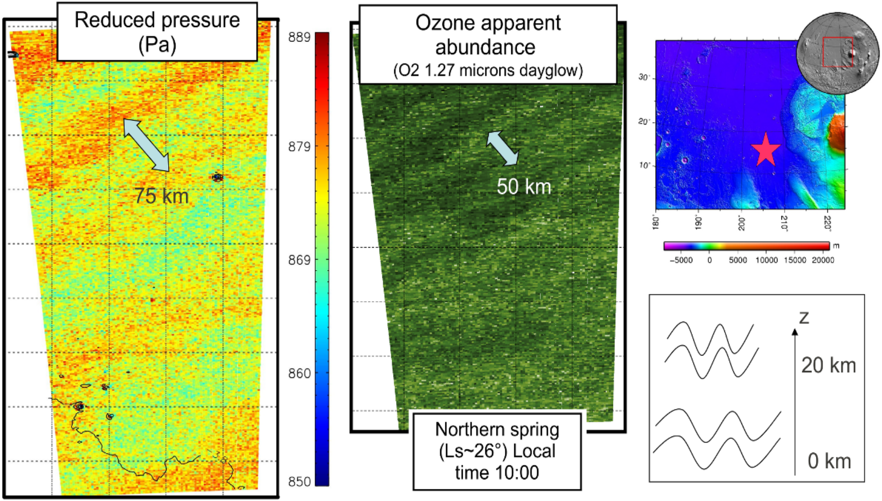
[MGS/MOC Image]

GWs are ubiquitous on Mars e.g. Mariner 9 images



[Briggs and Leovy, BAMS 1974]

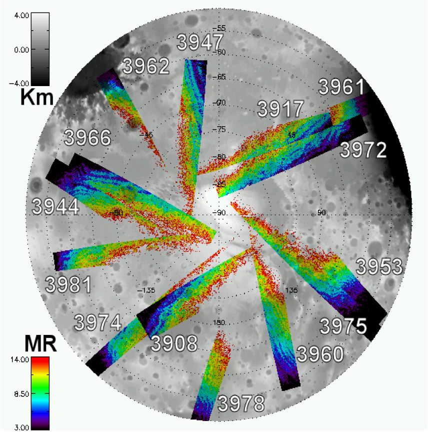
Putative GWs on OMEGA surface pressure maps



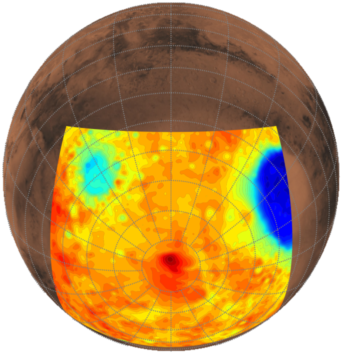
[Spiga et al., JGR, 2007]

Mapping of gravity waves by $O_2(a^1\Delta_g)$ airglow

OMEGA airglow observations



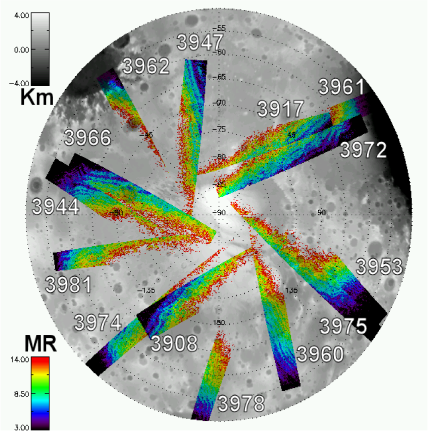
Mesoscale polar modeling



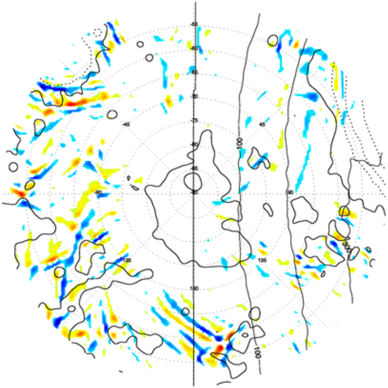
[Altieri et al. JGR 2012]

Mapping of gravity waves by $O_2(a^1\Delta_g)$ airglow

OMEGA airglow observations



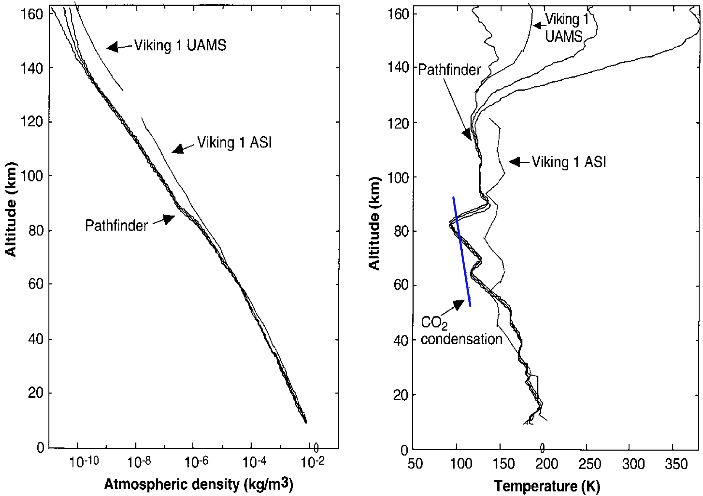
Mesoscale polar modeling



[Altieri et al. JGR 2012]

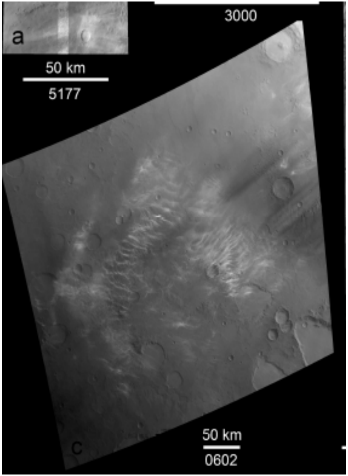
GW events observed in entry profiles

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

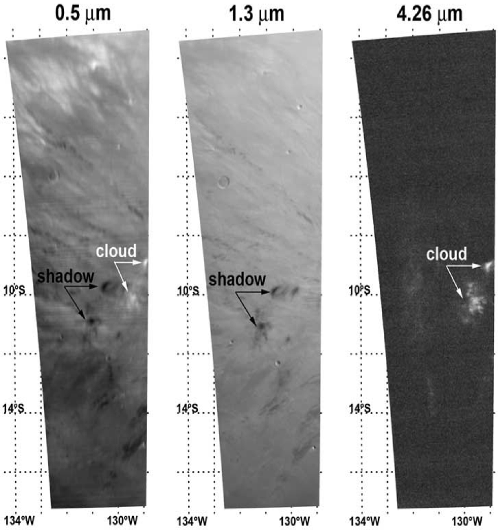


[Schofield, Science 1997; Magalhaes et al. JGR 1999]

Mesospheric CO_2 clouds

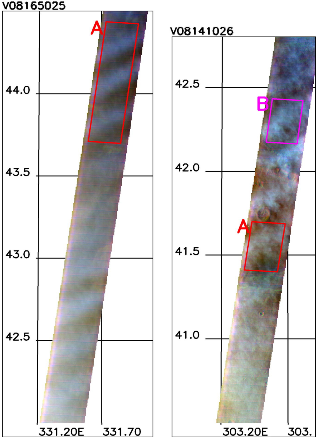


[MEx HRSC, Määttänen et al. Icarus 2010]



[MEx OMEGA, Montmessin et al. JGR 2007]

A link between GW activity and CO_2 clouds?



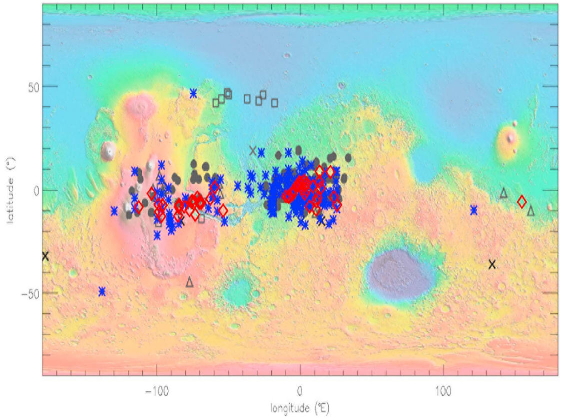
[McConnochie et al. Icarus 2010]

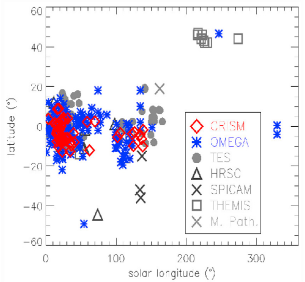
Clancy and Sandor GRL 1998

CO_2 ice clouds should form within the temperature minima of tidal and GWs in the mesosphere and be fairly common phenomena at low-to-mid latitudes during day/night

Variability of mesospheric CO_2 clouds

Recent observations by OMEGA, TES, SPICAM, HRSC, THEMIS, CRISM ...



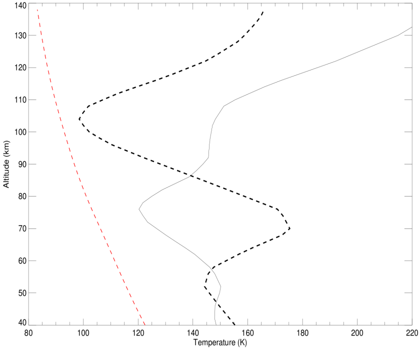


[Vincendon et al. JGR 2011]

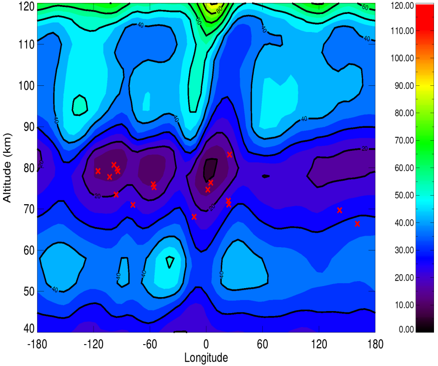
Global Circulation Modeling

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

T profiles night (dash) / day (full)



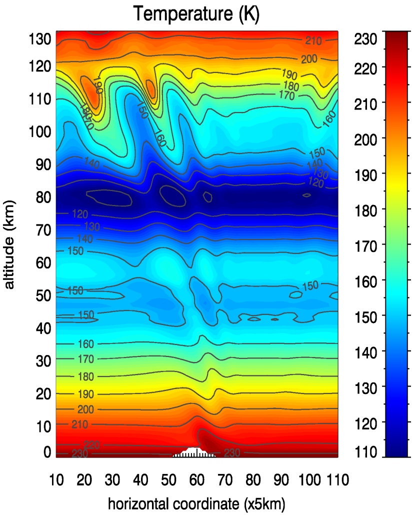
Spatial variations T - Tsat

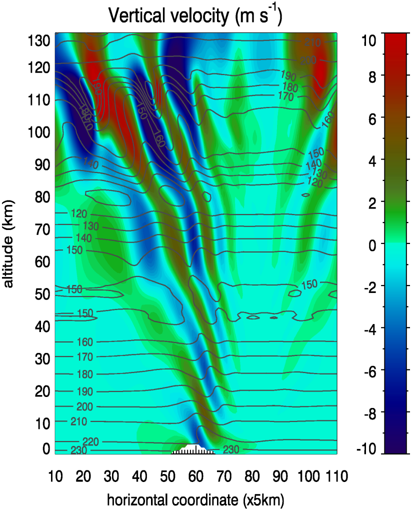


[L_s is $0 - 30^\circ$, latitude and longitude 0°. Gonzalez-Galindo et al. Icarus 2011]

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

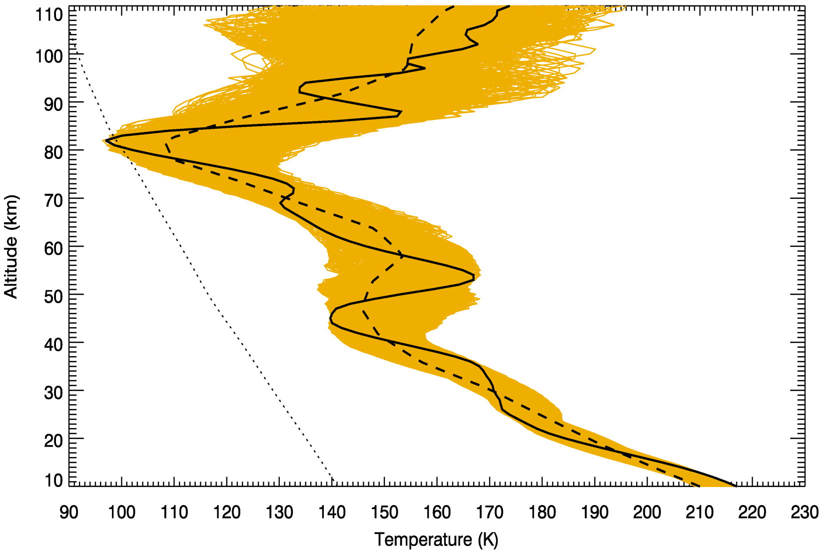




[Spiga et al. GRL 2012]

Gravity waves & subcondensation pockets

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

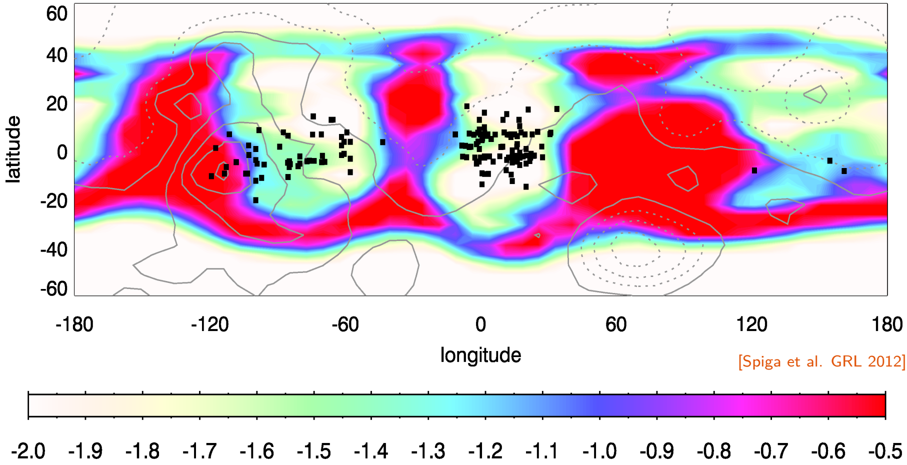


[Spiga et al. GRL 2012]

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

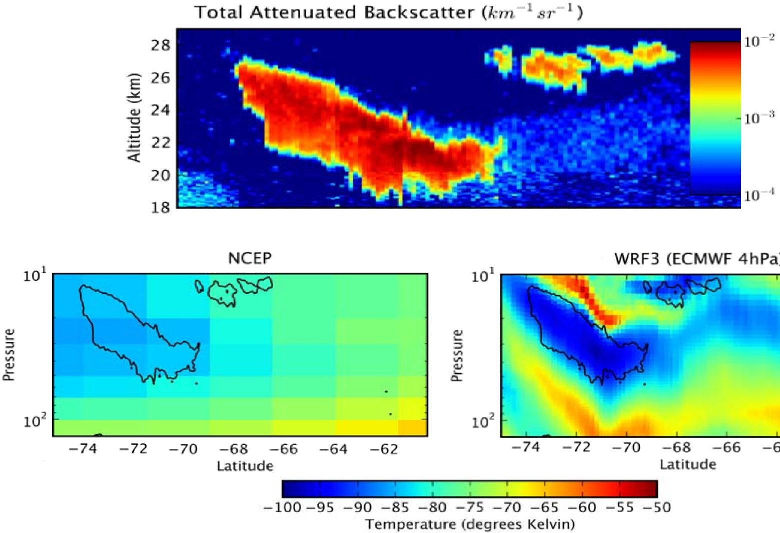
Northern spring CO_2 clouds

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



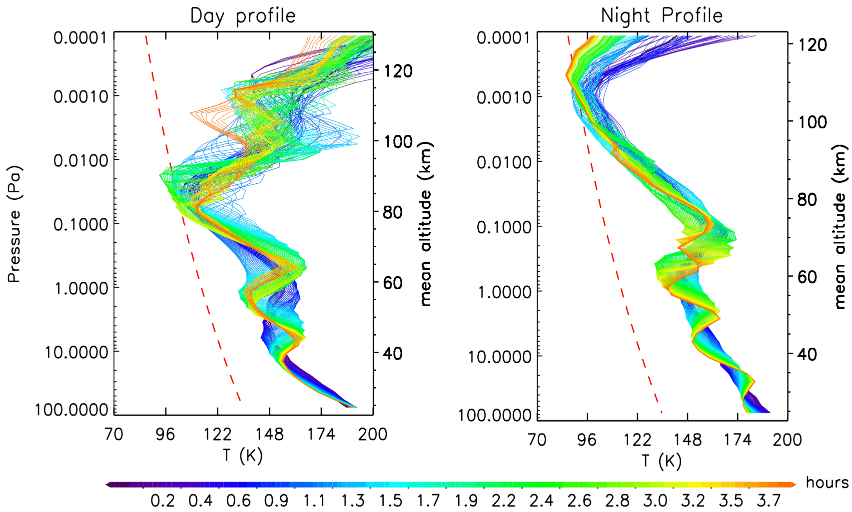
[Spiga et al. GRL 2012]

Wave-induced PSCs with $\tau \sim 1$ over Antarctica



[Noel et al. JGR 2009]

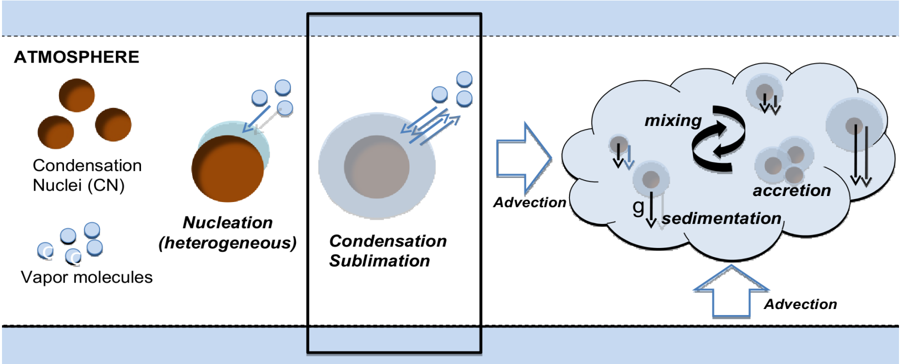
Idealized simulations of gravity-wave perturbations



[Spiga et al. GRL 2012; Listowski et al. Icarus 2014]

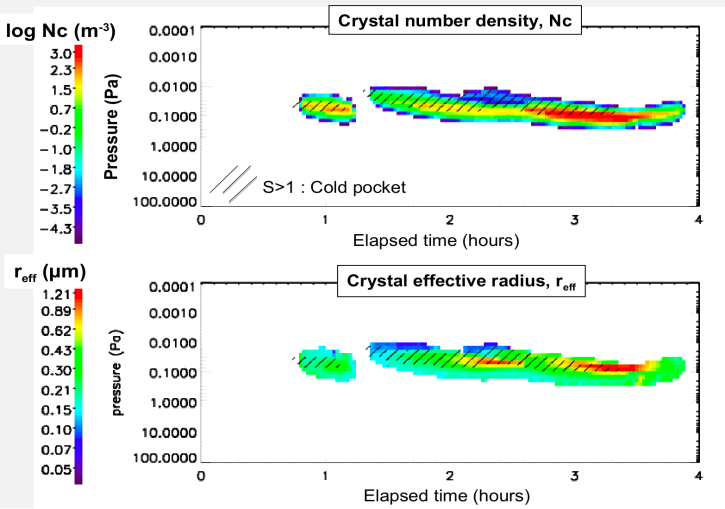
Microphysics of ice growth from pure gas phase

New theory formulated by Listowski et al. JGR 2013



CO_2 cloud microφ within GW-induced cold pockets

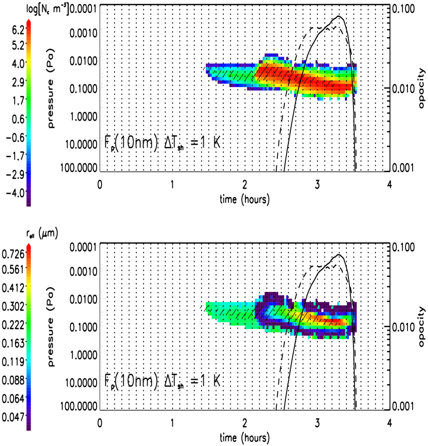
Using new theory formulated by Listowski et al. JGR 2013



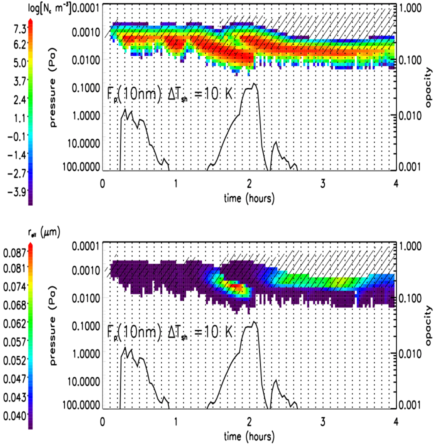
[Listowski et al. Icarus 2014]

CO_2 clouds w/ meteoritic condensation nuclei

Daytime clouds (70-80 km)



Nighttime clouds (90-100 km)

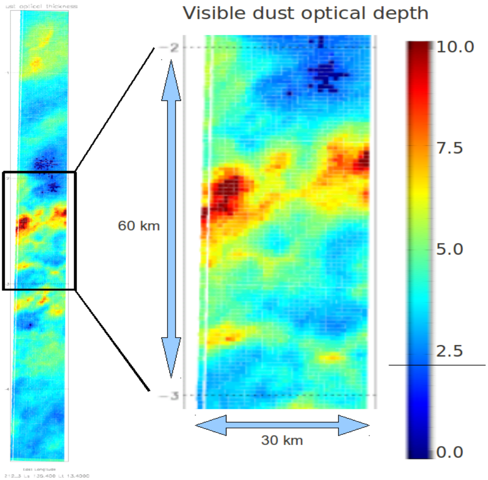


[Listowski et al. Icarus 2014]

Outline

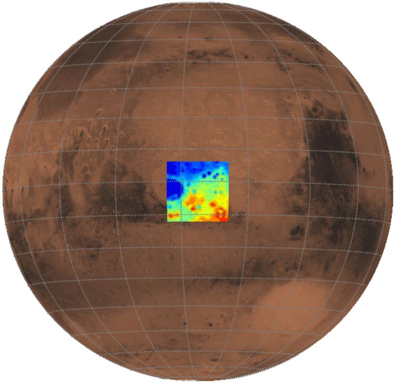
The "OMEGA storm" witnessed by Mars Express

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



[Adapted from Määttänen et al. Icarus 2009]

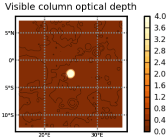
Mesoscale simulation

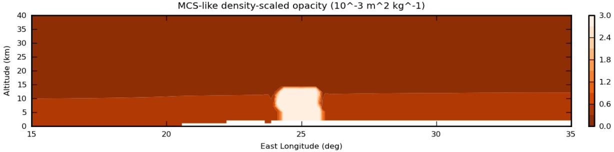


- LMD-MMM with tracers [*Spiga & Forget* JGR 2009]
- Dust radiative transfer and 2-moment transport scheme [*Madeleine et al.* JGR 2011]
- Recent dust optical indices [*Wolff et al.* JGR 2009]

- 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

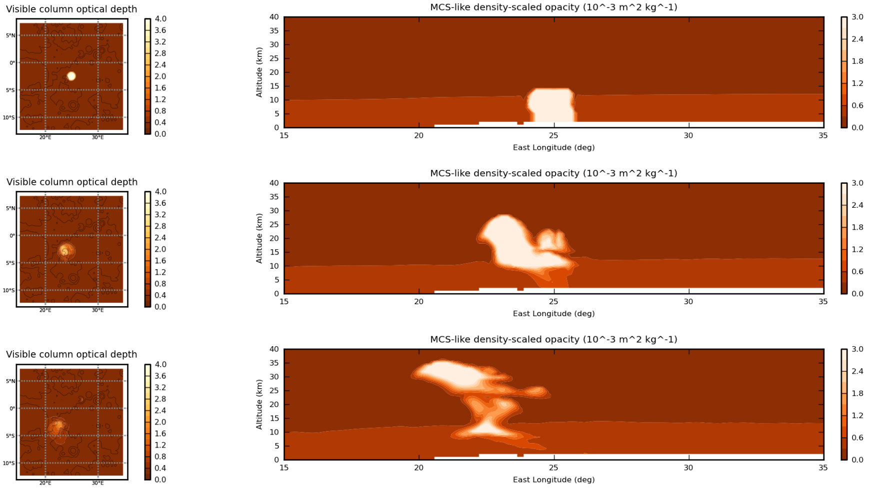
Afternoon. Local time 1400





[Spiga et al. JGR 2013, arxiv 1208.5030]

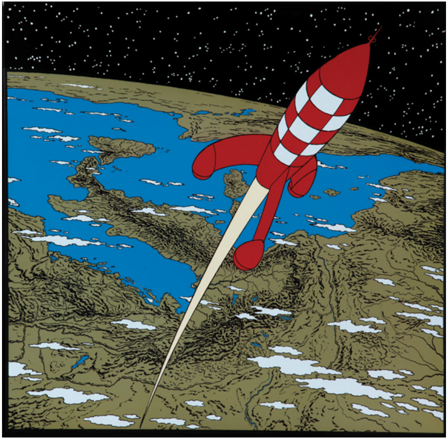
Afternoon. Local times 1400, 1600, 1800

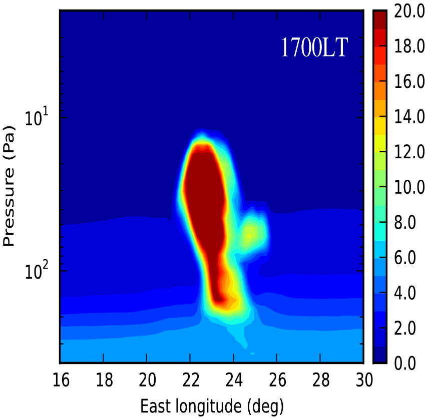


[Spiga et al. JGR 2013, arxiv 1208.5030]

"Rocket dust storms"!

Rapid and powerful vertical transport of dust particles

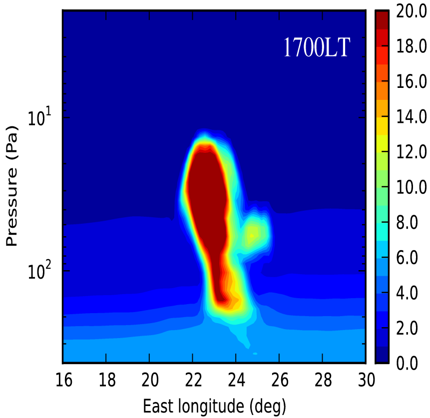




[Left picture extracted from Hergé Casterman 1954]

... or: "conio-cumulonimbus"

Dust-driven ($\kappa o \nu \iota o \varsigma$) deep convection on Mars

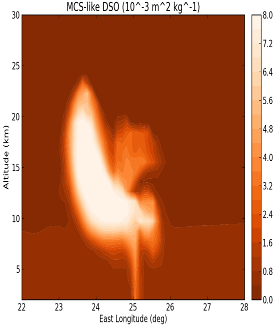


[Left picture downloaded from NOAA website]

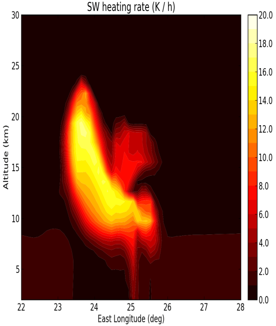
Rocket dust storm [a.k.a. conio-cumulonimbus]

Dust-driven deep convection on Mars

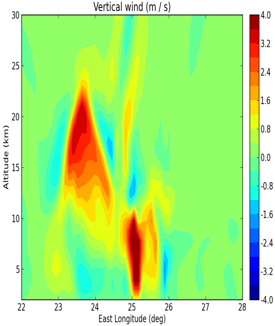
(DS) Optical depth



SW heating rate

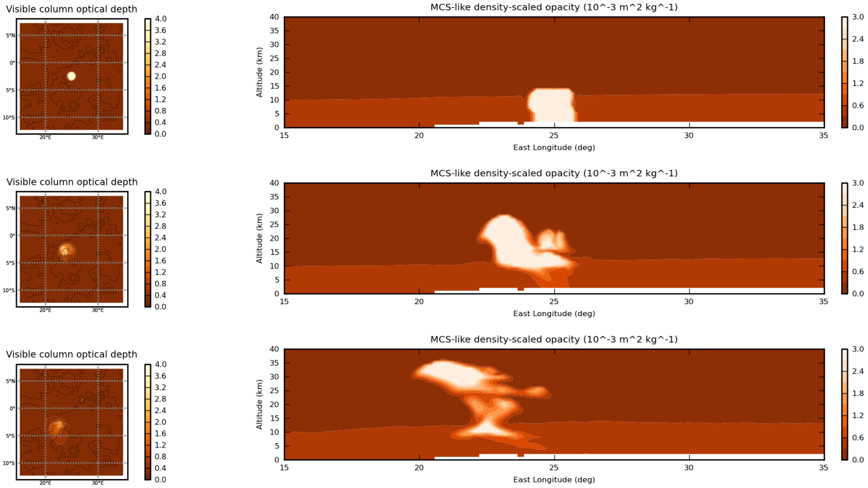


Vertical wind



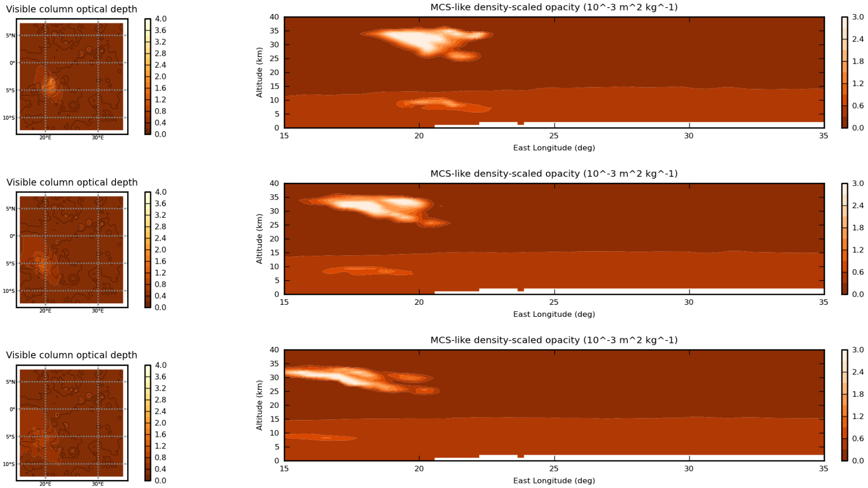
[Spiga et al. JGR 2013, arxiv 1208.5030]

Afternoon. Local times 1400, 1600, 1800



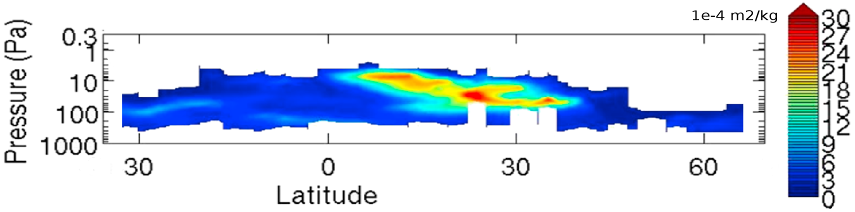
[Spiga et al. JGR 2013, arxiv 1208.5030]

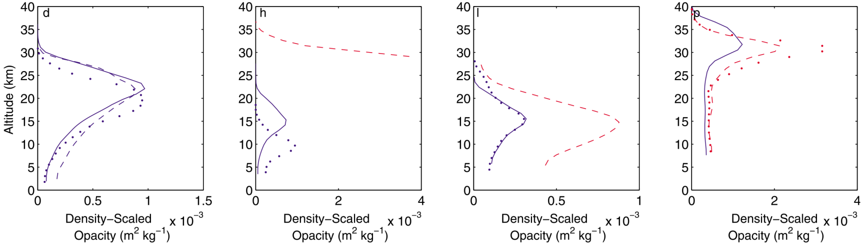
Evening. Local times 2000, 2200, 0000



[Spiga et al. JGR 2013, arxiv 1208.5030]

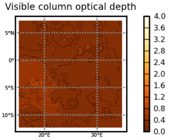
Detached layers of dust: MCS observations

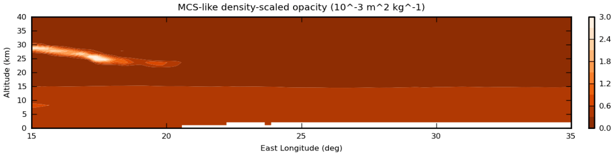


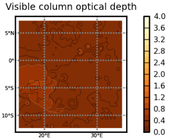


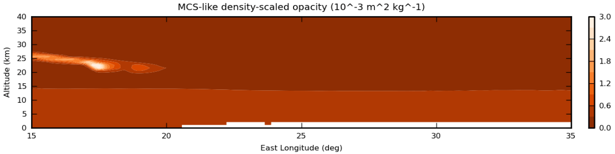
[Heavens et al. JGR 2011 (part 1 & 2)]

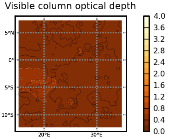
Nighttime. Local times 0200, 0400, 0600

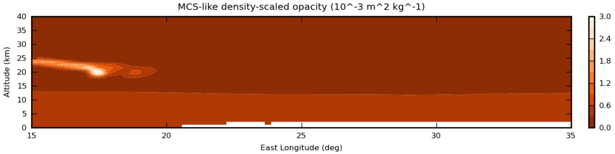






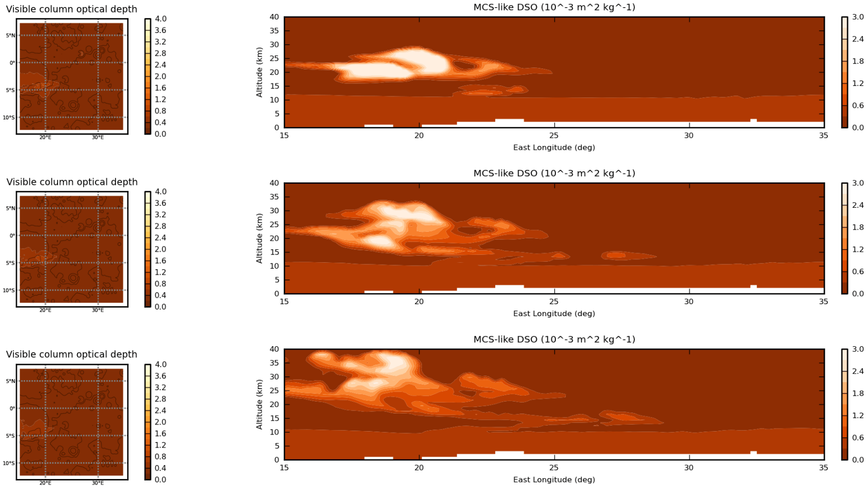






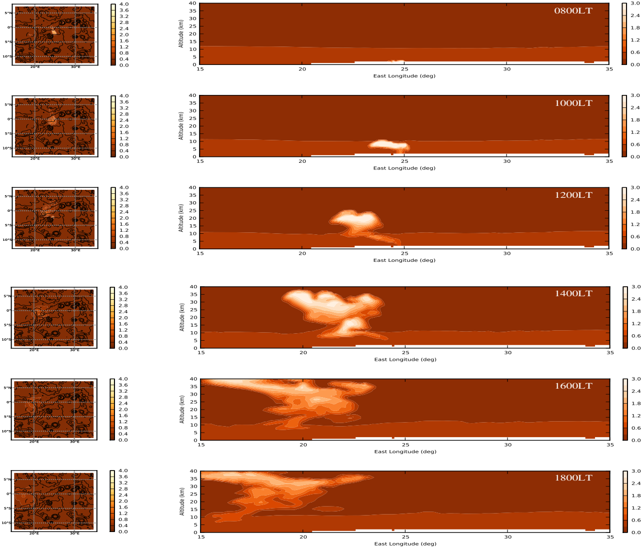
[Spiga et al. JGR 2013, arxiv 1208.5030]

Morning. Local times 0800, 1000, 1200



[Spiga et al. JGR 2013, arxiv 1208.5030]

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



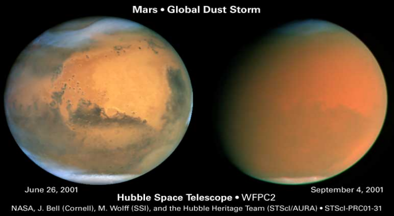
[Spiga et al. JGR 2013, arxiv 1208.5030]

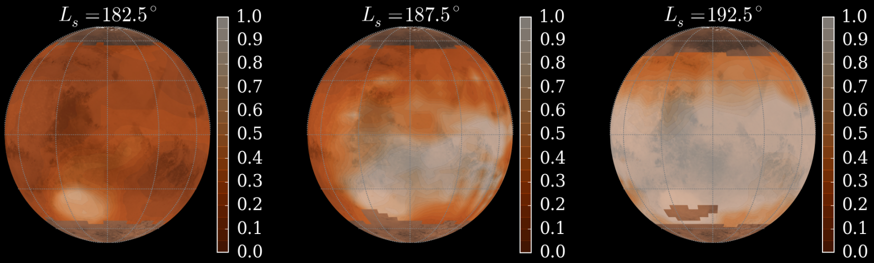
Implications of dusty deep convection on Mars

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.

The onset of the MY25 global dust storm

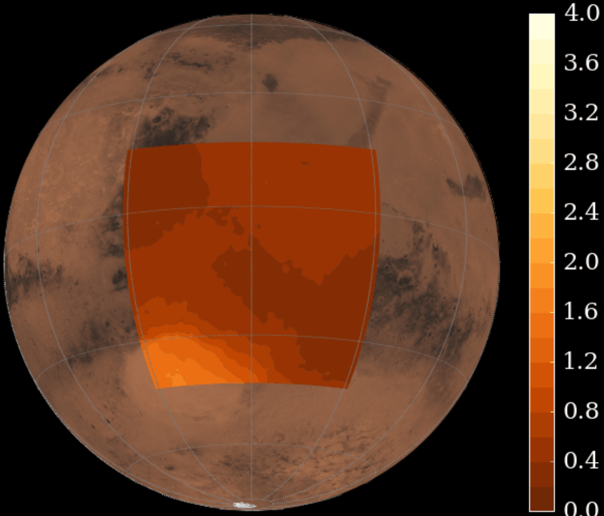




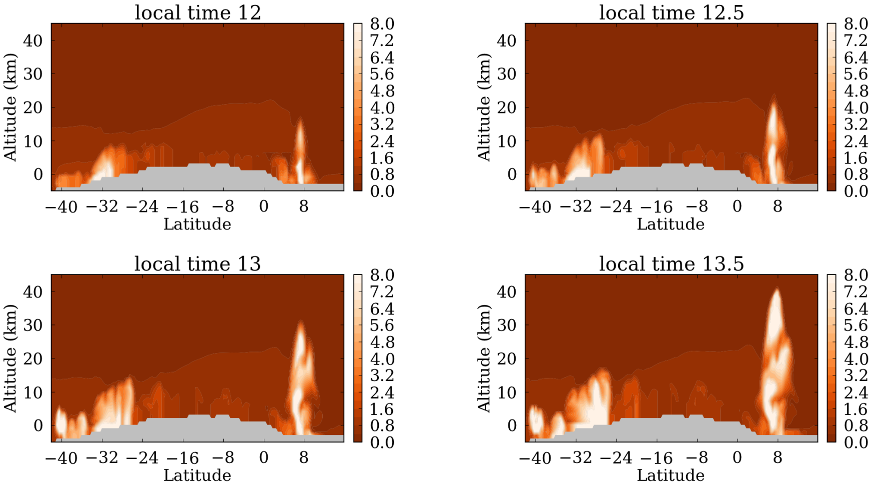
[Made after Thermal Emission Spectrometer by Smith et al. 2001]

A regional storm near Hellas ($L_s = 185°$)

lifting $\Rightarrow$ threshold $u_{*t} = 0.8$ m s^{-1} efficiency $\alpha = 2 \times 10^{-5}$ m^{-1}



Rocket dust storms in MY25 global dust storm?

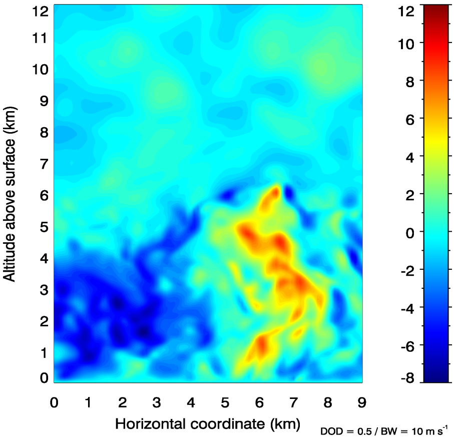


Outline

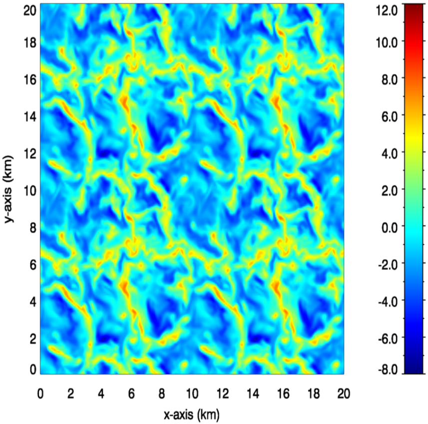
Turbulent convection in daytime boundary layer

Simulated through Large-Eddy Simulations [LES]

↓ Vertical ↑



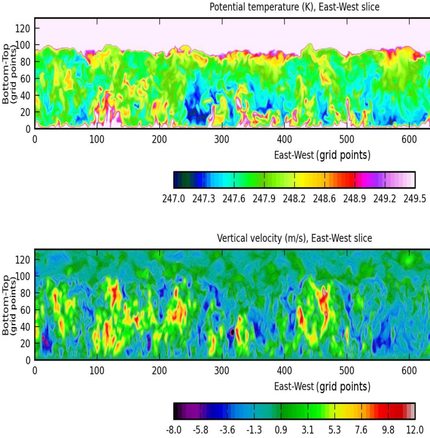
← Horizontal →

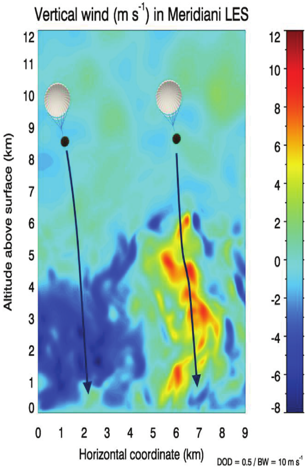


[Meridiani simulation for Exomars risk assessment]

Turbulent convection in daytime boundary layer

Simulated through Large-Eddy Simulations [LES]





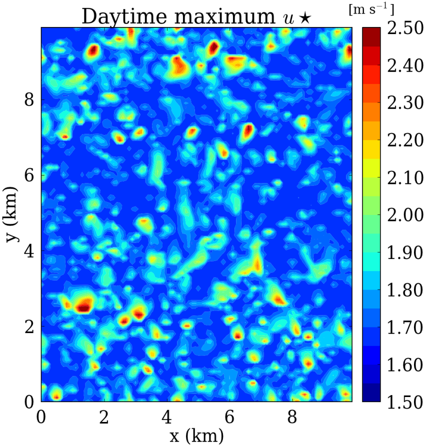
Animation: *xz* section showing tracer transport

[Spiga et al. QJRMS 2010; Colaitis et al. JGR 2013]

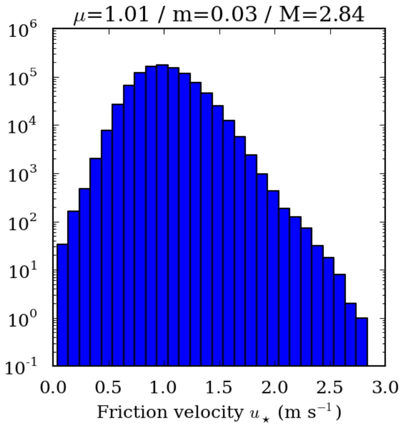
Friction velocity predicted by LES computations

Background wind is 30 m s^{-1}

Maximum map

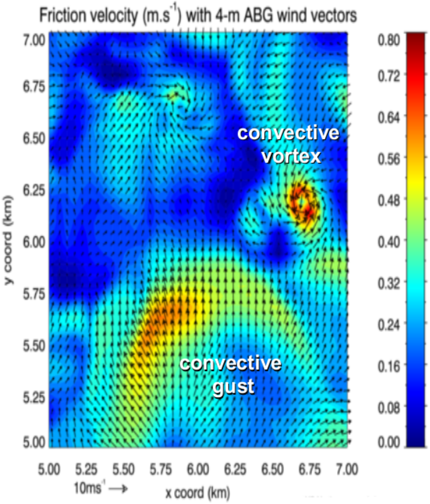


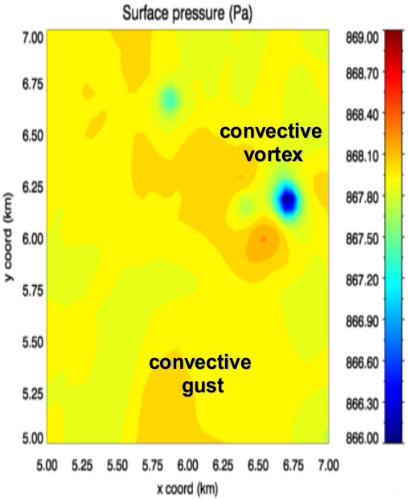
Histogram



[Mulholland et al. Icarus 2015]

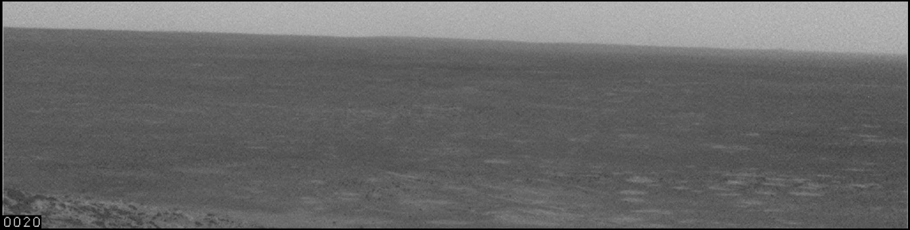
Microscale wind variability resolved by LES

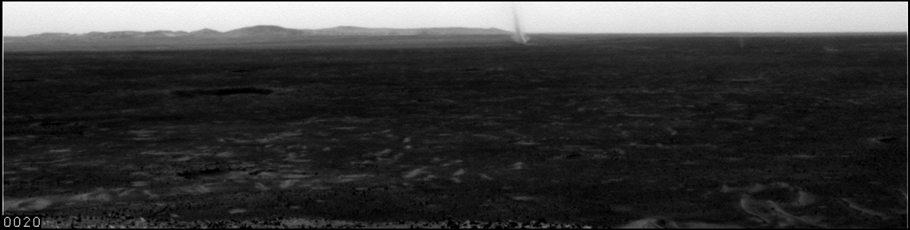




[Spiga and Lewis the Mars Journal 2010]

Dust devils observed by Spirit



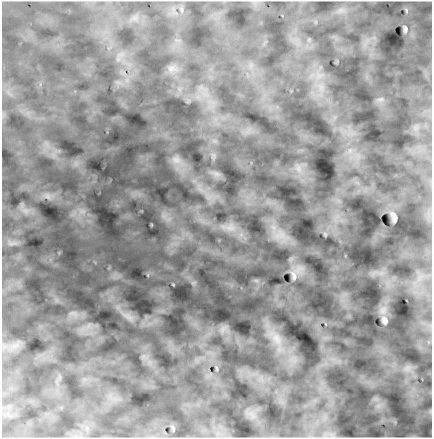


Mars PBL phenomena: Imagery

Dust devils

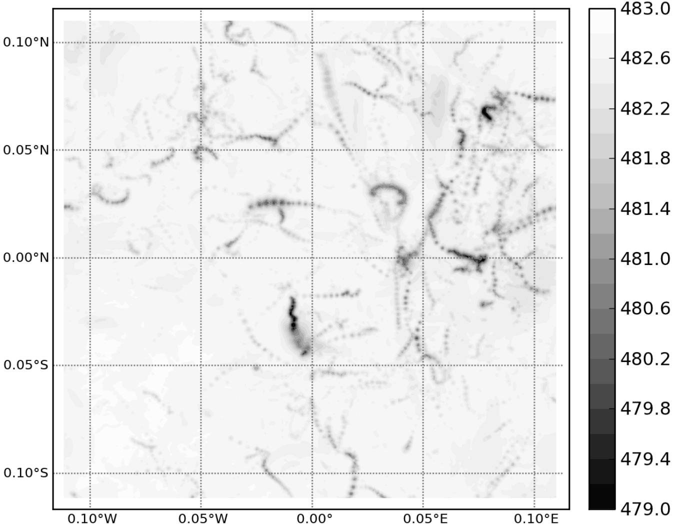
[Pancam on Spirit Rover]

Cloud streets

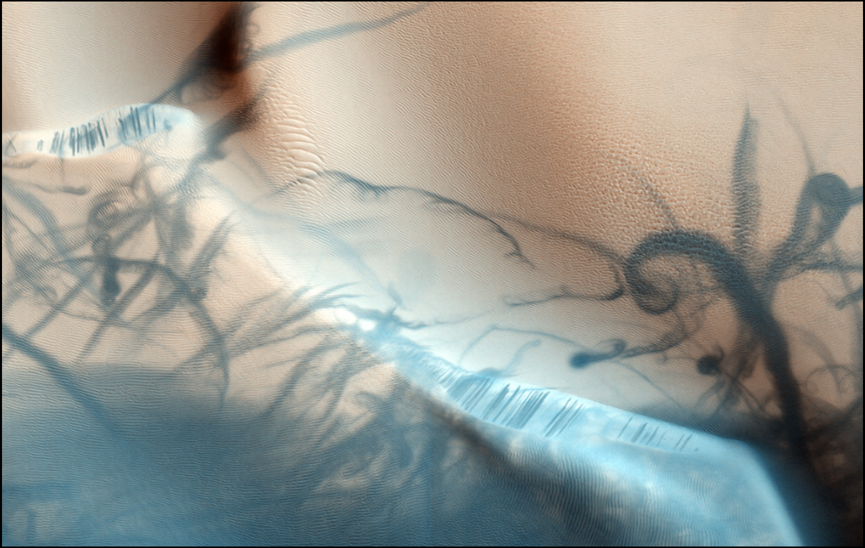


[Mars Orbital Camera on Mars Global Surveyor]

LES: daytime pressure minima in each point



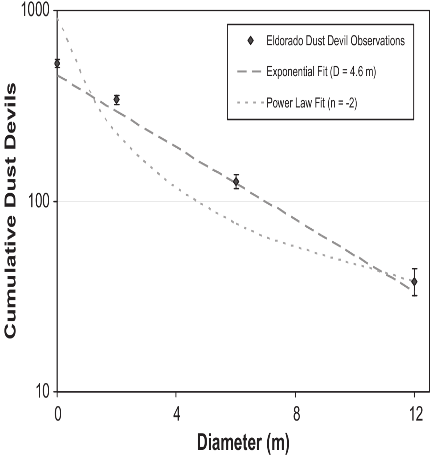
Graffitis martiens ! Champ de dunes Arabia Terra



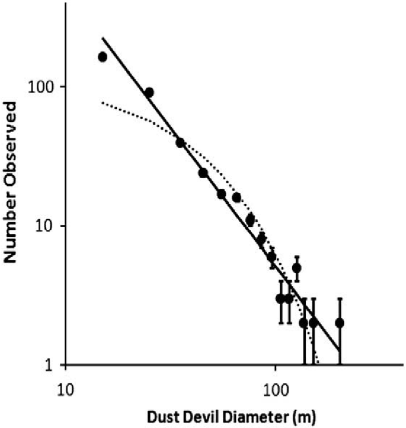
[HiRISE, Mars Reconnaissance Orbiter, 2009]

In measurements: Exponential or power law?

Exponential [Pathare et al. 2010]



Power law [Lorenz et al. 2009 2011]



Specific LES for dust devil studies

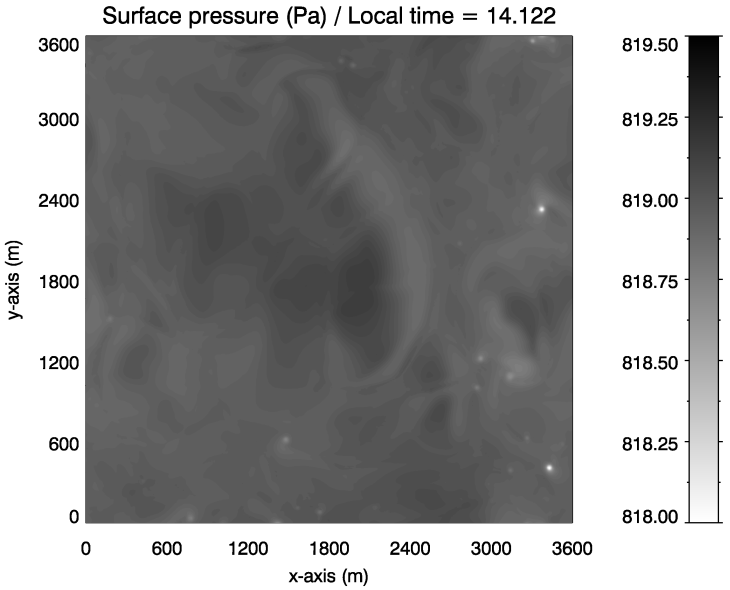
Dynamical settings

- LMD-LES by *Spiga et al.* QJRMS 2010
- 10 m grid spacing [timestep: 1/8 s]
- $369 \times 369 \times 101$ grid points
- Model top : 6 km
- No background wind

Phoenix environmental settings

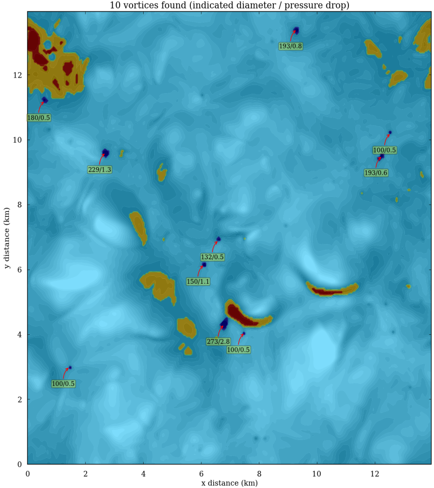
- Season $L_s = 90^\circ$ [see *Ellehoj et al.* JGR 2010]
- Initial temperature profile: early morning conditions from MCD
- Soil properties: TI = 200 tiu and A = 0.2
- Dust opacity $\tau = 0.3$

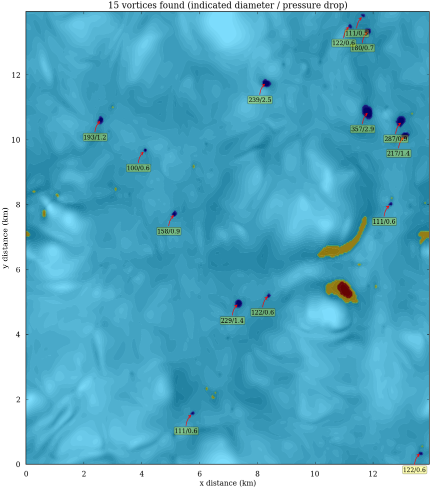
Convective vortices in LES



Detecting convective vortices and their sizes

In pressure fields predicted by Large-Eddy Simulations





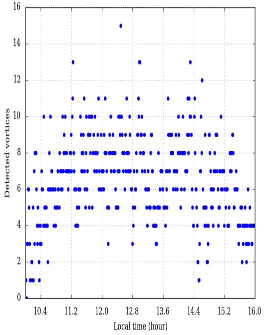
Variations with local time

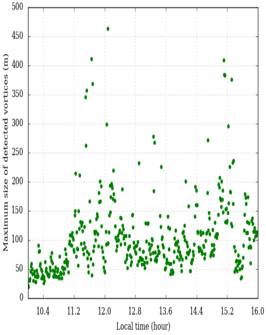
For domain-wide quantities

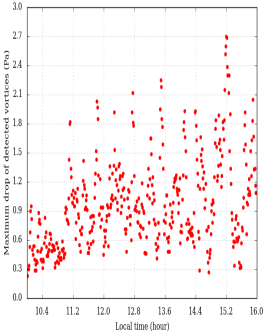
detected

maxsize

maxdrop



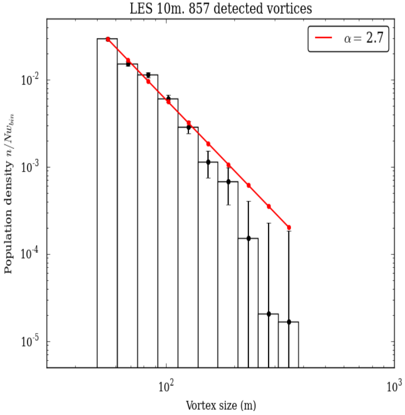




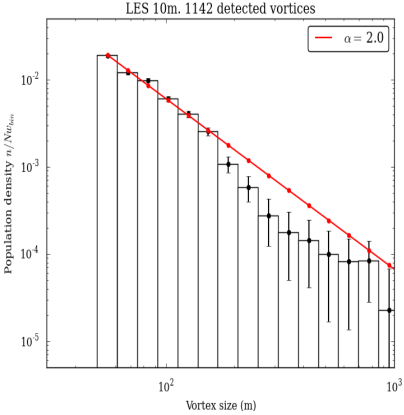
Size distribution of convective vortices in 10 m LES

Histogram with logarithmic axes and bins [Lorenz Icarus 2011; Newman Stat. Mech. 2005]

Strict size criterion

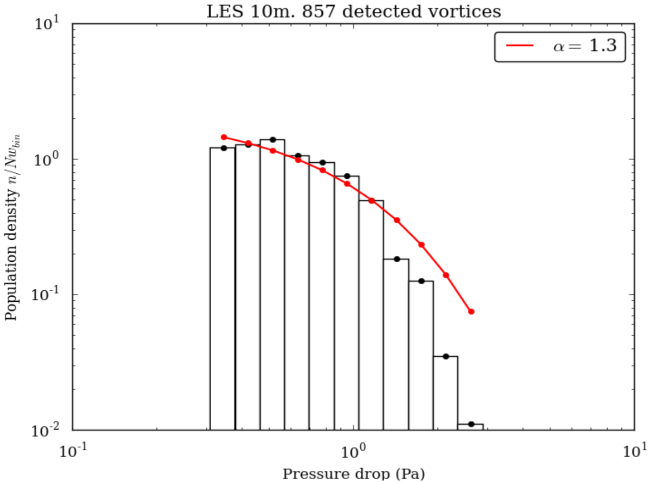


Generous size criterion

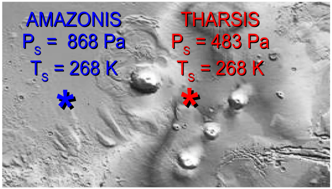


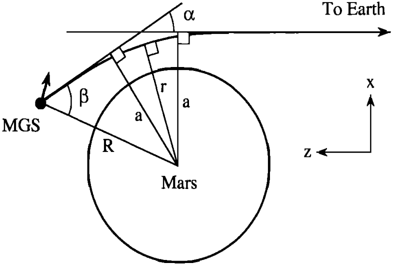
Distribution of pressure drop in 10 m LES

Histogram with logarithmic axes and bins

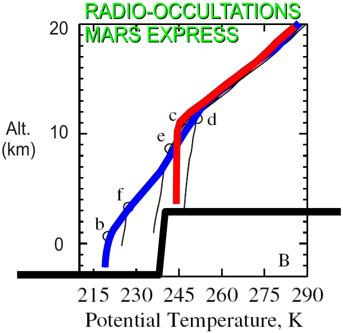


Mars Express radio-occultations



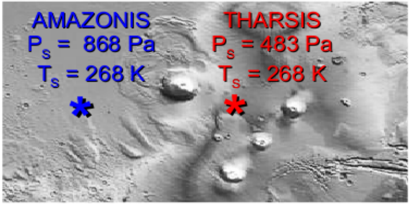


[Hinson et al., 1999]

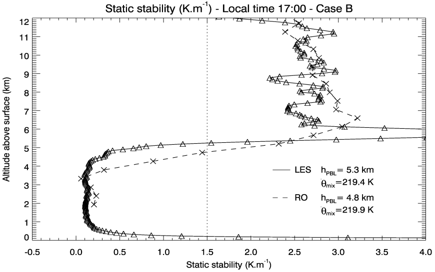


[Hinson et al., 2008]

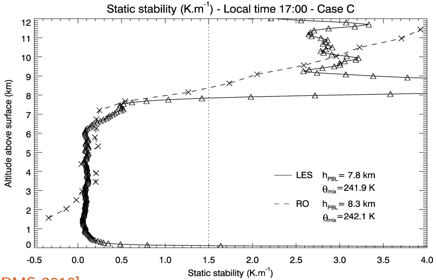
BL depth variability: observations vs. models



Lower plains [Amazonis]



Higher plateaus [Tharsis]



[Spiga et al., QJRMS 2010]

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

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

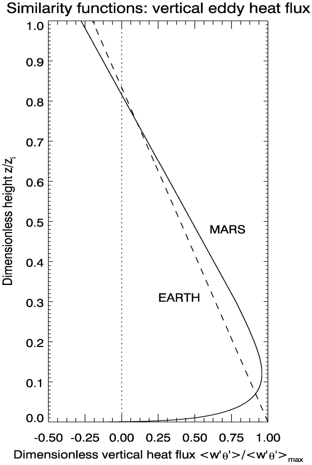
Earth (arid terrains)

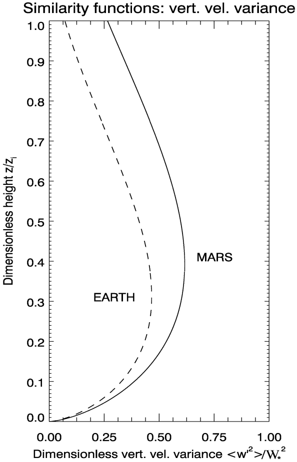
$$\frac{\partial \theta}{\partial t} \sim -\frac{\partial \langle w'\theta' \rangle}{\partial z}$$

[Spiga et al., QJRMS 2010]

Dimensionless analysis of Mars mixed layer

$$\frac{\langle w'\theta' \rangle}{\langle w'\theta' \rangle_{\mathrm{max}}} = \mathcal{F}\left(\frac{z}{z_{\mathrm{i}}}\right) \qquad \frac{\langle w'^2 \rangle}{W_*^{\,2}} = \mathcal{V}\left(\frac{z}{z_{\mathrm{i}}}\right)$$

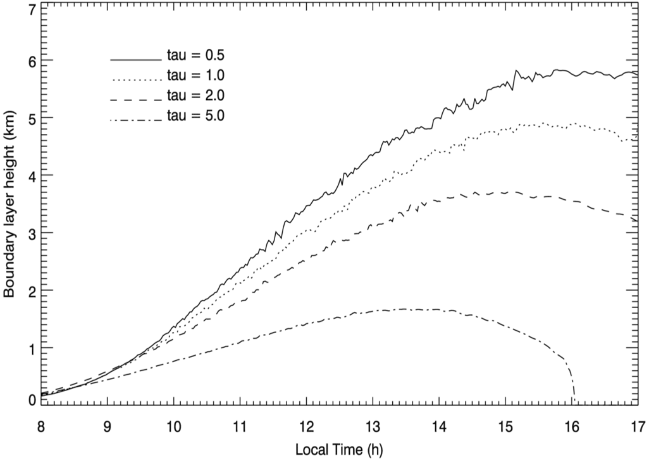




[Spiga et al., QJRMS 2010]

Large-Eddy Simulations: sensitivity study

Boundary layer height



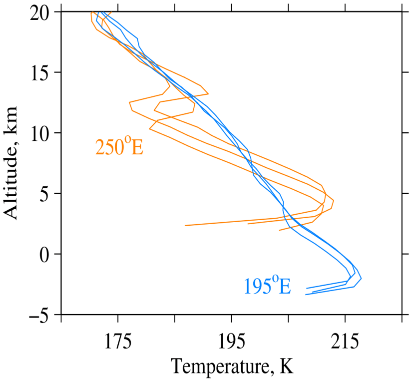
[Exomars risk assessment for Meridiani candidate case]

Outline

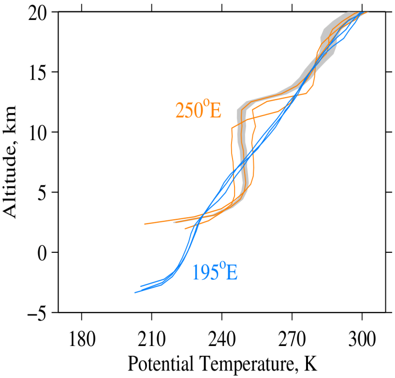
MGS nighttime radio-occultations

Amazonis (blue) vs. Tharsis (orange). Lat $20-25^{\circ}$N. Local time 4am. $L_s = 140^{\circ}$

Temperature



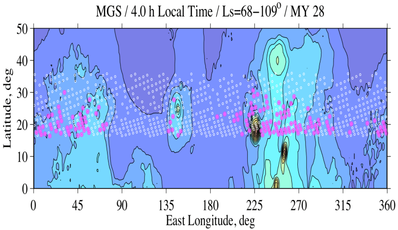
Potential temperature



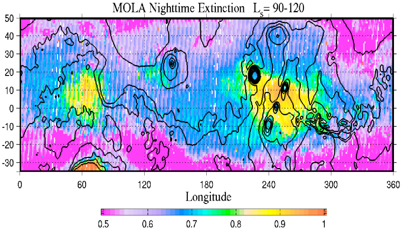
[Hinson et al. Icarus 2014]

Nighttime mixed layers and possible causes

Mixed layers

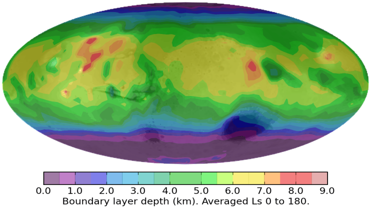


Water ice clouds

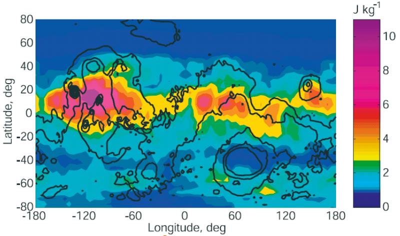


[Left: Hinson et al. 2014; Right: Wilson et al. 2007]

PBL depth



Gravity waves

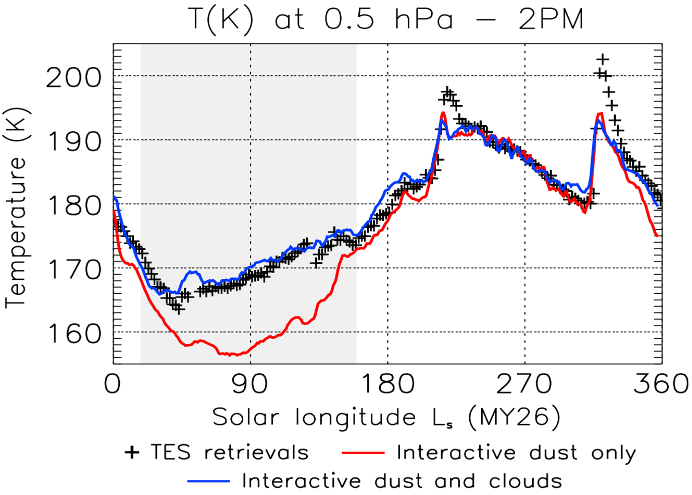


[Left: cf. Colaitis et al. 2013; Right: Creasey et al. 2006]

Possible causes for nighttime mixed layers

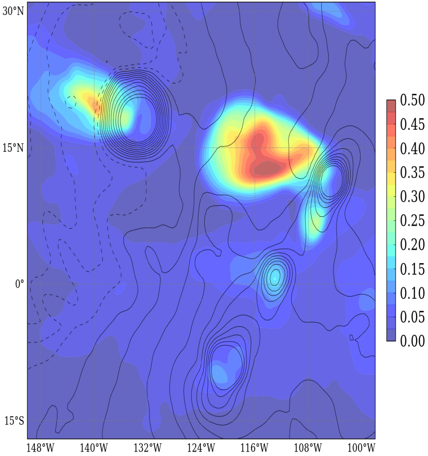
- ☞ daytime convective boundary layer
- ☞ convective dust storm
- ☞ gravity wave propagation and breaking
- ☞ H_2O ice clouds

Large-scale effect of radiatively-active H_2O clouds

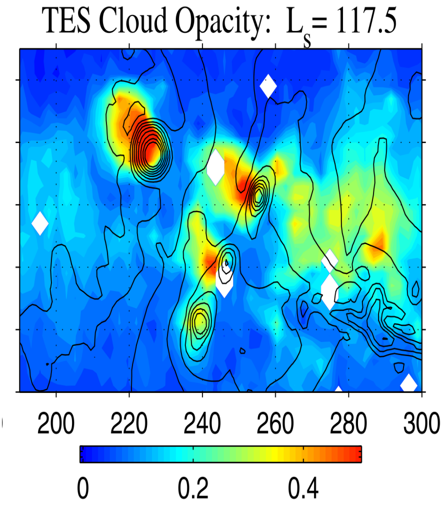


[Madeleine et al. GRL 2012]

Tharsis summer clouds in daytime $L_s \sim 120^\circ$

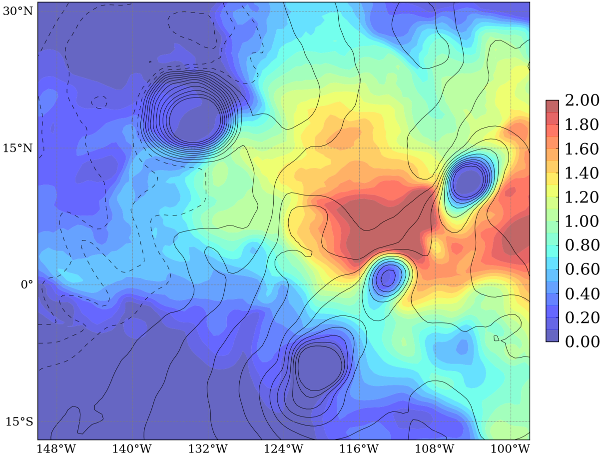


[LMD mesoscale model]



[Wilson et al. GRL 2007]

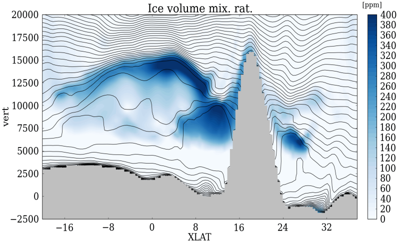
Tharsis summer clouds in nighttime $L_s \sim 120°$



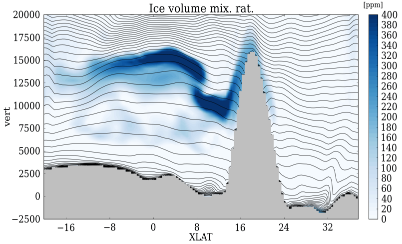
Mesoscale simulations of radiatively active clouds

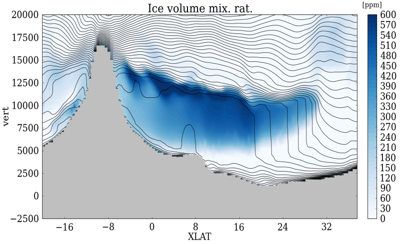
Water ice clouds shaded, potential temperature contoured

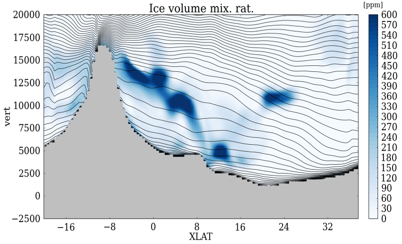
With RAC



Without RAC



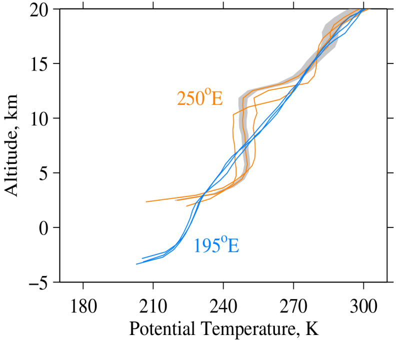




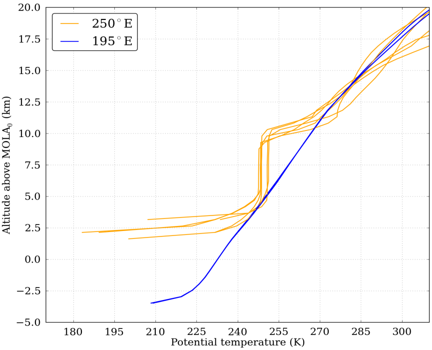
Nighttime mixed layers

Latitude $20 - 25°$N / local time 4am / northern summer $L_s = 140°$

MGS occultations

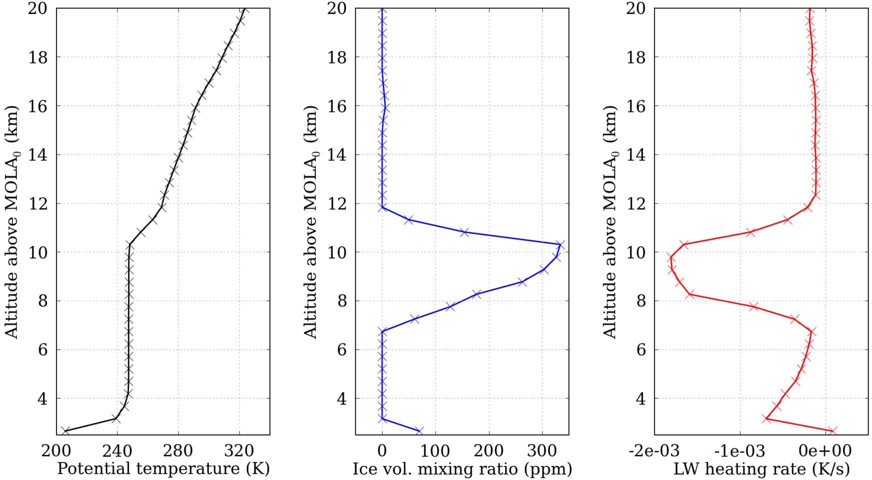


Mesoscale simulation

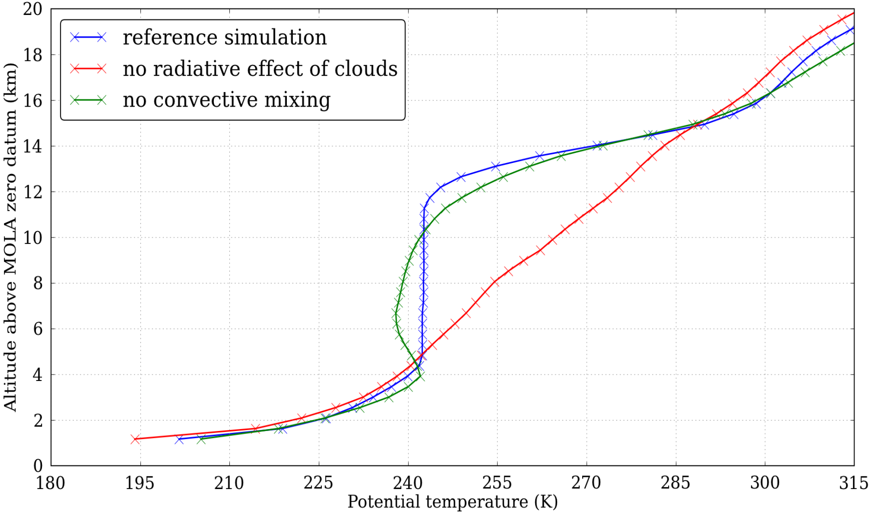


[Hinson et al. Icarus 2014, Spiga et al. in preparation]

'Radiative' convection in H_2O ice clouds at night



'Radiative' convection in H_2O ice clouds at night



Convective mixing caused by nighttime IR cooling of H_2O ice clouds

- ☞ A change of perspective about Martian H_2O ice clouds
- ☞ Mixing of water vapor, heat, momentum ...
- ☞ Strong vertical motions? (high-res runs ongoing!)
- ☞ Source of gravity waves?
- ☞ Impact on precipitation? Comparison with Phoenix LIDAR?
- ☞ Large-scale effects?

Outline

Venus convective & wavy cloud layer

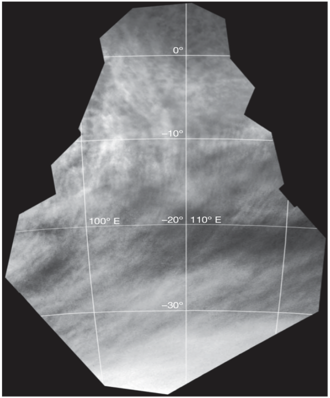


Figure 3 | A mosaic of VMC ultraviolet images showing streaks, wave trains and convection cells (orbit 116). The elongated orbit of Venus Express allows us to zoom into the cloud features while the spacecraft approaches the planet. This mosaic shows that mottled and chaotic cloud patterns at low latitudes give way to approximately zonally oriented streaks at about −15° latitude. This indicates a transition from a dynamical regime that is dominated by local convection at the subsolar point to a quasi-laminar flow.

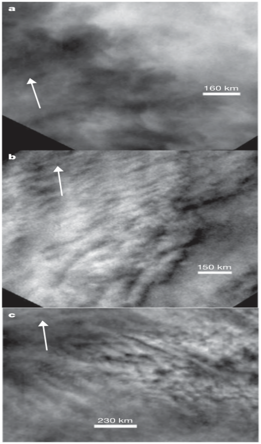
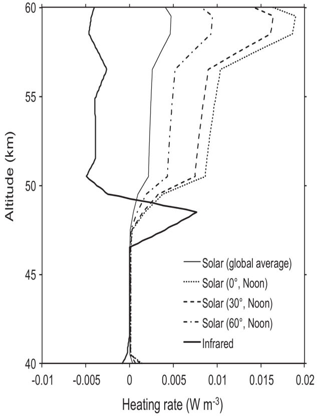


Figure 5 | Three VMC ultraviolet images of the upper cloud deck near the subsolar point. The arrows point to the north. **a,** Wave-like structures transforming into a convective mottled morphology (17° N, −143° E), LST = 14:32. **b,** Streaks and convective cells on the equator (0° N, −150° E), LST = 14:41. **c,** Small convection cells downstream of the subsolar point (10° N, 125° E), LST = 13:16.

[Markiewicz et al. Nature 2007]

Venus Large-Eddy Simulations

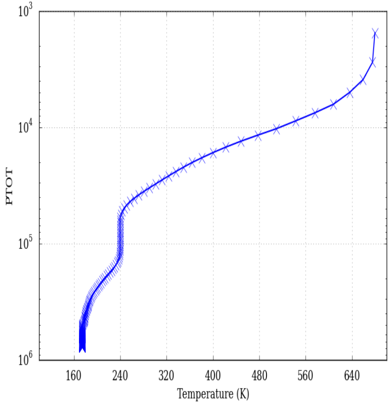
with prescribed radiative forcing



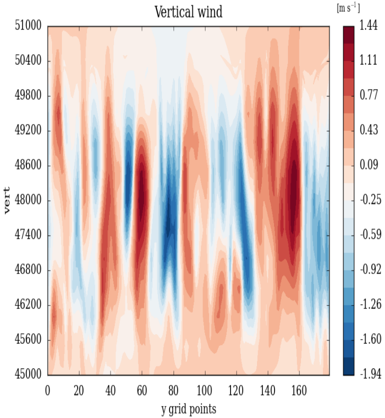
- ☞ Modeling work reference: Baker et al. 1998; Imamura et al. 2014
- ☞ Work in progress (M2 internship of M. Lefèvre).
- ☞ 200m horizontal resolution
  181 × 181 grid points
- ☞ GCM SW & LW heating rates at latitude 30°

Convective mixing within the cloud layer

Potential temperature

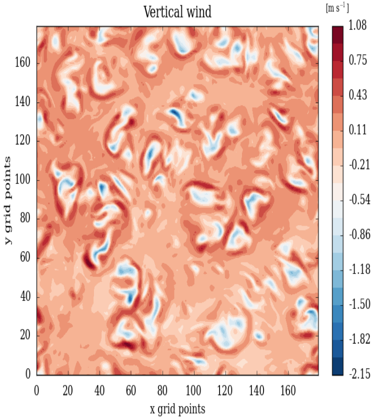


Vertical wind

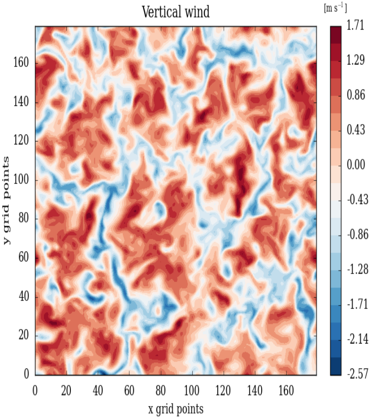


Convective cells: typical of penetrative convection

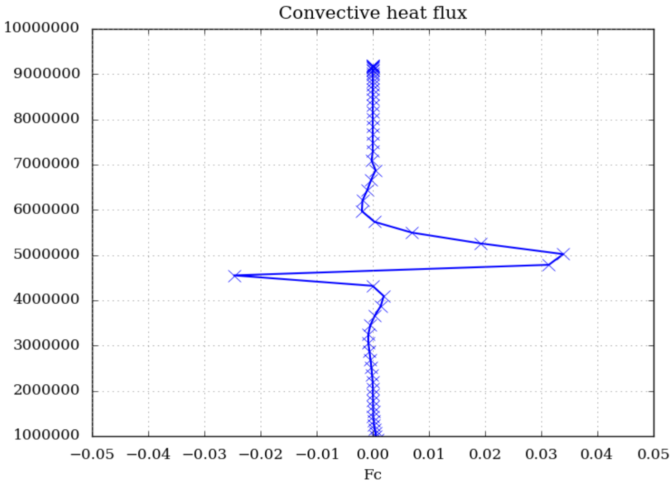
Top of convective layer



Middle of convective layer



Vertical eddy heat flux



Outline

Rich mesoscale and microscale meteorology!

- ☞ Powerful slope winds; spectacular polar katabatic jumps.
- ☞ Gravity waves: ubiquitous and strong perturbations (CO_2 clouds)
- ☞ Rocket dust storms: radiatively-induced deep convection
- ☞ PBL convection: not-so-shallow, radiatively controlled ($\neq$ Earth)
- ☞ Water ice clouds could be convective *in the night*
- ☞ Towards comparative planetology with the Venus case

Selected references and contact

- ☞ Papers in PDF available
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