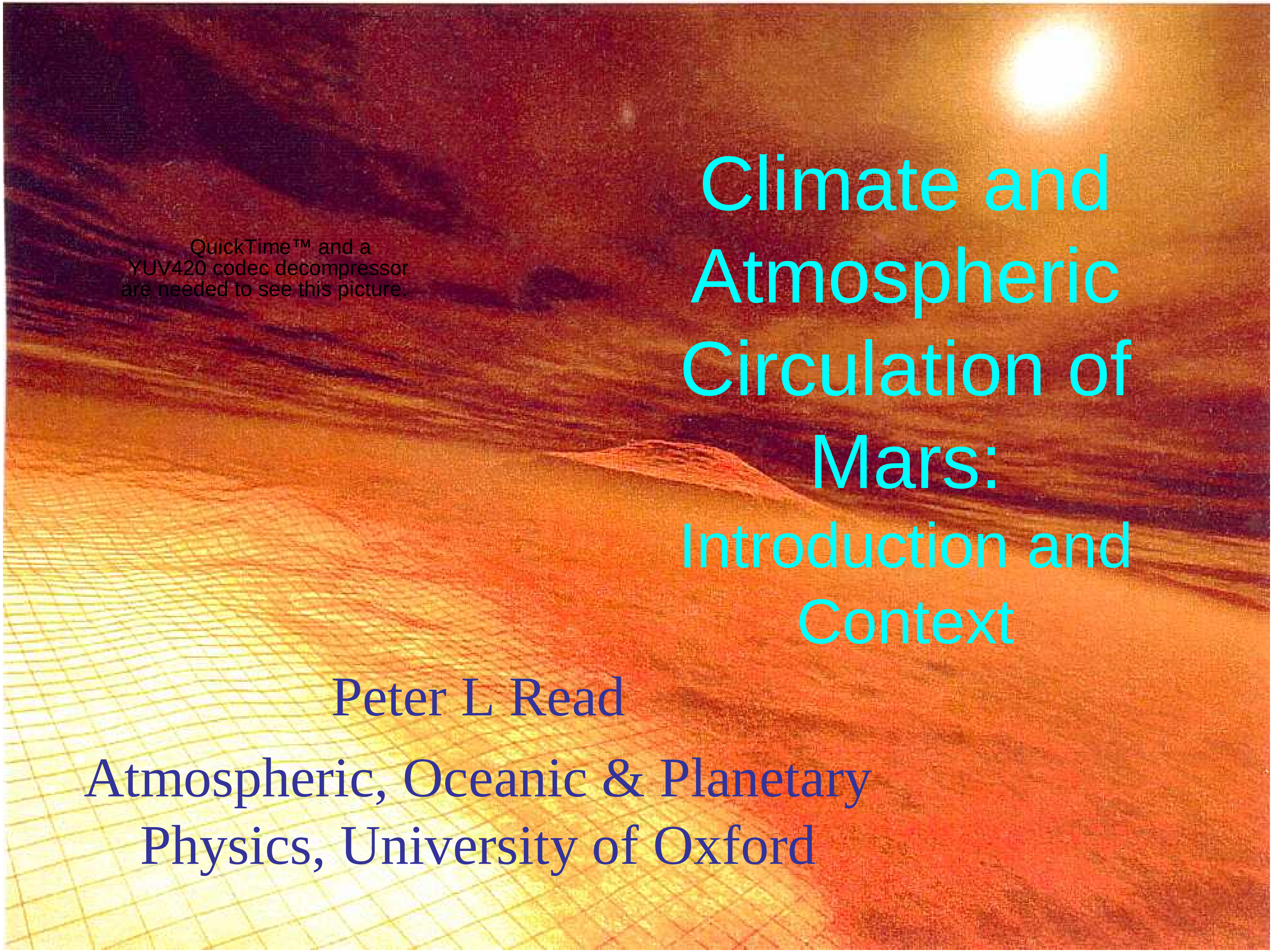


Climate and Atmospheric Circulation of Mars:

Introduction and Context

Peter L Read

Atmospheric, Oceanic & Planetary Physics, University of Oxford

Motivating questions

- Overview and phenomenology
  - Planetary parameters and ‘geography’ of Mars
  - Zonal mean circulations as a function of season
  - CO_2 condensation cycle
- Form and style of Martian atmospheric circulation?
- Key processes affecting Martian climate?
- The Martian climate and circulation in context…..comparative planetary circulation regimes?

Books?

- D. G. Andrews - Intro…..
- J. T. Houghton - The Physics of Atmospheres (CUP)

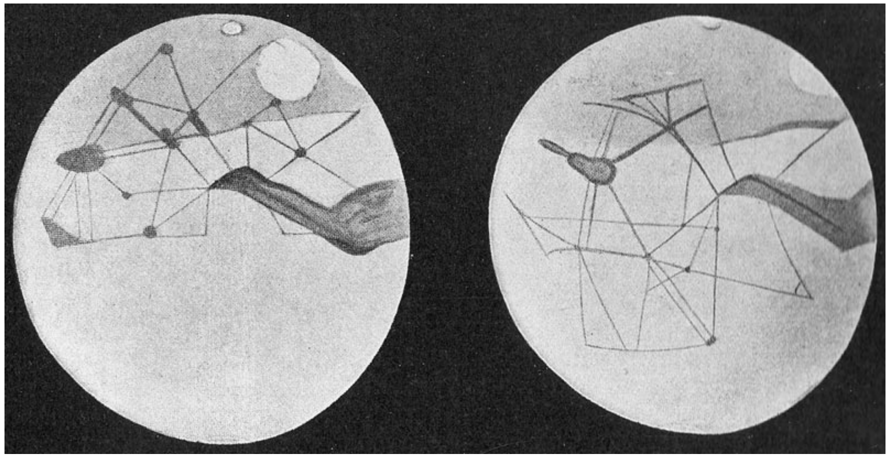
ALSO

- I. N. James - Introduction to Circulating Atmospheres (CUP)
- P. L. Read & S. R. Lewis - The Martian Climate Revisited (Springer-Praxis)

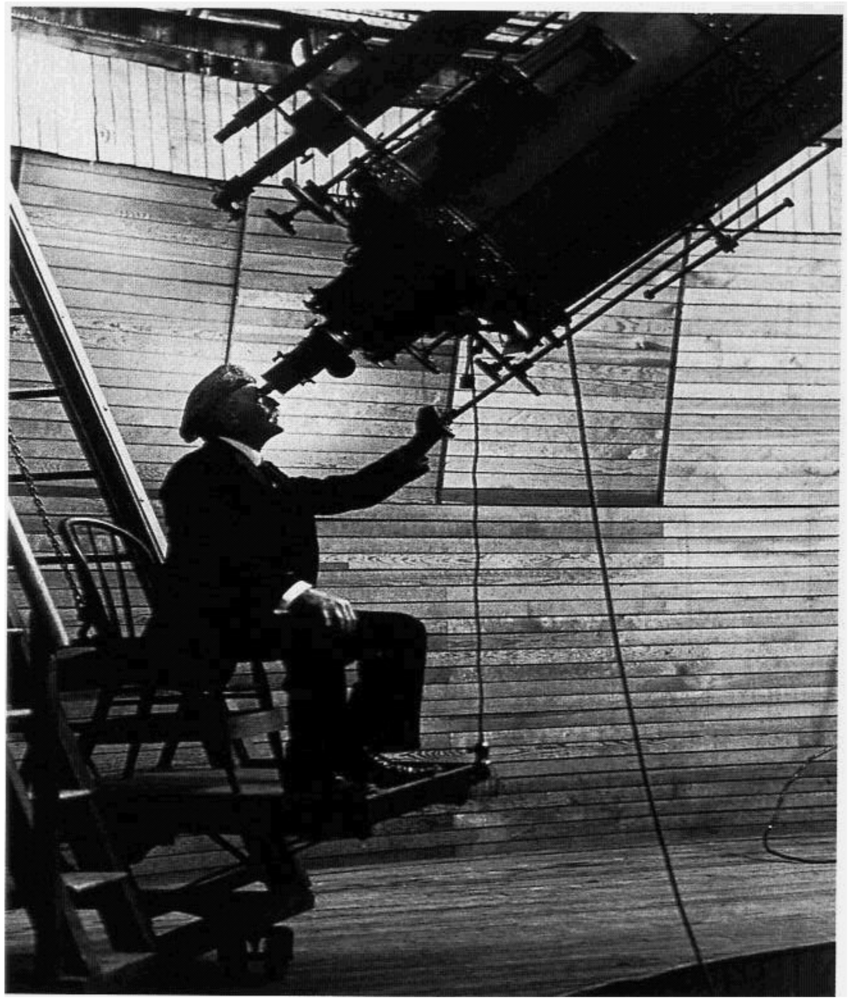
Ground-based observations

Percival Lowell

Lowell Observatory
(Arizona)



[Image source: Wikimedia Commons]



Mars from Hubble Space Telescope

Mars Pathfinder (1997)

Mars Exploration Rovers (2004)

Orbiting spacecraft:

Mars Reconnaissance Orbiter (NASA)

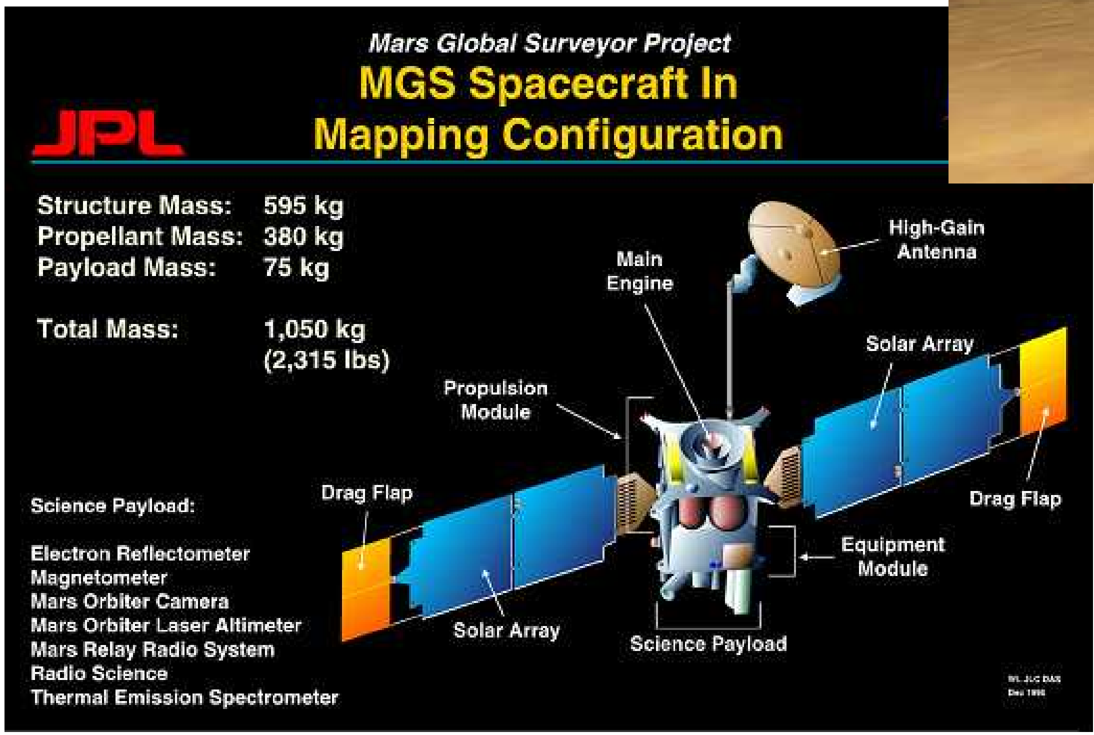
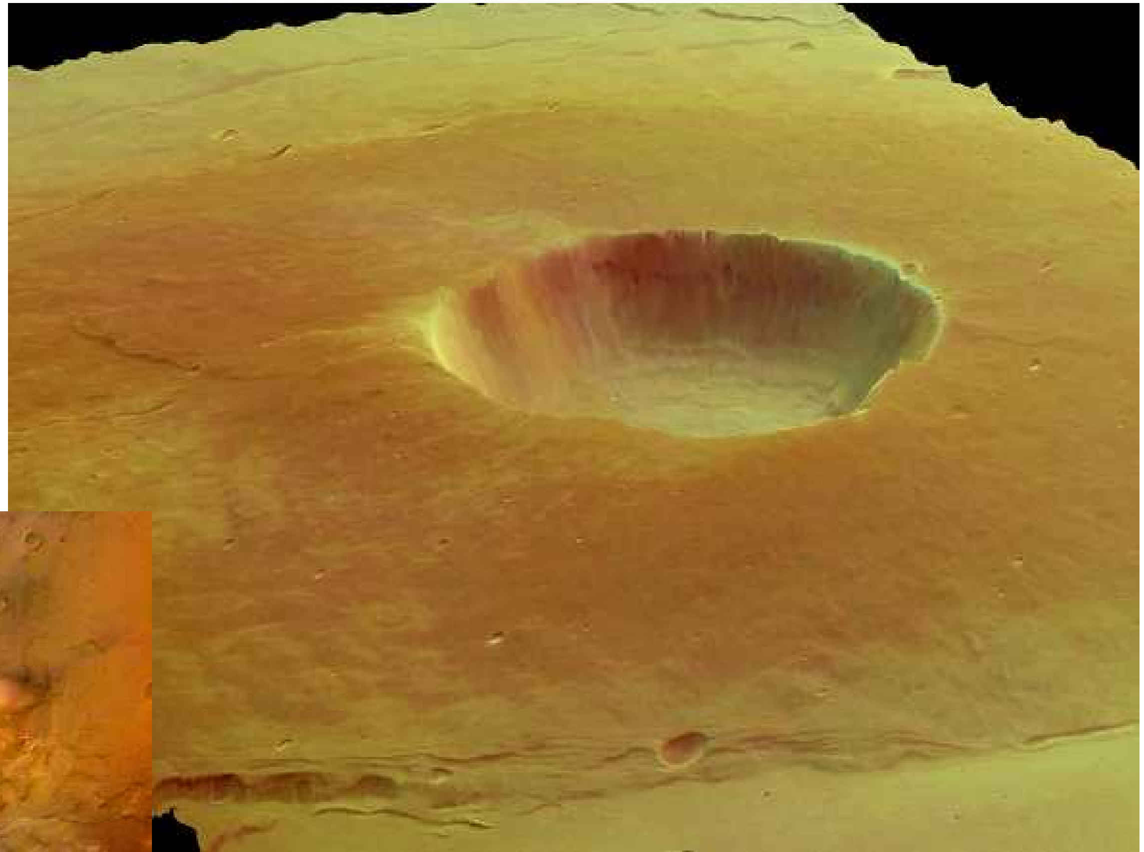
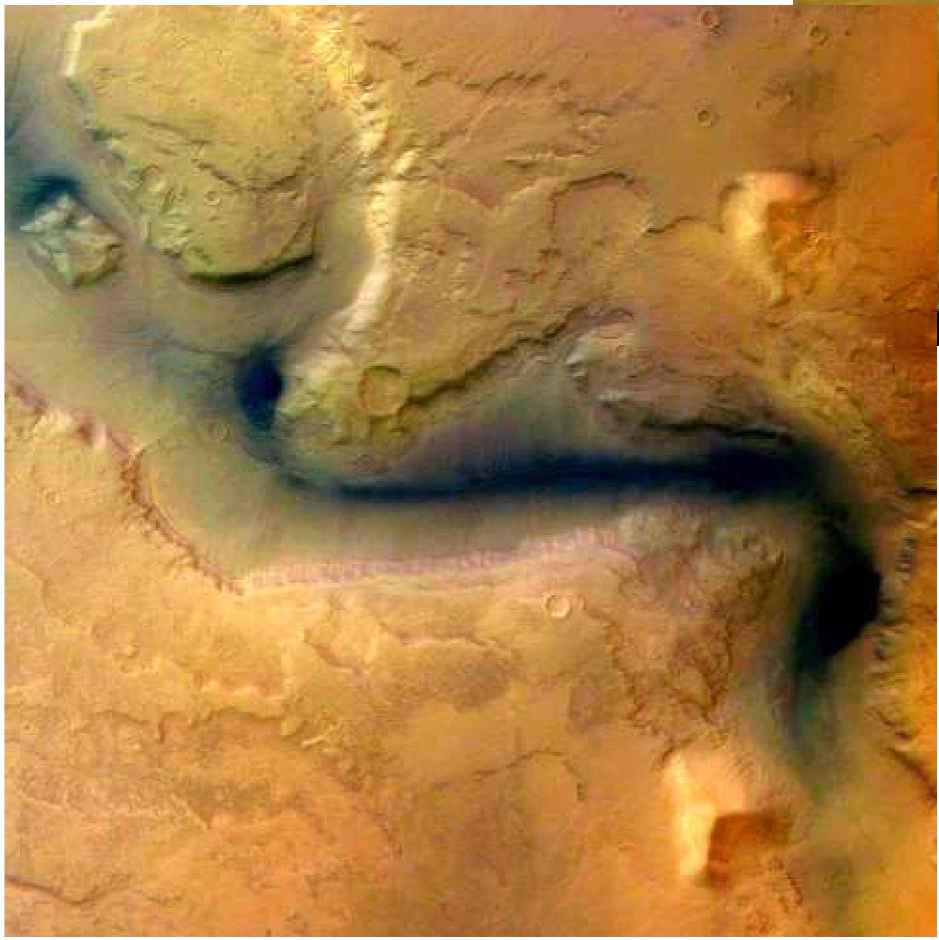


Image credits: NASA/JPL/Caltech

Mars Express orbiter (ESA)

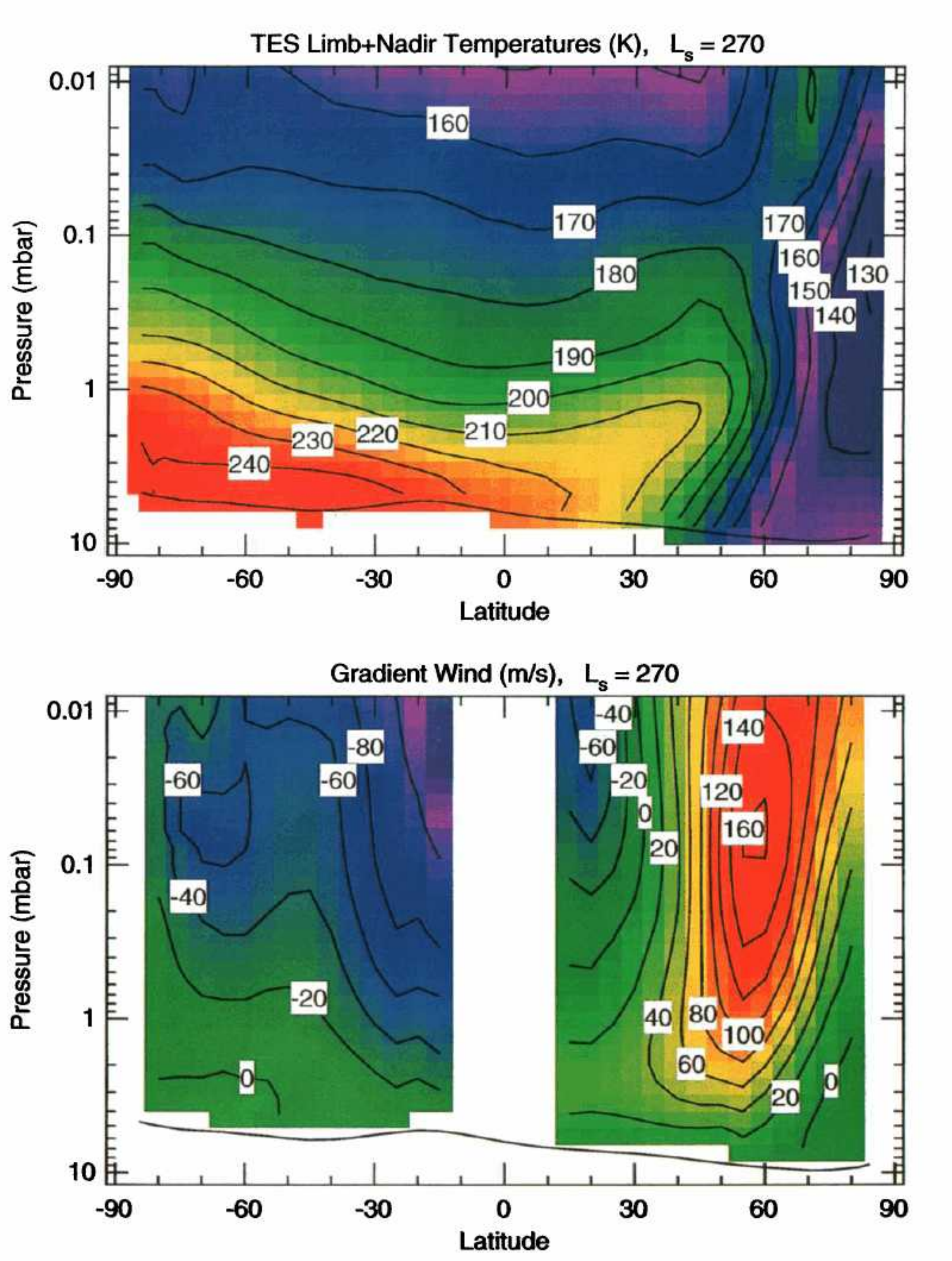




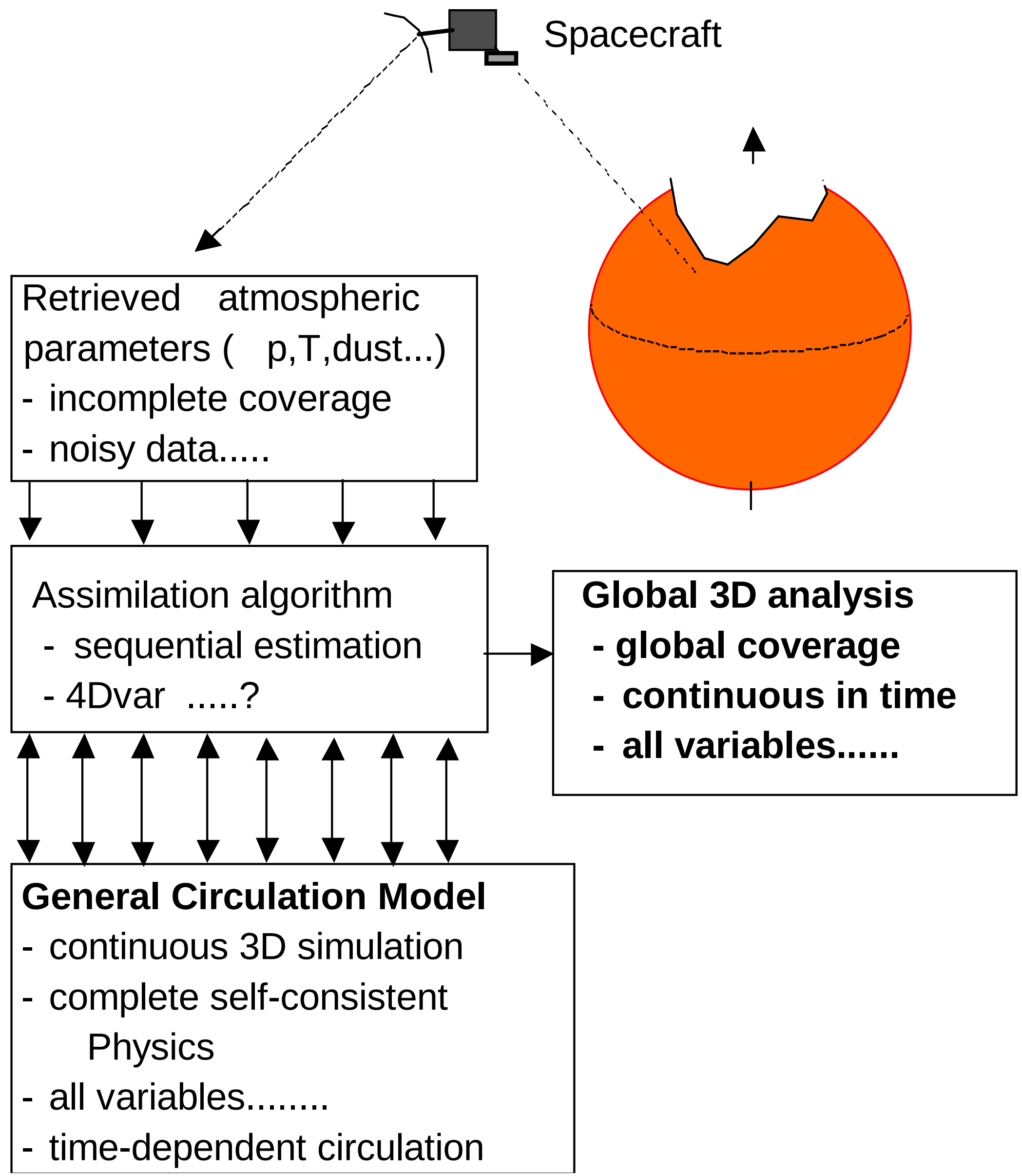
- Stereo imaging
- Infrared sounding/mapping
- UV/visible/radio occultation
- Subsurface radar
- Magnetic field and particle environment

MGS/TES Atmospheric mapping

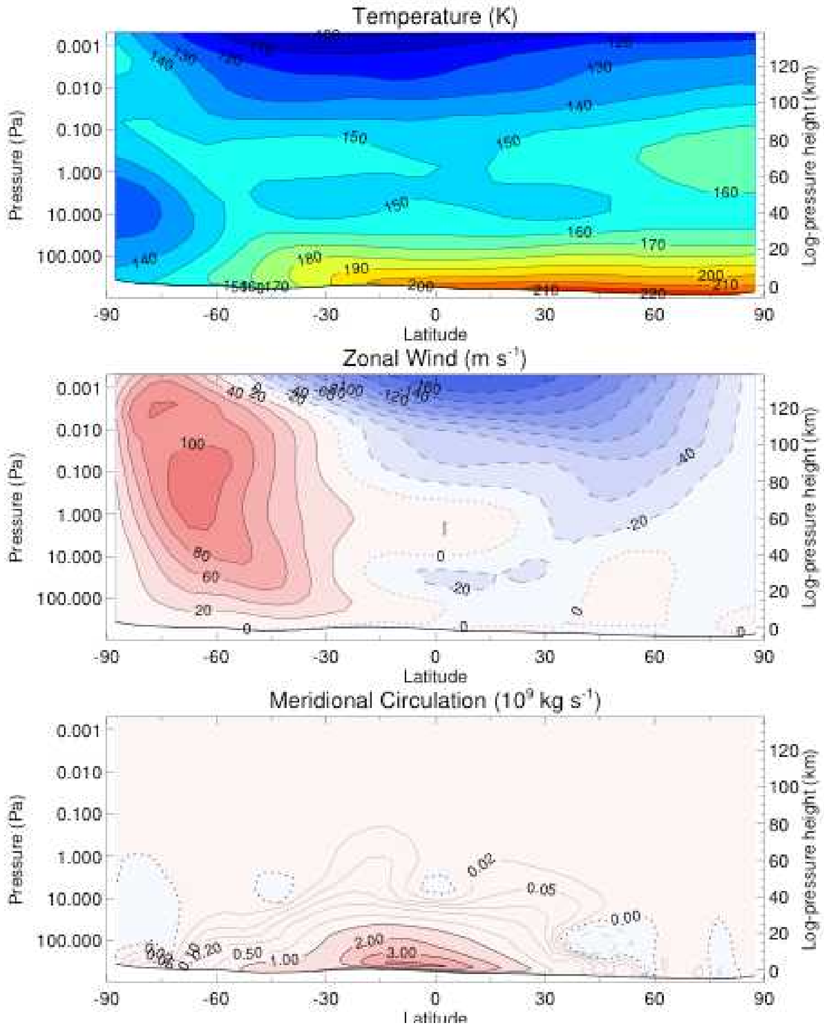
From: Smith et al. (2000)
J. Geophys. Res., 106, 23929



DATA ASSIMILATION



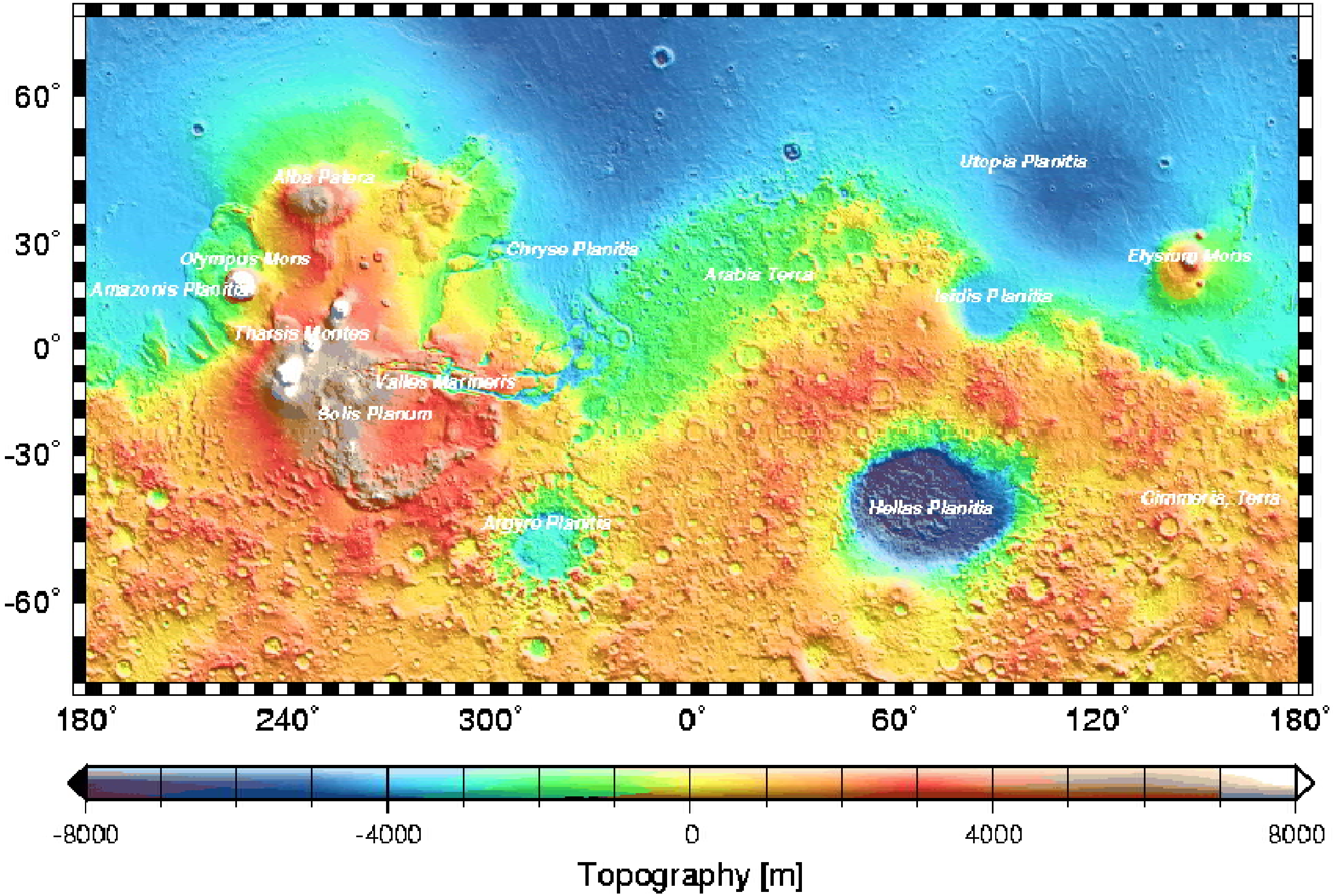
LMD-Oxford/OU-IAA European Mars Climate model



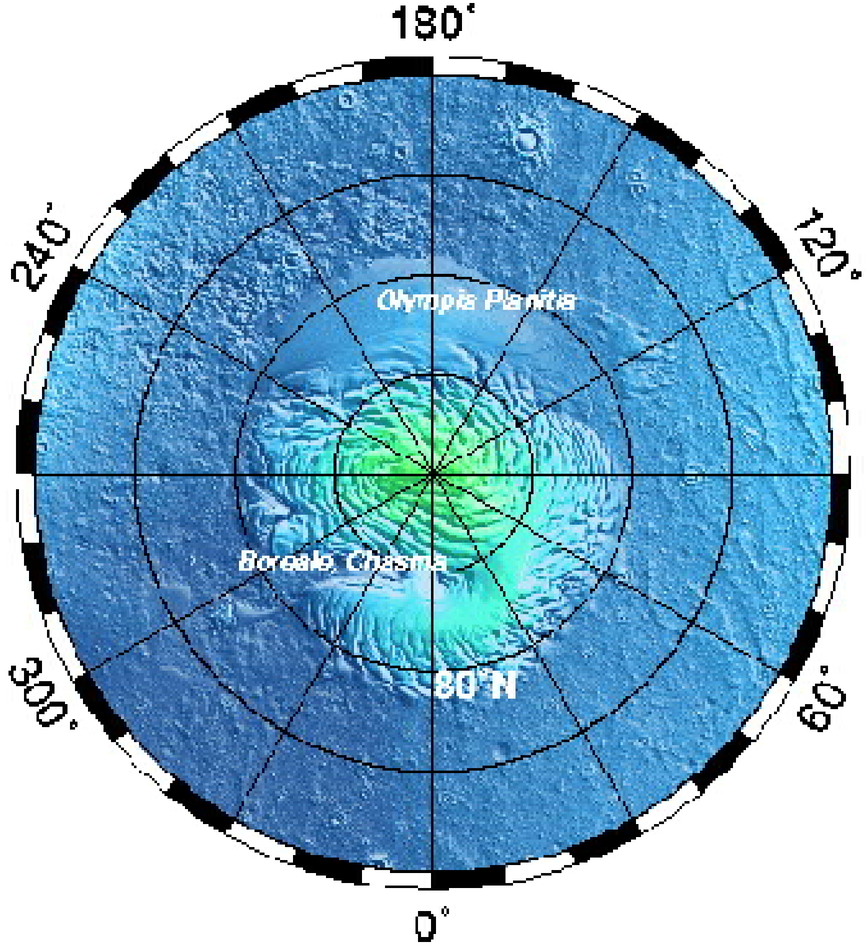
- Global numerical model of Martian atmospheric circulation (cf Met Office, NCEP, ECMWF…)
- High resolution dynamics
  - Typically T31 (3.75º x 3.75º)
  - Most recently up to T170 (512 x 256)
  - 32 vertical levels stretched to ~120 km alt. ($s = p/p_s$)
  - Surface topography & thermal properties
- Radiative transfer (solar heating and IR cooling)
- Seasonal and diurnal cycles
- CO_2, dust and H_2O transport
- Boundary layer mixing
- Sub-gridscale orographic drag

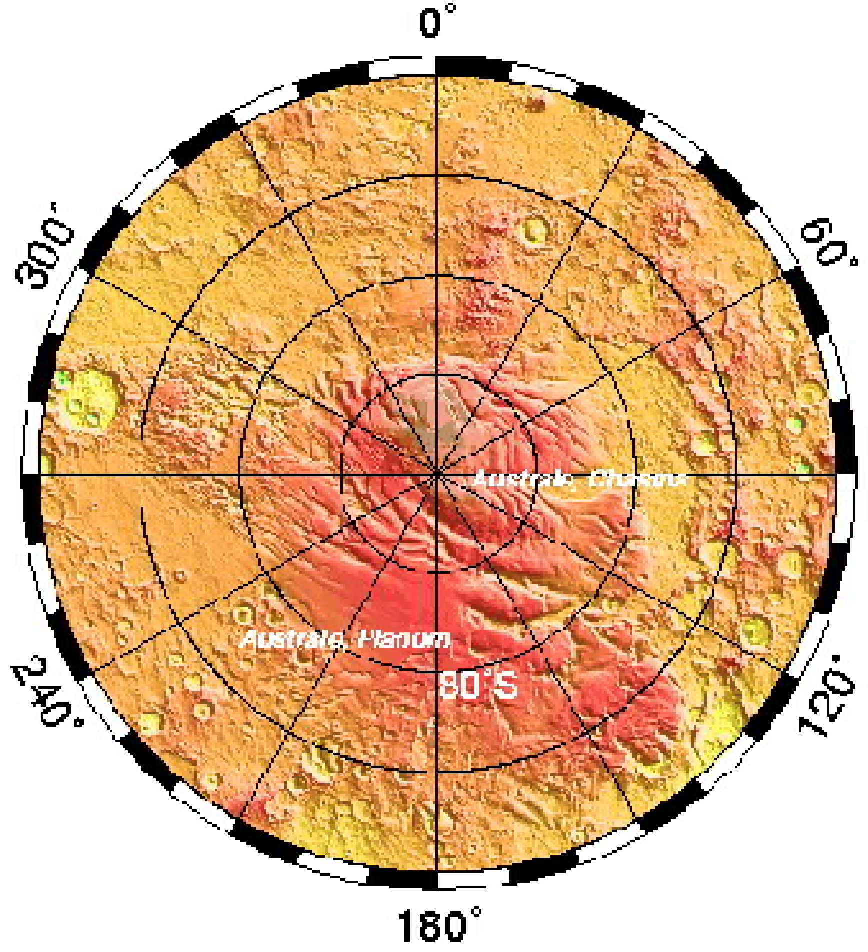
	Earth	Mars
Mean orbital radius (10^{11} m) Distance from Sun (AU)	1.50 0.98 - 1.02	2.28 1.38 - 1.67
Orbital eccentricity	0.017	0.093
L_s of perihelion (°)	281	251
Planetary obliquity	23.93°	25.19°
Rotation rate, Ω (10^{-5} s^{-1})	7.294	7.088
Solar day, sol (s)	86,400	88,775
Year length (sol) Year length (Earth days)	365.24 365.24	668.6 686.98
Equatorial radius (10^6 m)	6.378	3.396
Surface gravity, g (m s^{-2})	9.81	3.72
Surface pressure (Pa)	101,300	600 (variable)
Atmospheric constituents (molar ratio)	N_2 (77%) O_2 (21 %) H_2O (1 %) Ar (0.9 %)	CO_2 (95 %) N_2 (2.7 %) Ar (1.6 %) O_2 (0.13 %)
Gas constant R (m^2 s^{-2} K^{-1})	287	210
c_p/R	3.5	4.4
Mean Solar Constant (W m^{-2})	1367	589
Bond Albedo	0.306	0.25
Equilibrium temperature, T_e (K)	256	210
Scale height, $H = RT_e/g$ (km)	7.5	10.8
Surface temperature (K)	230-315	140-290
Dry adiabatic lapse rate (K km^{-1})	9.8	4.5
Buoyancy frequency, N (10^{-2} s^{-1})	1.1	0.6
Deformation radius, $L = NH/\Omega$ (km)	1100	920

MOLA Topography

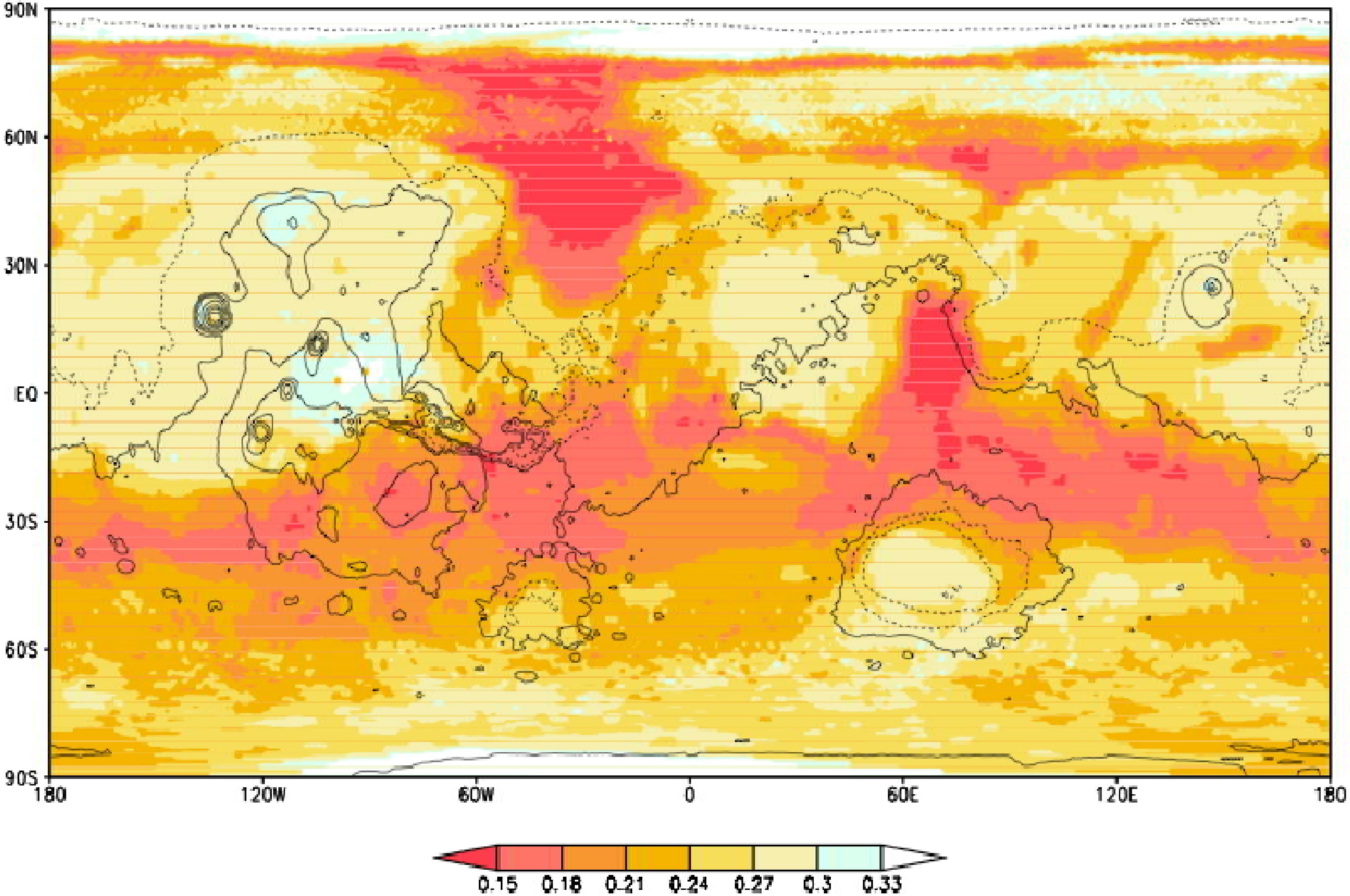


MOLA topography: polar regions

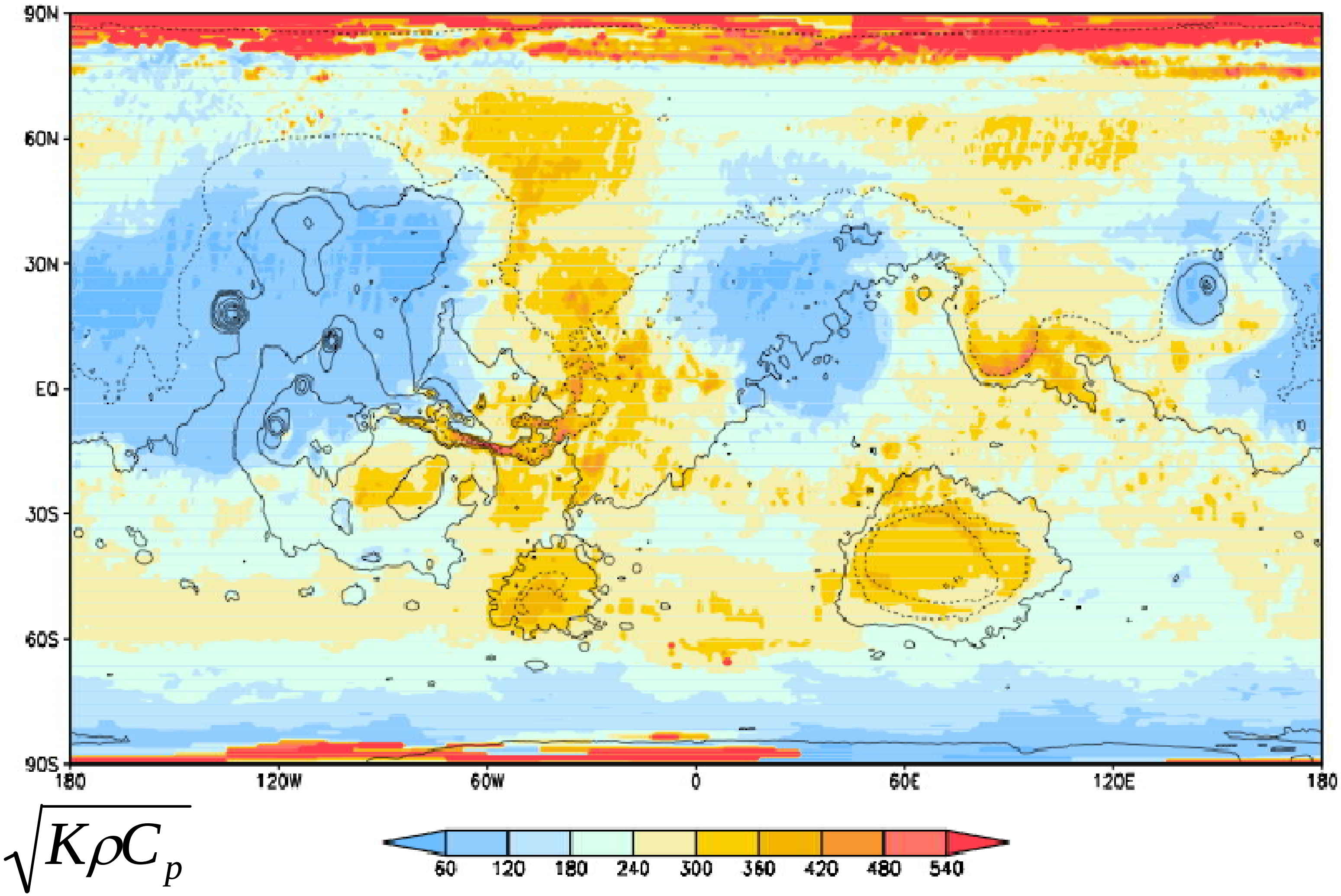




Mars surface properties: albedo (Viking)



Mars surface properties: thermal inertia (MGS + Viking)

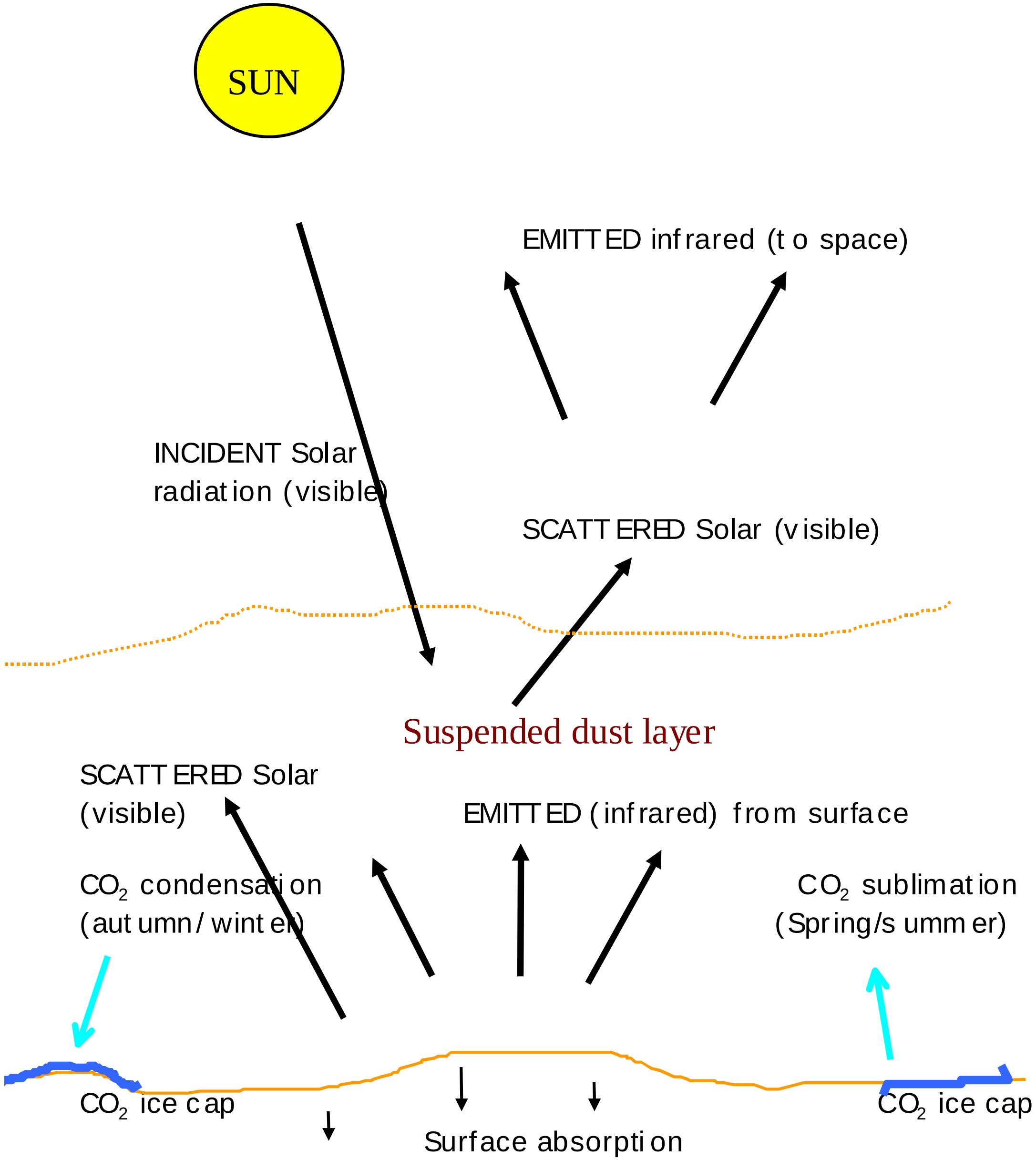


$$I = \sqrt{K \rho C_p}$$

Physical processes needed to model large-scale atmosphere

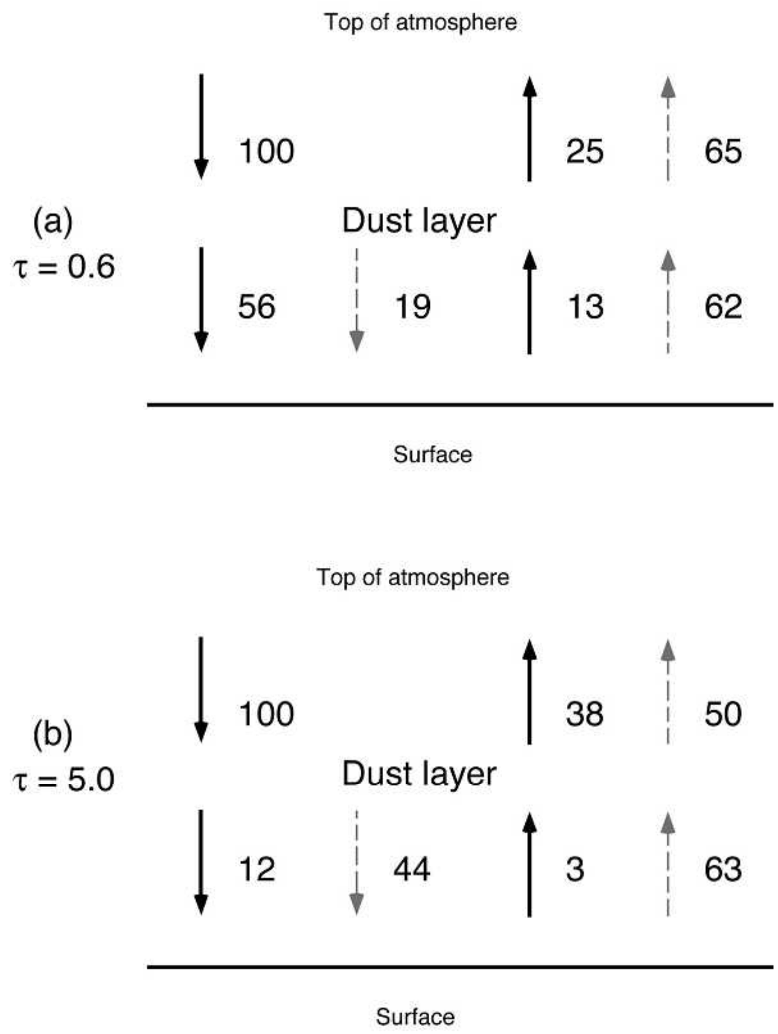
- Radiative transfer
  - Solar heating of surface, and atmosphere via dust absorption
  - Infrared CO_2 band cooling (especially around 667 cm^{-1})
  - nonLTE near-infrared heating of CO_2 and nonLTE cooling effects above ~60-80 km.
- Surface processes, thermal diffusion in soil model
- Convective mixing
- Planetary boundary layer
  - Turbulence closure
- Orographic drag and internal gravity wave breaking
- CO_2 condensation, snow and sublimation (NB peculiar to Mars)
- Radiatively interactive dust transport, lifting and deposition
- Water vapour transport, sources and sinks…..

SCHEMATIC ENERGY BUDGET

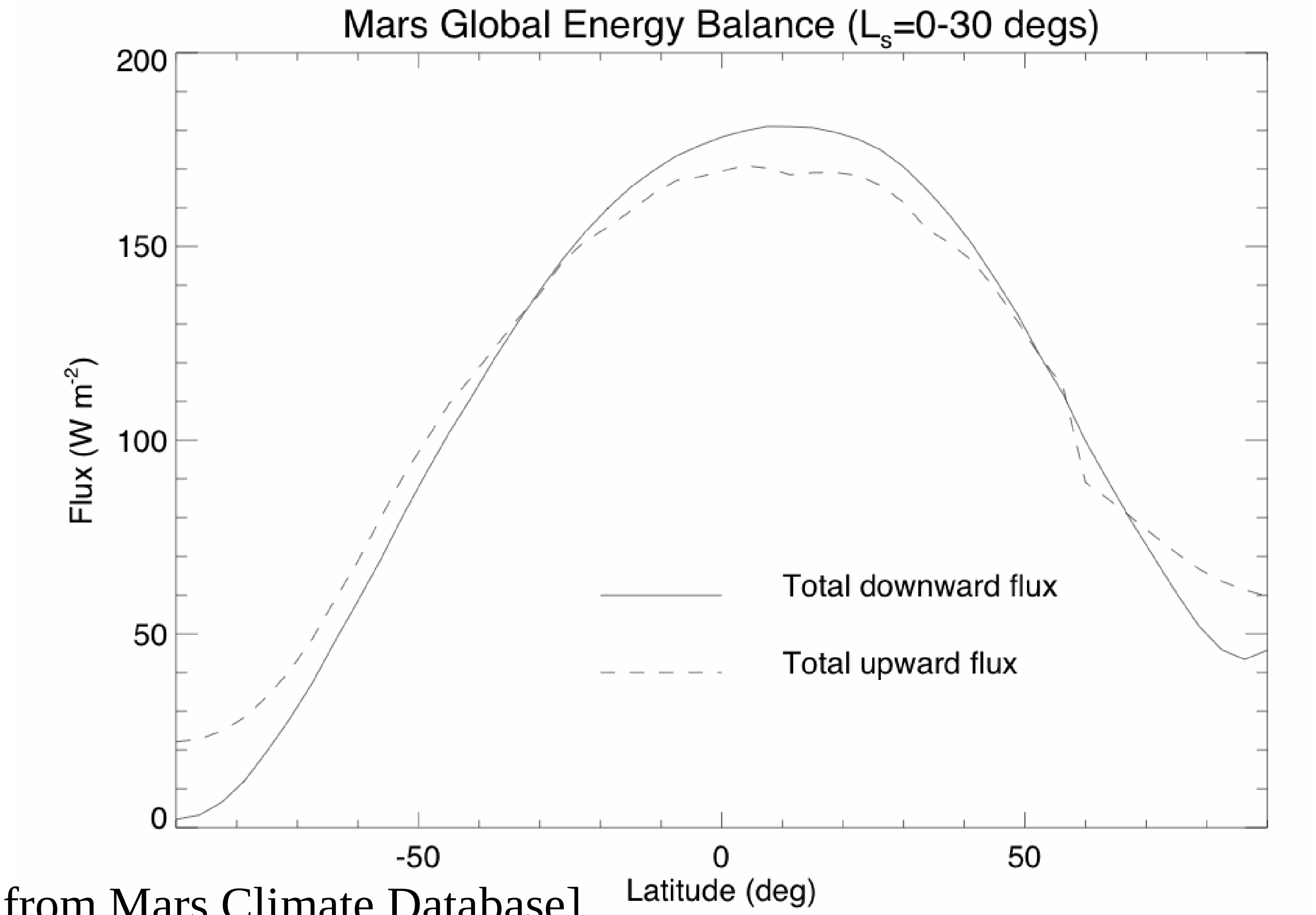


Quantitative energy budget

- Mid-latitude energy radiative energy fluxes
  - Roughly in balance
  - Computed in UK Mars GCM
- 100 (arbitrary) units of solar input [solid]
- ~90-100 (arbitrary) units of infrared emission to space
- Absorption of solar radiation by dust and at surface

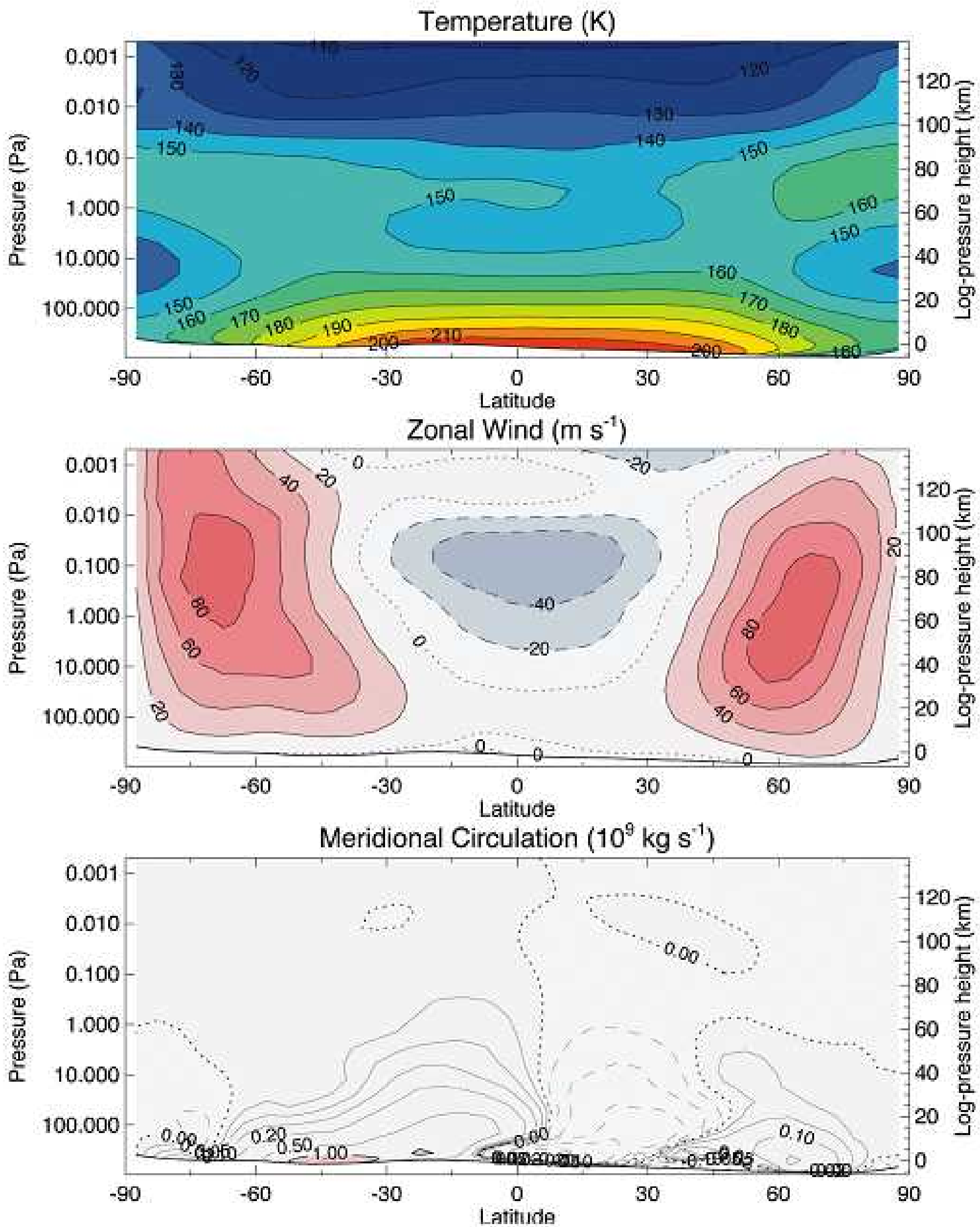


Global Energy Budget



[Data from Mars Climate Database]

Mars Annual mean circulation
[Read & Lewis 2004]

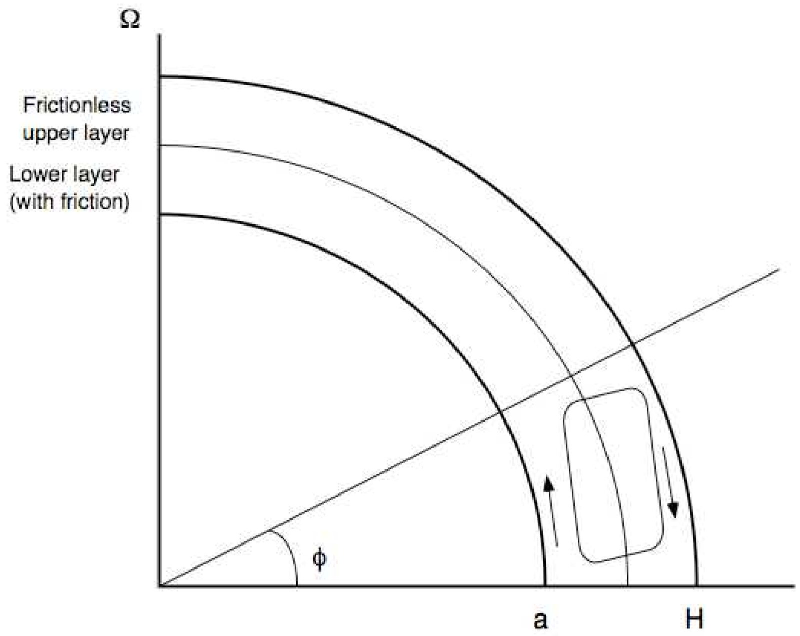


Seasonal variations of the zonal mean circulation on Mars (Oxford MGCM)

QuickTime™ and a
Animation decompressor
are needed to see this picture.

Held-Hou model of Hadley circulations

- ‘Nearly inviscid’ symmetric Hadley circulation
  - Held & Hou, *J. Atmos. Sci.*, ***37,*** 515-533 (1980)
- Upper (poleward) branch conserves angular momentum
- Zonal flow ‘balanced’
  - *Geostrophic/thermal wind*
  - *Cyclostrophic?*
- Surface winds assumed to be ‘small’ (~0)
- Thermal ‘eddy diffusion’ assumed negligible



Held & Hou analytical model of Hadley circulation

- Take a radiative equilibrium potential temperature profile, θ_E

$$\theta_E = \theta_{E0} - \frac{2}{3}\Delta\theta P_2(\sin\phi) \approx \theta_{E0} - \frac{\Delta\theta}{a^2} y^2 \quad [\text{noting } \sin\phi \approx y/a]$$

- Find a zonal wind, u_M, which conserves angular momentum from the equator ($m = \Omega a^2 = \Omega a^2 \cos^2\phi + ua\cos\phi$)

$$u_M = \frac{\Omega a^2 \sin^2\phi}{a\cos\phi} \approx \frac{\Omega y^2}{a}$$

- Approximate vertical wind shear and apply the thermal wind eqn

$$\frac{\partial u}{\partial z} \approx \frac{u_M}{H} = \frac{\Omega y^2}{aH} = -\frac{g}{2\Omega\theta_0 \sin\phi}\frac{\partial\theta}{\partial y}$$

- Rearrange and integrate to find θ_M, consistent with AM conservation

$$\frac{\partial\theta}{\partial y} = -\frac{2\Omega^2\theta_0}{a^2 gH} y^3; \quad \text{so that} \quad \theta_M = \theta_{M0} - \frac{\Omega^2\theta_0}{2a^2 gH} y^4$$

- The Hadley cell lies between *y* = ±*Y* with $\theta = \theta_E$ for |*y*| > *Y*
  - Offsets $\theta_M = \theta_E$ at *y* = ±*Y*
  - No net heating/cooling across the Hadley regime so, assuming heating is linear in $\theta_E - \theta_M$

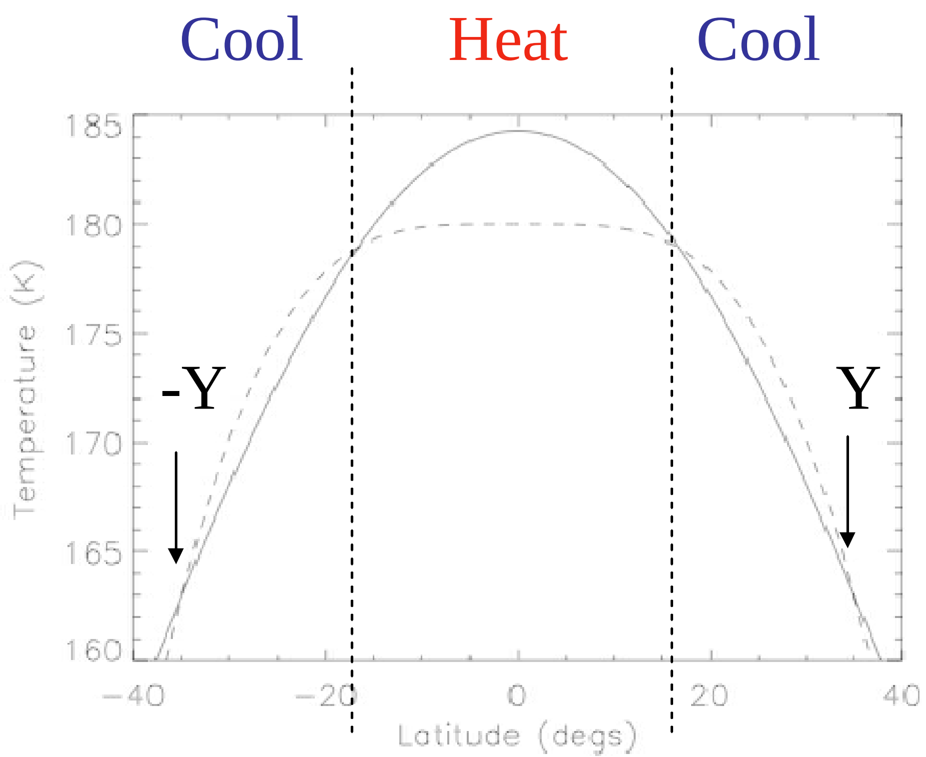
$$\int_0^Y \theta_M dy = \int_0^Y \theta_E dy$$

- This gives two equations which can be solved for *Y* and $\theta_E - \theta_M$

$$Y = \left(\frac{5gH\Delta\theta}{3\Omega^2\theta_0} \right)^{\frac{1}{2}} \qquad \theta_{E0} - \theta_{M0} = \frac{5gH\Delta\theta^2}{18a^2\Omega^2\theta_0}$$

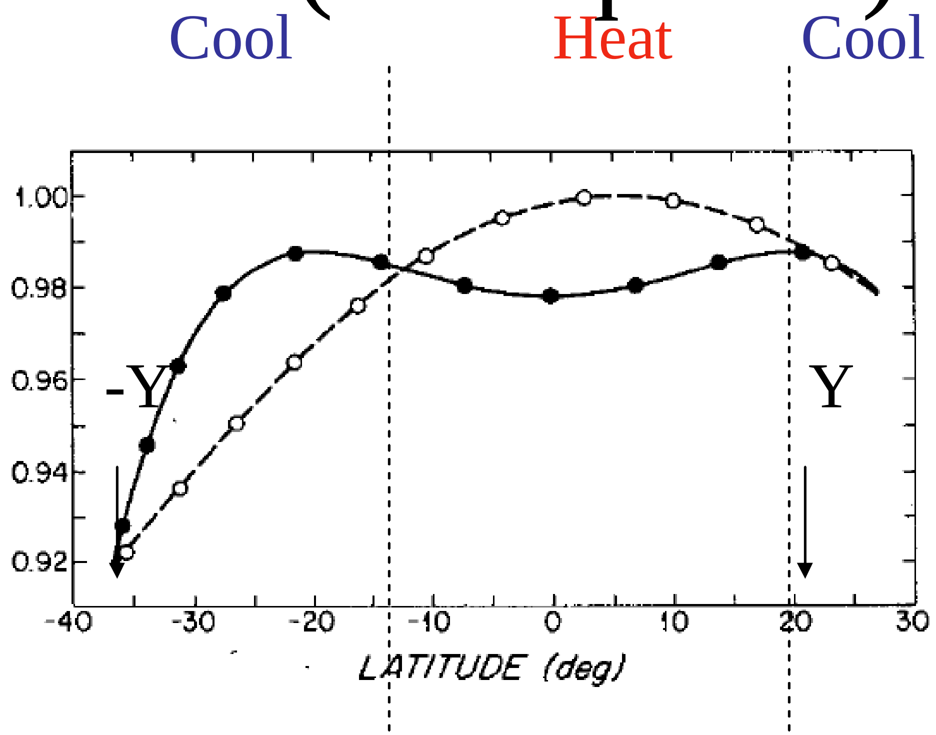
- For typical Earth values, *Y* ~ 2000 km and $\theta_E - \theta_M$ ~ *0.8* K

Held-Hou temperature structure



- Heating rate determined by difference between θ_M and θ_E

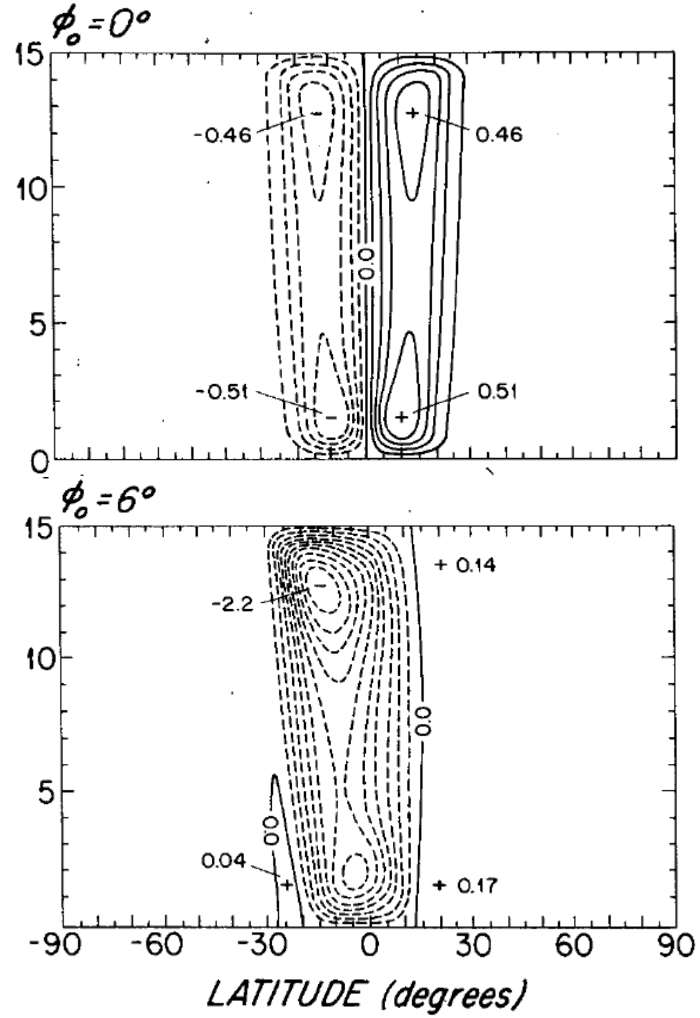
Held-Hou temperature structure (off-equator)



- Heating rate determined by difference between θ_M and θ_E
- Lindzen & Hou (1988, *J. Atmos. Sci.*, **45**, 2416)

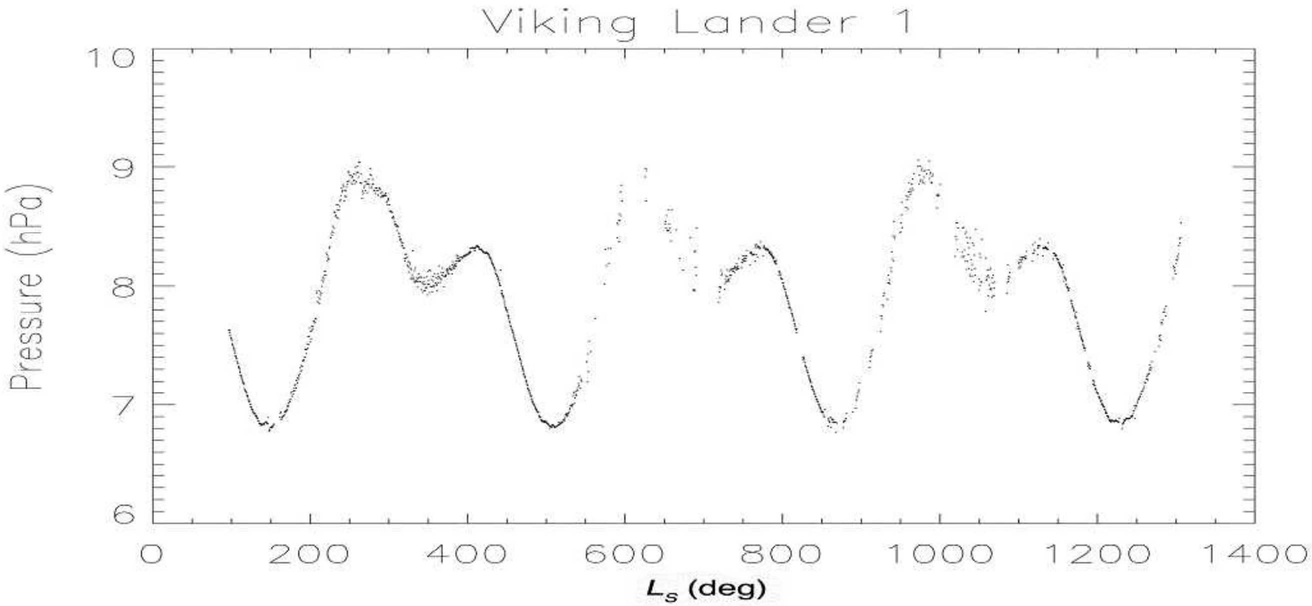
Held-Hou modified for off-equatorial heating

- Original Held-Hou model designed for solar heating centred on the equator
- Can also modify for off-equatorial heating distribution
  - Lindzen & Hou (1988, *J. Atmos. Sci.*, **45**, 2416)
- Small offset leads to almost complete dominance of one Hadley cell

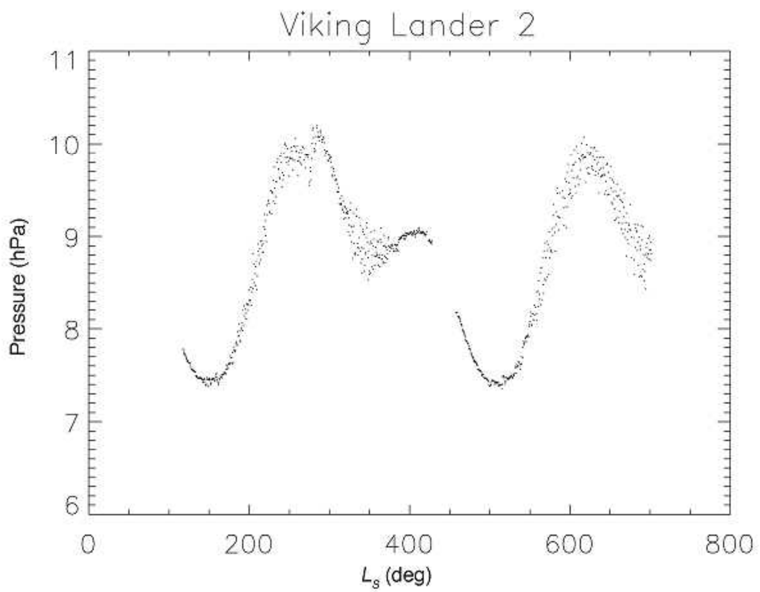


Pressure variations

- VL1 (23^{o}N)

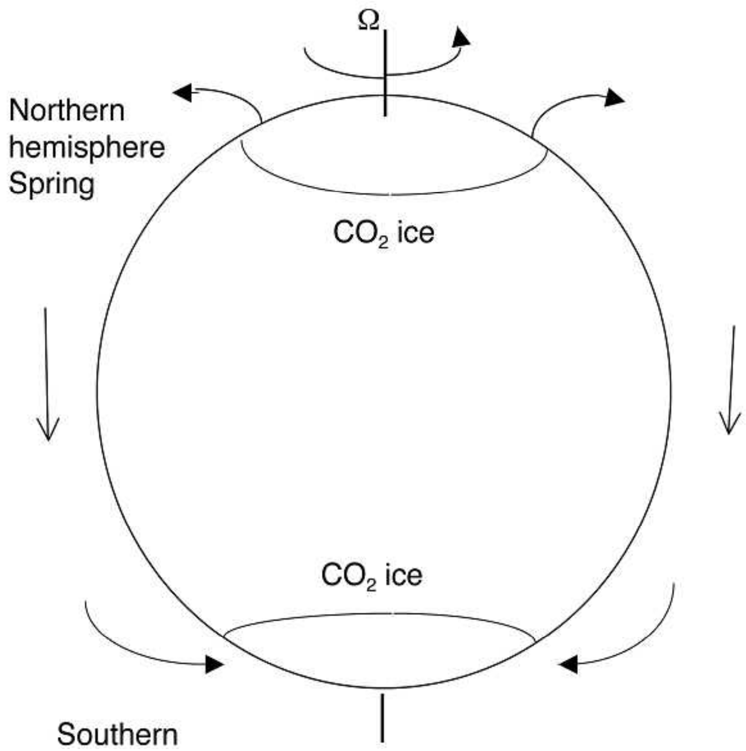


- VL2 (48^{o}N)

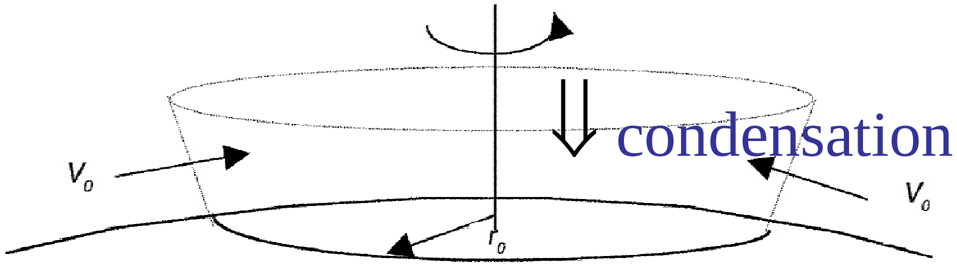


Seasonal CO_2 cycle on Mars: condensation flow

- CO_2 sublimes/condenses at T~140 K (around p~600 Pa)
- Latent heat L = 5.9 x 10^5 J kg^{-1}
- This temperature is regularly reached during polar winter on Mars, so that a substantial mass of CO_2 is transported between the poles during the seasonal cycle
- ~1/3 of atmospheric mass condenses onto winter pole
- How does this modify the atmospheric circulation?



Seasonal CO_2 condensation



Mass balance

- To answer these questions we formulate a simple model, based on the assumption that, during polar night, the condensation rate for CO_2 ice is determined by a *local* energy balance such that
- Radiative heat loss = latent heat release on condensation
- Thus for unit area at the condensation temperature T_c

$$\varepsilon\sigma T_c^4 = L\partial M_c / \partial t$$

where M_c is the mass of condensate per unit area.

Mass balance

- Consider mass coming from the other hemisphere to condense onto the winter pole. We conserve mass across a vertical ‘cylindrical’ surface at radius r_0 from the pole. Thus

$$\int_0^{r_0} \partial M_c / \partial t \, 2\pi r dr = \int_0^{\infty} v_0 \rho 2\pi r_0 dz$$

- If we take the density variation with height to be $\rho = \rho_0 \exp(-z/H)$, where H is the density scale height (around 10km on Mars) then we can evaluate the above integrals

$$2\pi r_0 H v_0 \rho_0 = \pi r_0^2 \varepsilon \sigma T_c^4 / L$$

- So that we can evaluate the vertically-averaged meridional wind v_0 as

$$v_0 = \varepsilon \sigma T_c^4 r_0 / [2\rho_0 H L]$$

- Putting in suitable numbers for Mars gives $v_0 \sim 0.5$ m s^{-1}

Implications for zonal wind?

- To estimate this, simplify the zonal equation of motion

$$\partial u / \partial t + fv \approx -u / \tau_{drag}$$

- Where f is the Coriolis parameter and τ_{drag} a frictional time-scale. In the steady state

$$u \approx -fv_0 \tau_{drag}$$

- For Mars, take $f \sim 10^{-4}$ s^{-1}, τ_{drag} ~ 2 days and v_0 ~ 0.5 m s^{-1}. This gives u ~ 10 m s$^{-1.}$
- Such a flow is significant close to the ground, but only a small perturbation to the zonal wind in the middle and upper atmosphere.

Effects of topography: geostrophic contours

- Potential vorticity equation for the nonlinear free surface equations (derived in Further GFD eq. 14)

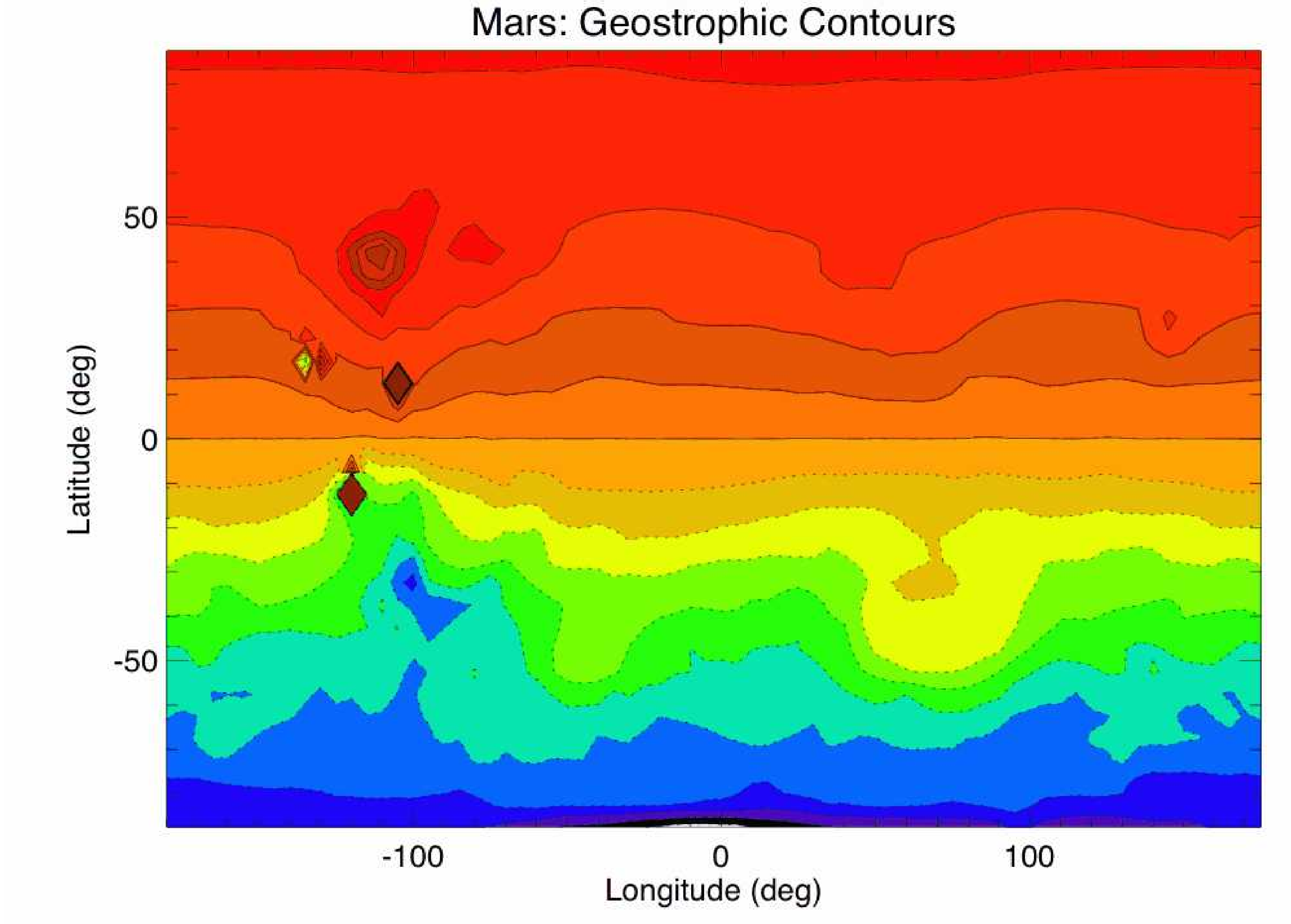
$$\left(\frac{\partial}{\partial t}+u\frac{\partial}{\partial x}+v\frac{\partial}{\partial y}\right)\left(\frac{f+\xi}{h}\right)=0$$

- Where ξ is the *relative* vorticity and *h* the depth of a fluid column.
- For weak flow

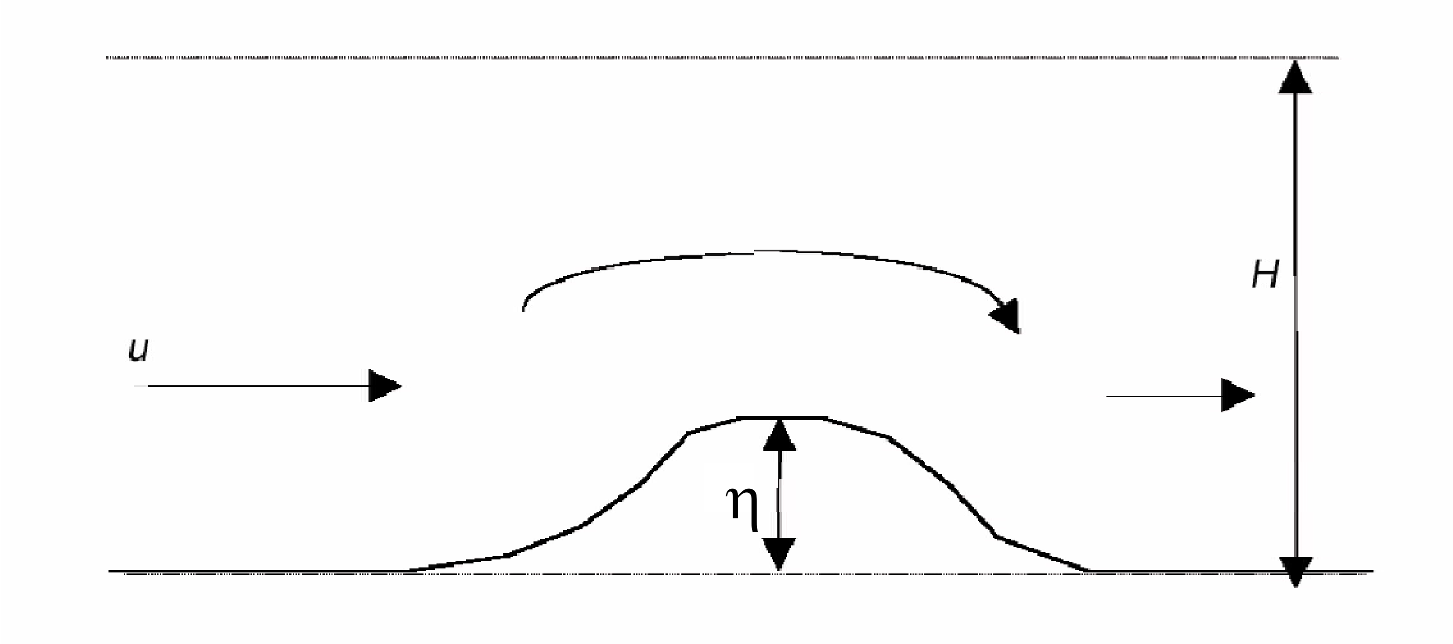
$$\frac{f+\xi}{h}\approx\frac{f}{h}$$

- If PV is conserved, we therefore expect flow to follow contours of *f/h*.
- We can plot $f/(H - \eta)$ as an estimate of the fluid `depth', if *H* is the atmospheric scale height and $\eta(x,y)$ is the height of the topography.
- Note that this *only* applies if the flow is weak and on timescales over which PV is conserved. These may be short (~days) on Mars where diabatic processes are strong.

Effects of topography:



Effects of topography: stationary Rossby waves



- Consider the effects of topography on a zonal flow *u* as generation of uplift. This can be analysed using the quasi-geostrophic *vorticity equation*

(1) $$\left(\frac{\partial}{\partial t} + u_g \frac{\partial}{\partial x} + v_g \frac{\partial}{\partial y}\right)\zeta = f_0 \frac{\partial w_a}{\partial z}$$

- Where the *absolute vorticity* ζ *is* $\zeta = f_0 + \beta y - \frac{\partial u_g}{\partial y} + \frac{\partial v_g}{\partial x}$

Stationary Rossby waves

- Over topography, η, the flow is deflected upwards with speed w at the lower boundary, so

$$\frac{\partial w_a}{\partial z} \approx -\frac{w}{H} = -\frac{\mathbf{u}_g \cdot \nabla \eta}{H}$$

- Now consider *barotropic flow* and *linearise* (1) about a steady, uniform, zonal flow $U(y)$, so that $\boldsymbol{u_g} = (U+u,v)$.
- Neglecting products of u, v, η and their derivatives, the vorticity equation becomes

$$U\frac{\partial \nabla^2 \psi}{\partial x} + v\left(\beta - \frac{\partial^2 U}{\partial y^2}\right) = -f_0 \frac{U}{H}\frac{\partial \eta}{\partial x} \qquad (2)$$

- Where $(u,v) = (-\partial\psi/\partial y, \partial\psi/\partial x)$

- Look for wave-like solutions

$$\psi = \psi_0 \exp(i[kx + ly]), \text{ so } \nabla^2\psi = -(k^2 + l^2)\psi = -K^2\psi$$

- Take topography to be composed of a series of wave-like components

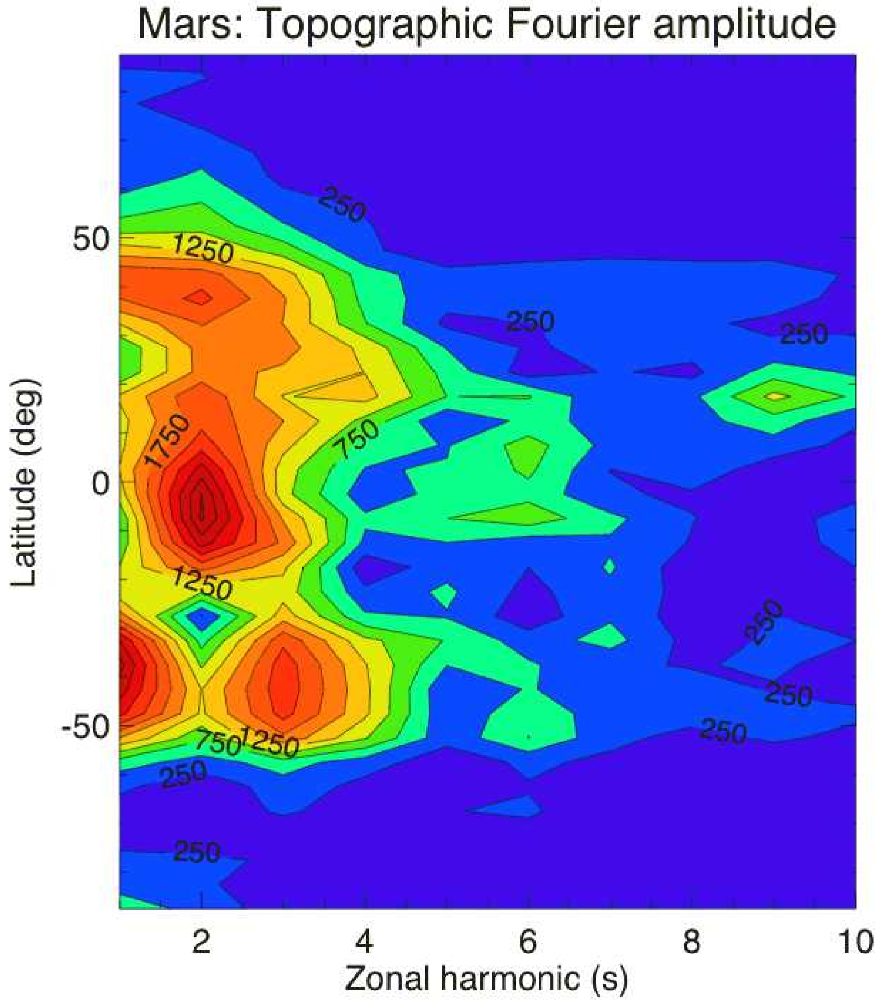
$$\eta = \eta_0 \exp(i[kx + ly]).$$

- We can now solve (2) for the amplitude of ψ for each wavenumber K to give

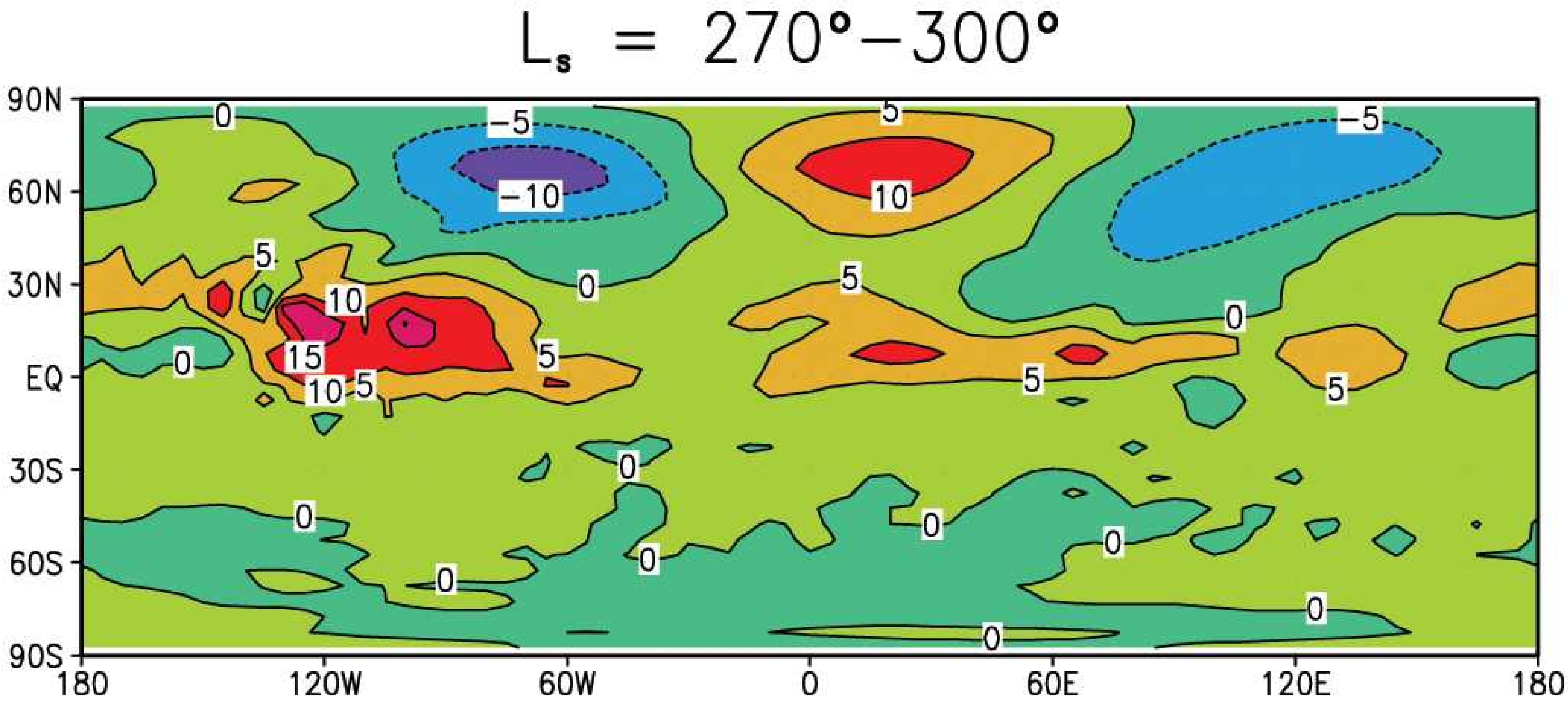
$$\psi_0 = \frac{f_0\eta_0}{(H[K^2 - \beta'/U])}$$

- Where $\beta' = \beta - \partial^2 U/\partial y^2$
- There is a resonant response to topography at $K = \sqrt{\beta'/U}$
- [Compare the *Charney-Drazin criterion* for stationary waves.]
- For Mars, this implies stationary waves of planetary wavenumbers 1-3 might be expected in the *winter* hemisphere ONLY (so $U > 0$).

Stationary waves: Mars topographic spectrum

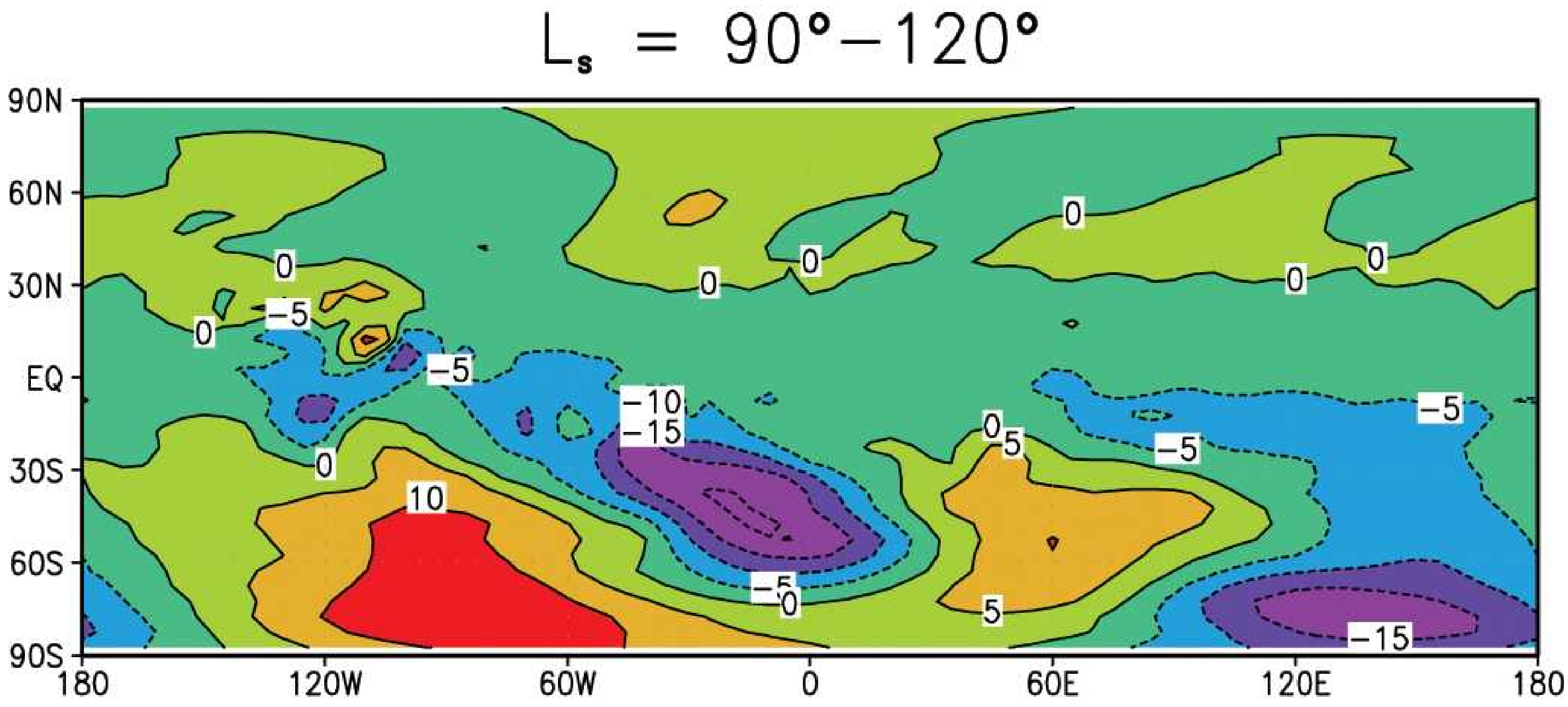


Stationary waves: NH Winter



(meridional velocity v, m s^{-1})

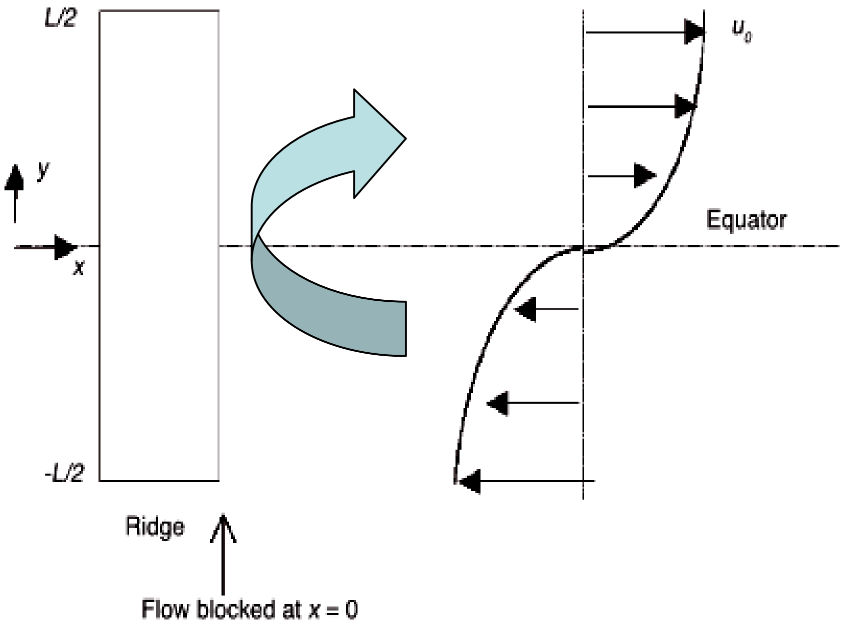
Stationary waves: SH Winter



(meridional velocity v, m s^{-1})

Western boundary currents: 'Monsoon circulations'

- Mars has major continent-sized mountain ridges which cross the equator. These rise to altitudes comparable to the pressure scale height and can block flow at low latitudes.
- These obstacles can facilitate north-south flow across the equator (normally inhibited by PV constraints) in the lower branch of the Hadley circulation inf the form of frictional (or inertial) western boundary currents.
- Such flows are similar to those occurring in the Earth's oceans, e.g. the Gulf Stream



- Consider barotropic, non-divergent flow on an equatorial β-plane. The *x* and *y* components of the equation of motion and continuity equation are

$$-\beta y v = -\frac{\partial \Phi}{\partial x} - r(u - u_0(y)) \qquad (1)$$

$$\beta y u = -\frac{\partial \Phi}{\partial y} - r v \qquad (2)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad (3)$$

- Where *r* is the surface drag parameter and $u_0(y)$ is the imposed zonal flow
- Take $\partial(2)/\partial x$- $\partial(1)/\partial y$ to obtain a vorticity equation

$$\beta v = -r\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right) - r\frac{du_0(y)}{dy}$$

- Or, in terms of streamfunction ψ

$$\beta v + r\nabla^2\psi = -r\frac{du_0(y)}{dy} \qquad (4)$$

- For solsticial conditions on Mars, we can approximate the basic, thermally-forced zonal flow as

$$u_0(y) = U_0 \sin\left(\frac{\pi y}{L}\right); \text{ for } -\frac{L}{2} < y < \frac{L}{2}$$

- Hence (4) becomes

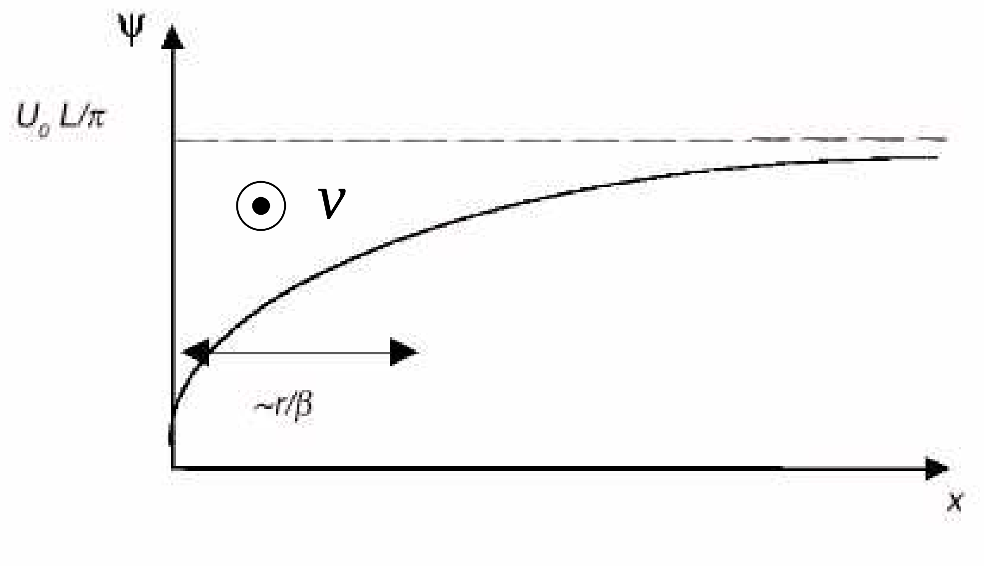
$$\beta \frac{\partial \psi}{\partial x} + r\nabla^2 \psi = -\left(\frac{r\pi U_0}{L}\right)\cos\left(\frac{\pi y}{L}\right) \qquad (5)$$

- This has the general (separable) solution

$$\psi = [A_1 \exp(ax) + A_2 \exp(bx) + U_0 L / \pi]\cos\left(\frac{\pi y}{L}\right)$$

- Where $a, b = -\frac{\beta}{2r} \pm \left(\frac{\beta^2}{4r^2} - \frac{\pi^2}{L^2}\right)^{1/2}$

Western boundary currents

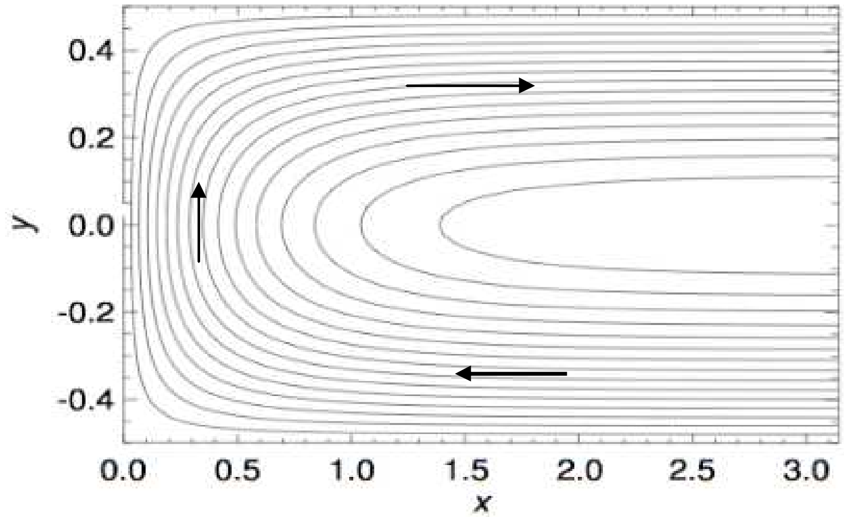


- Boundary conditions are $\psi=0$ at $x=0$ and ψ is bounded as $x\to\infty$.
- Also take $\partial\psi/\partial y = U_0$ at $y = L/2$ and $\partial\psi/\partial y = -U_0$ at $y = -L/2$.
- We take the low friction limit, $r\to 0$, which implies $a\to 0$ and $b\to -\beta/r$.
- The solution then tends to the form

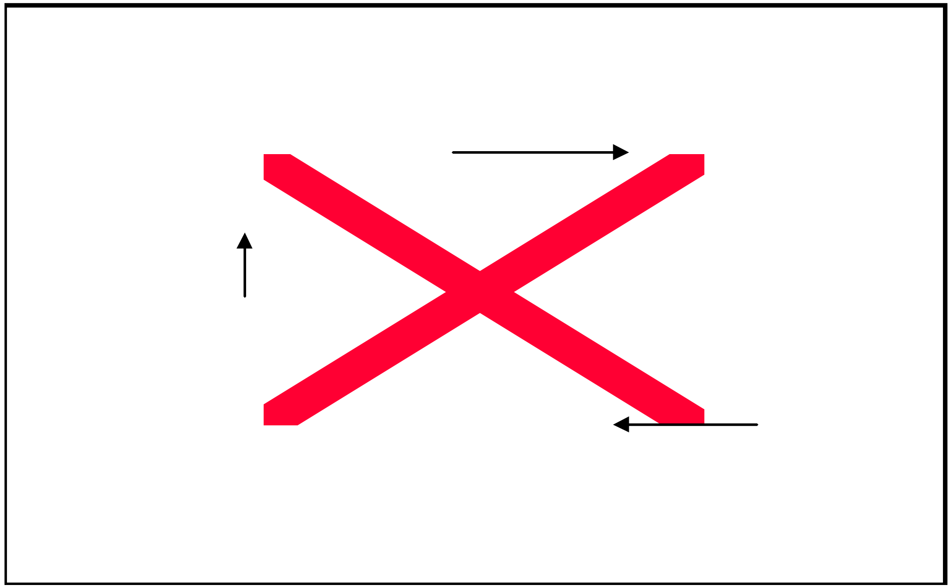
$$\psi = \left(\frac{U_0 L}{\pi}\right)\left[1-\exp\left(\frac{-\beta x}{r}\right)\right]\cos\left(\frac{\pi y}{L}\right)$$

Cross-equatorial WBCs

- Moderate friction:
  $\beta/r = 2$



- Weak friction:
  $\beta/r = 5$



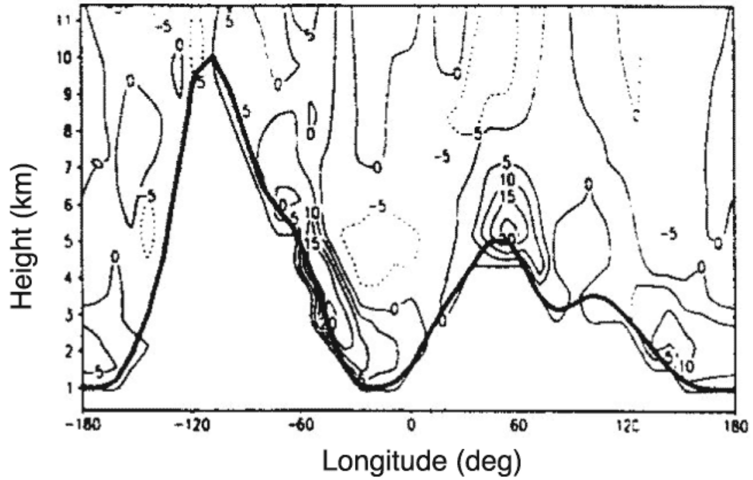
‘Monsoonal’ WBCs on Mars: SGCMs

- Oxford SGCM: T21L20

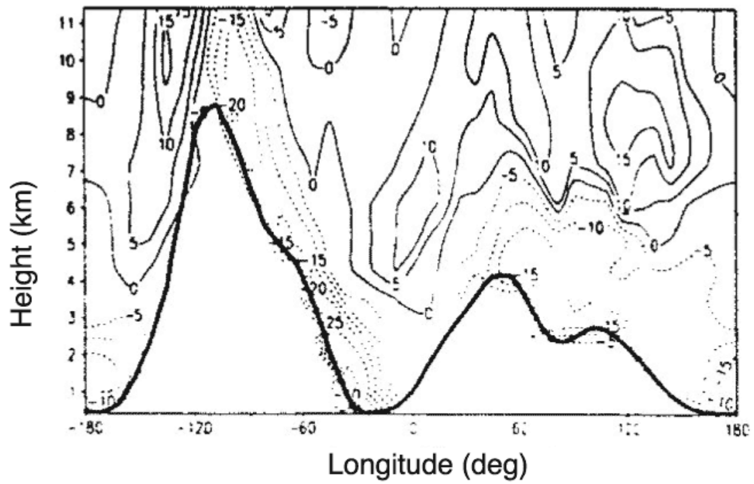
- Oxford SGCM: T42L20

‘Monsoonal’ WBCs on Mars: full GCMs

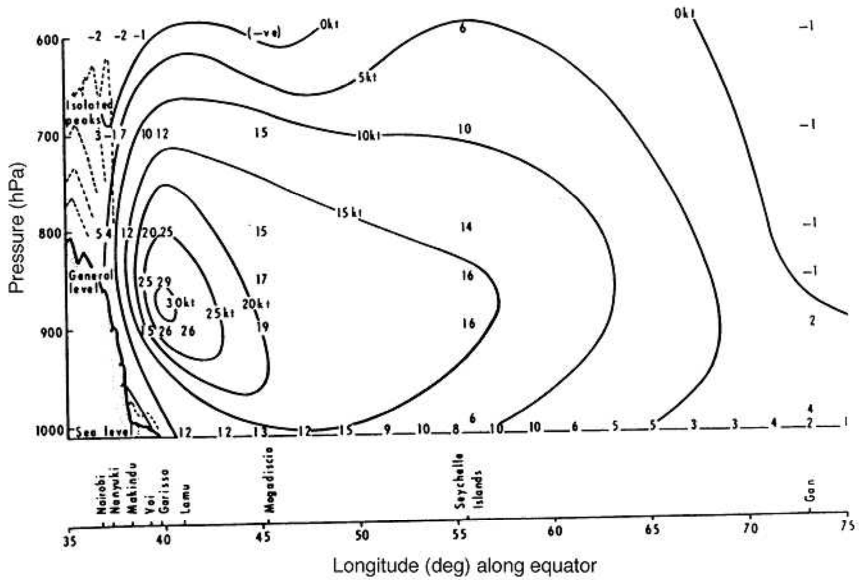
- NASA Ames GCM: NH winter



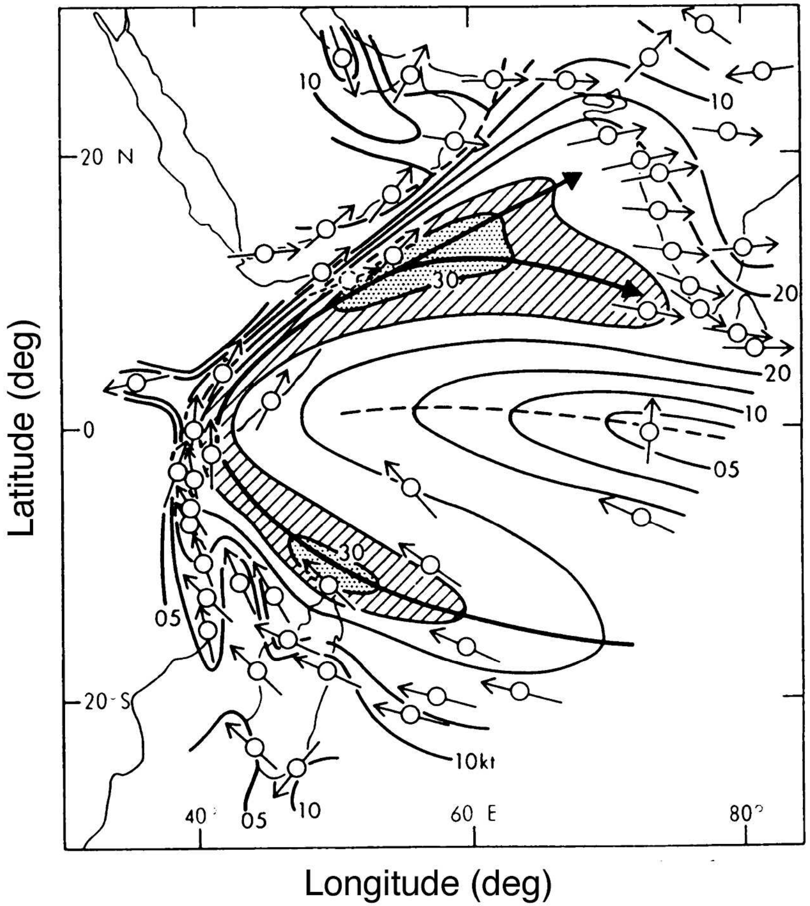
- NASA Ames GCM: SH winter



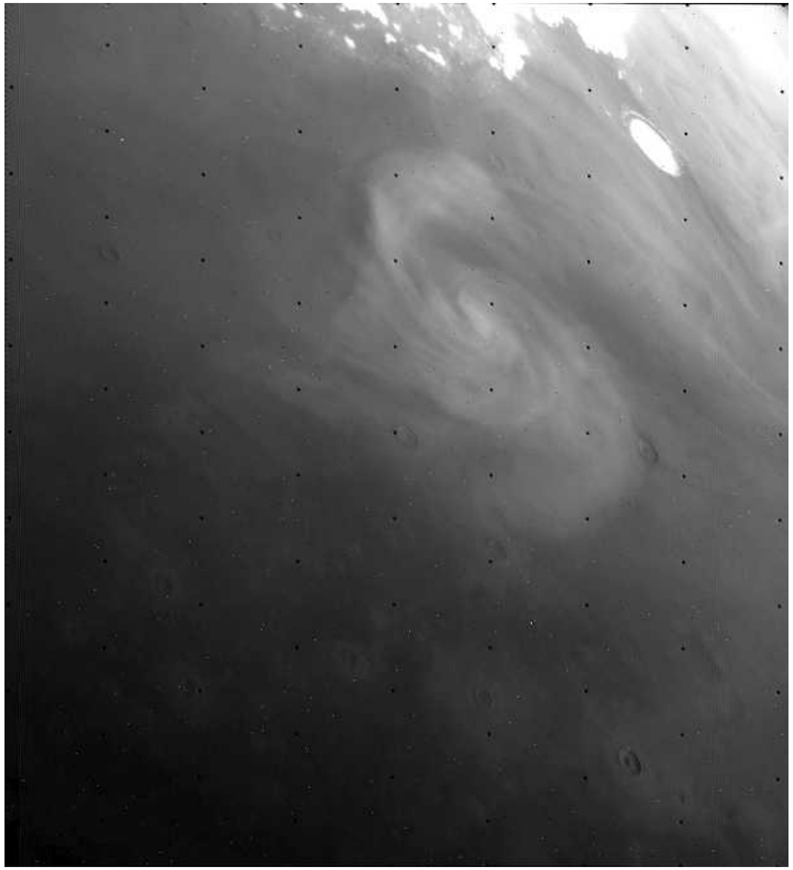
The East African Monsoon Jet

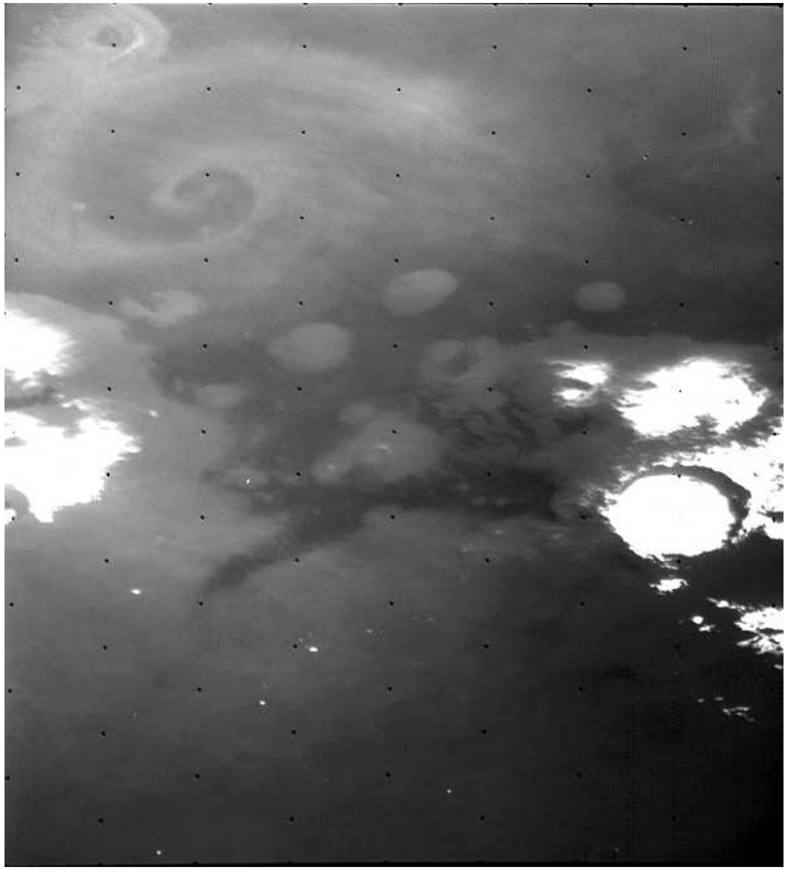


- A 'monsoonal' WBC in the Earth's atmosphere
- Discovered in the 1960s
  - J. Findlater (1969, *Quart. J. R. Meteorol. Soc.*, **95**, 362)



Martian spiral cyclones





- Small-scale cyclonic storms in NH summer (Viking orbiter images)
- Visible in H_2O ice clouds

Baroclinic instability on Mars

- Stable stratification and N-S temperature gradient ->
- Sloping convection
- Eady model predicts growing modes for

$$\lambda_c \geq 2.6 \frac{NH}{f_0}$$

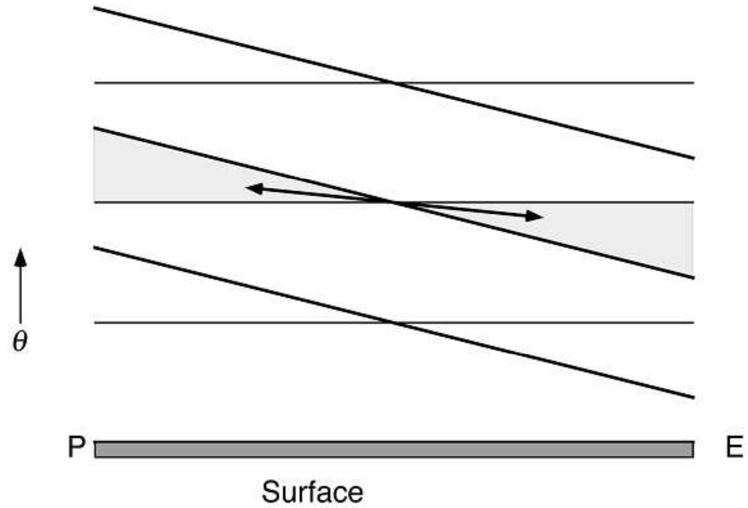
- Maximum growth rate at

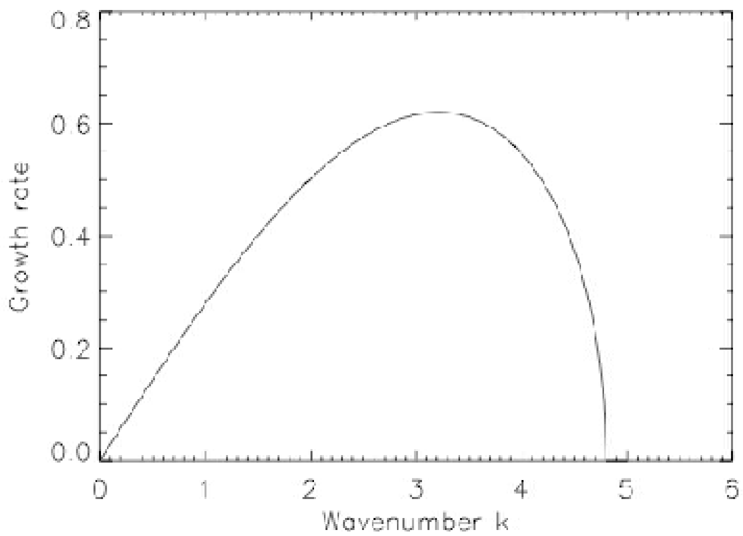
$$\lambda_{\max} \approx 3.9 \frac{NH}{f_0}$$

- With e-folding timescale

$$\tau_{\max} \approx 3.2 \frac{N}{f_0 \Lambda}$$

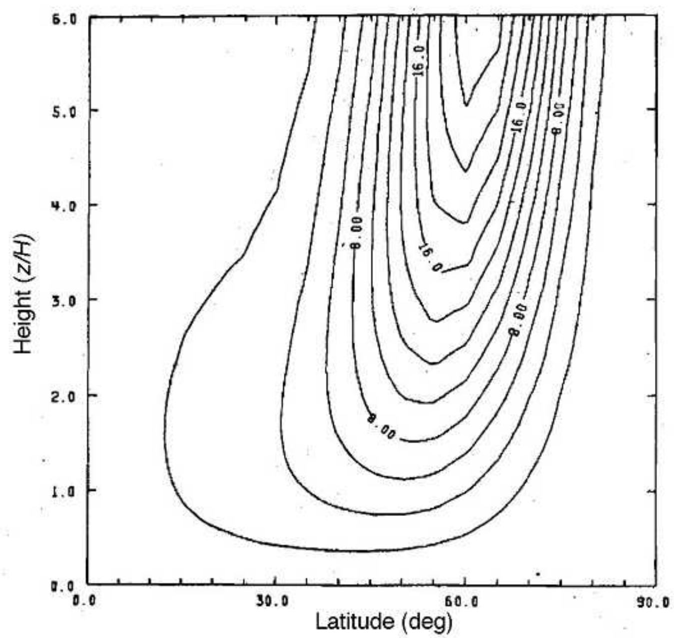
- For Mars, N~10^{-2} s^{-1}, H~10 km, f_0~10^{-4} s^{-1} and ΔU~ 50 m s^{-1}
- -> λ_{max}~3900 km (m ~2-3 at 60^o lat.) ; τ_{max}~ 17 hours

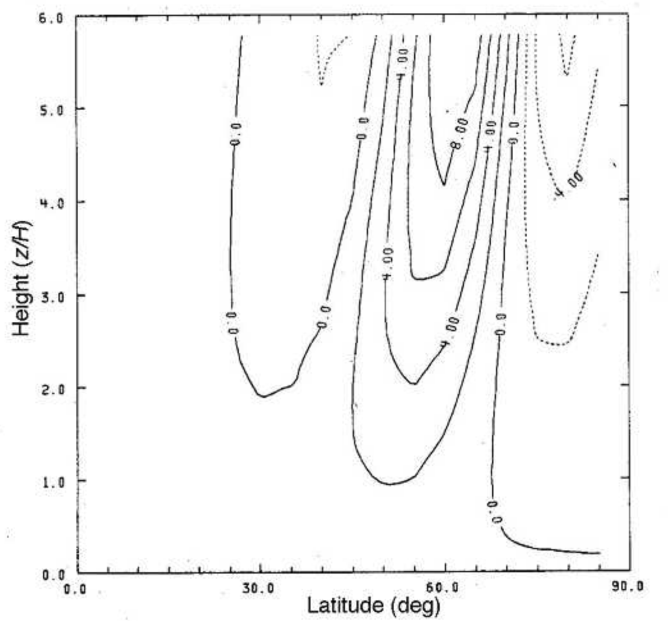




Baroclinic instability in the Martian atmosphere:

Barnes (1984) *J. Atmos. Sci.*, **41**, 1536-1550

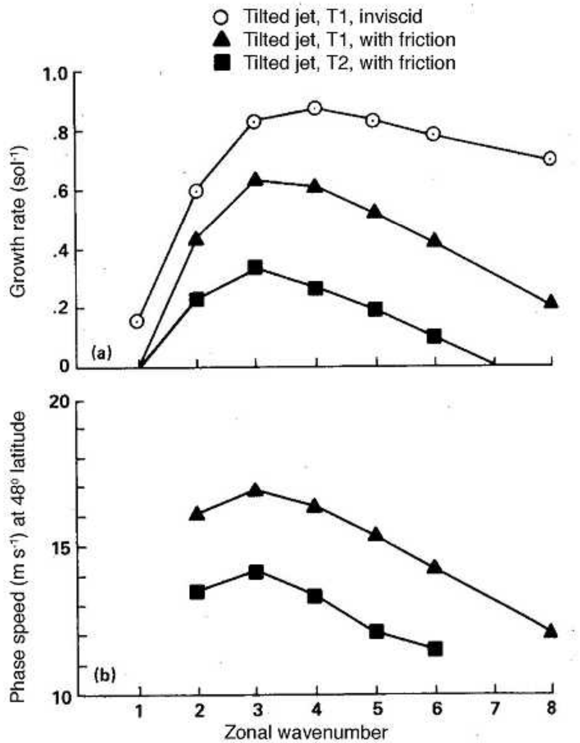


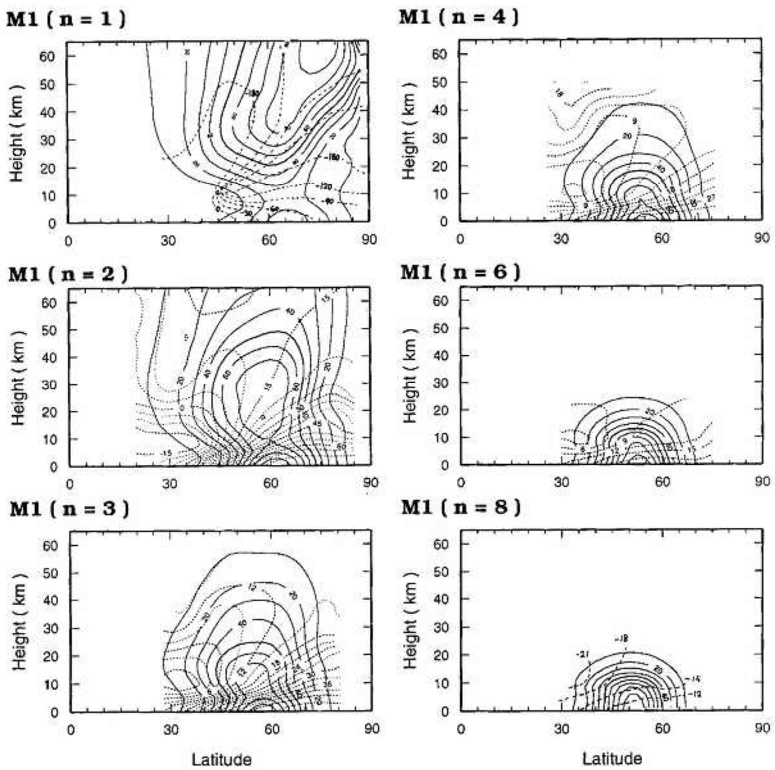


- Reasonably realistic mid-latitude zonal jet
- Q_y changes sign in latitude, and at the ground
  - Baroclinic and/or barotropic instability

‘Realistic’ baroclinic instability on Mars

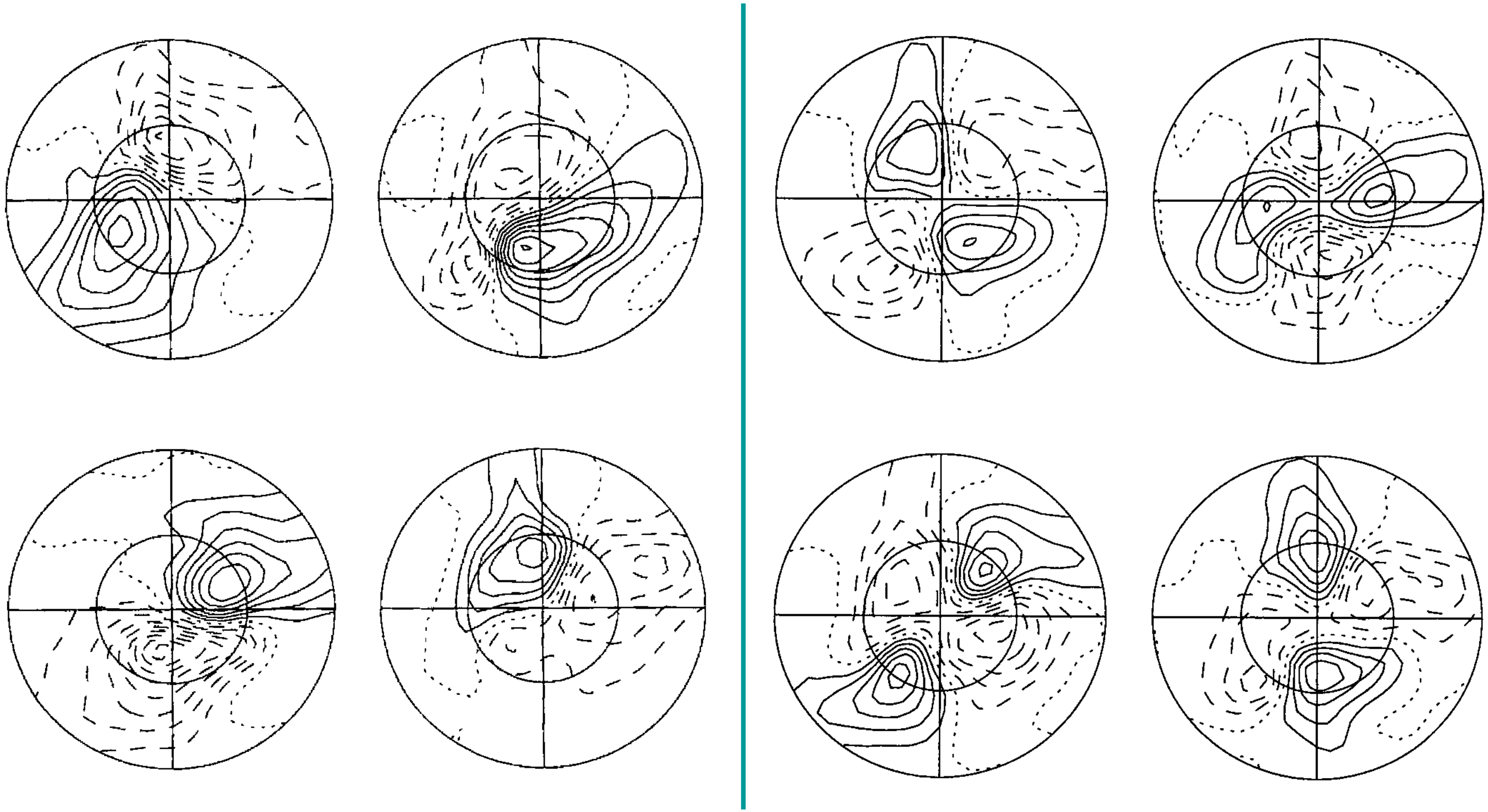
[Tanaka & Arai (1999) *Earth Plan. Space*, **51,** 225-232]





- Maximum growth around *m* = *2*-3
- Low *m* growing waves are deep *internal modes*
- Higher *m* growing waves are shallow *external modes*

Mars GCM: transient patterns in surface pressure

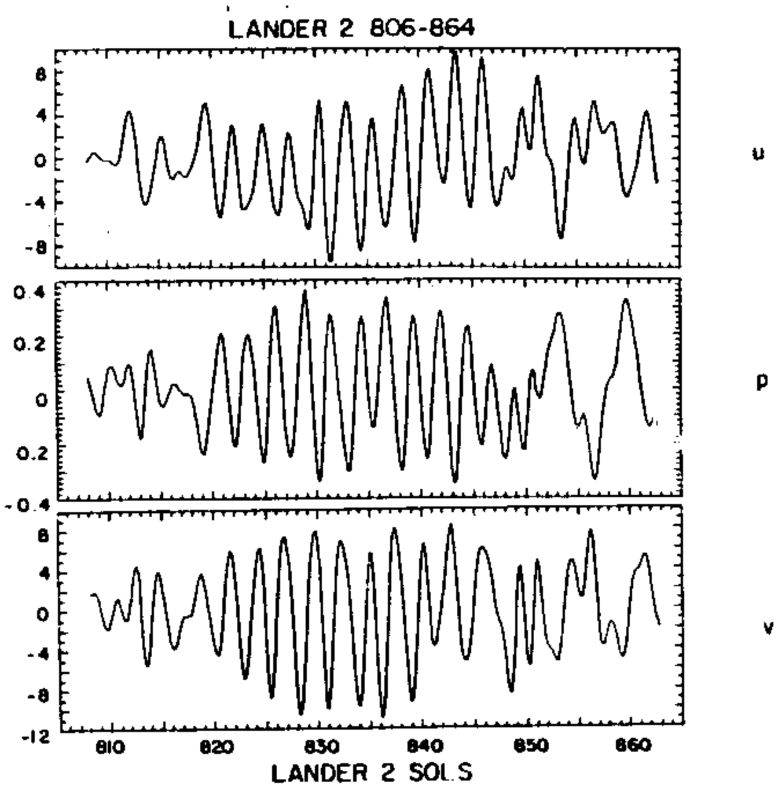


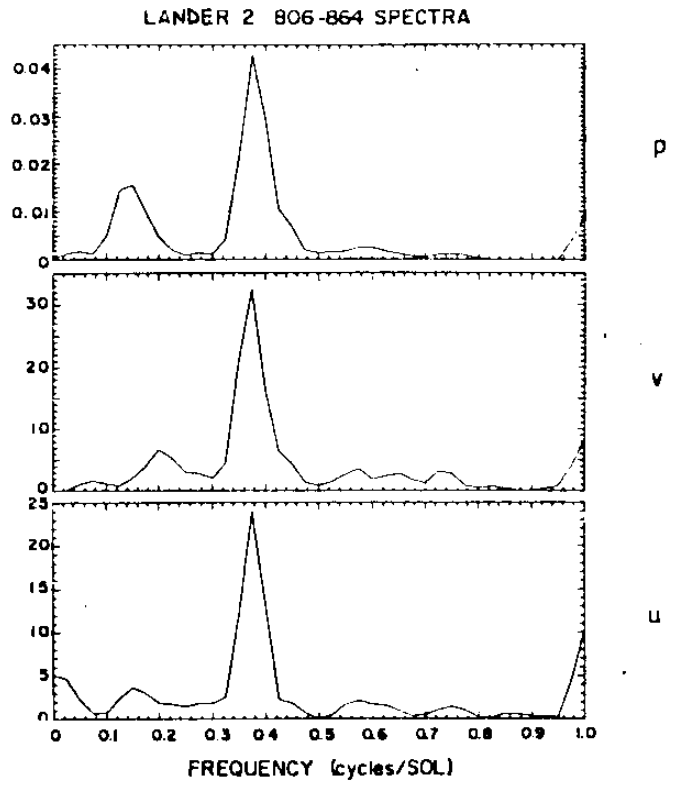
Mars GCM: transient patterns in surface pressure

QuickTime™ and a
Video decompressor
are needed to see this picture.

Mars: surface variations

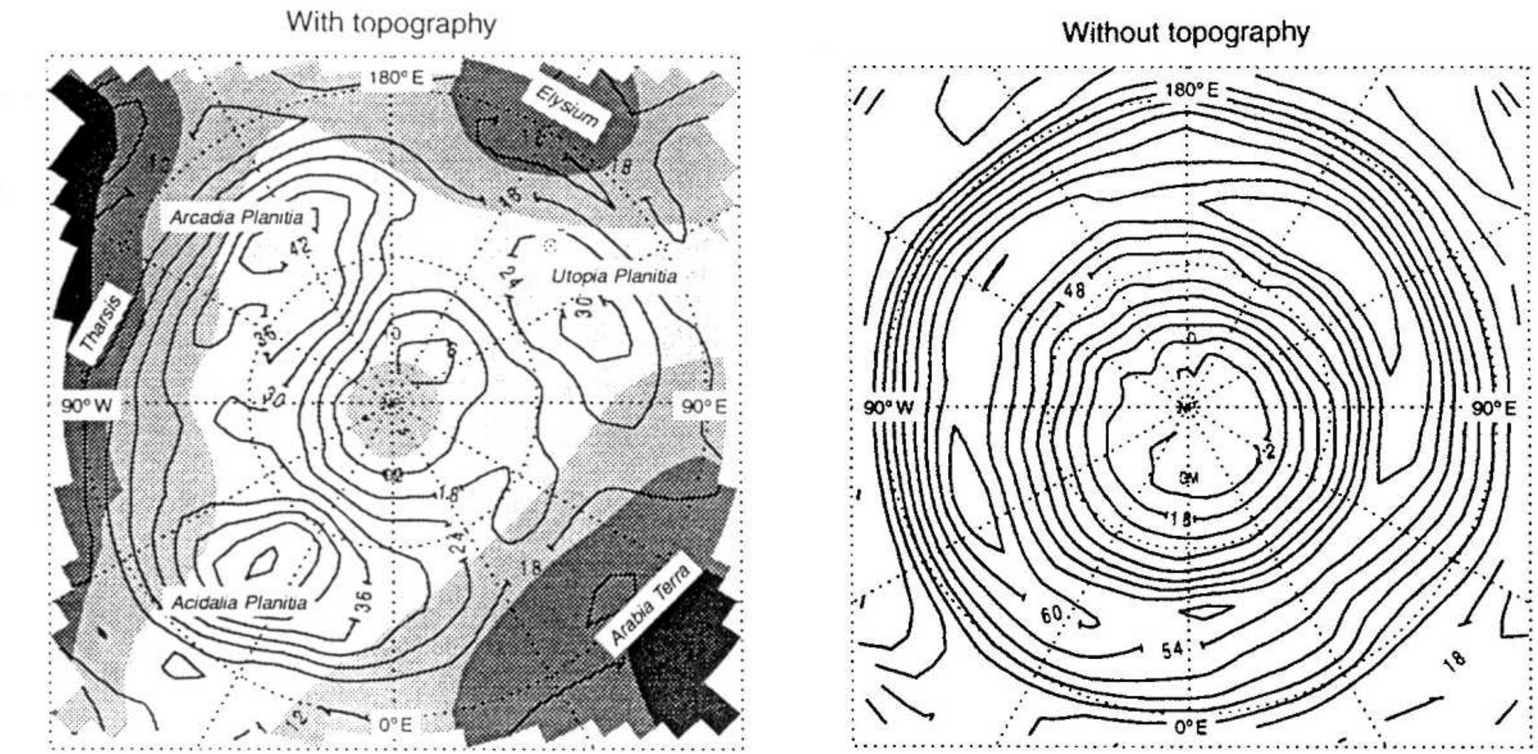
Viking Lander 2





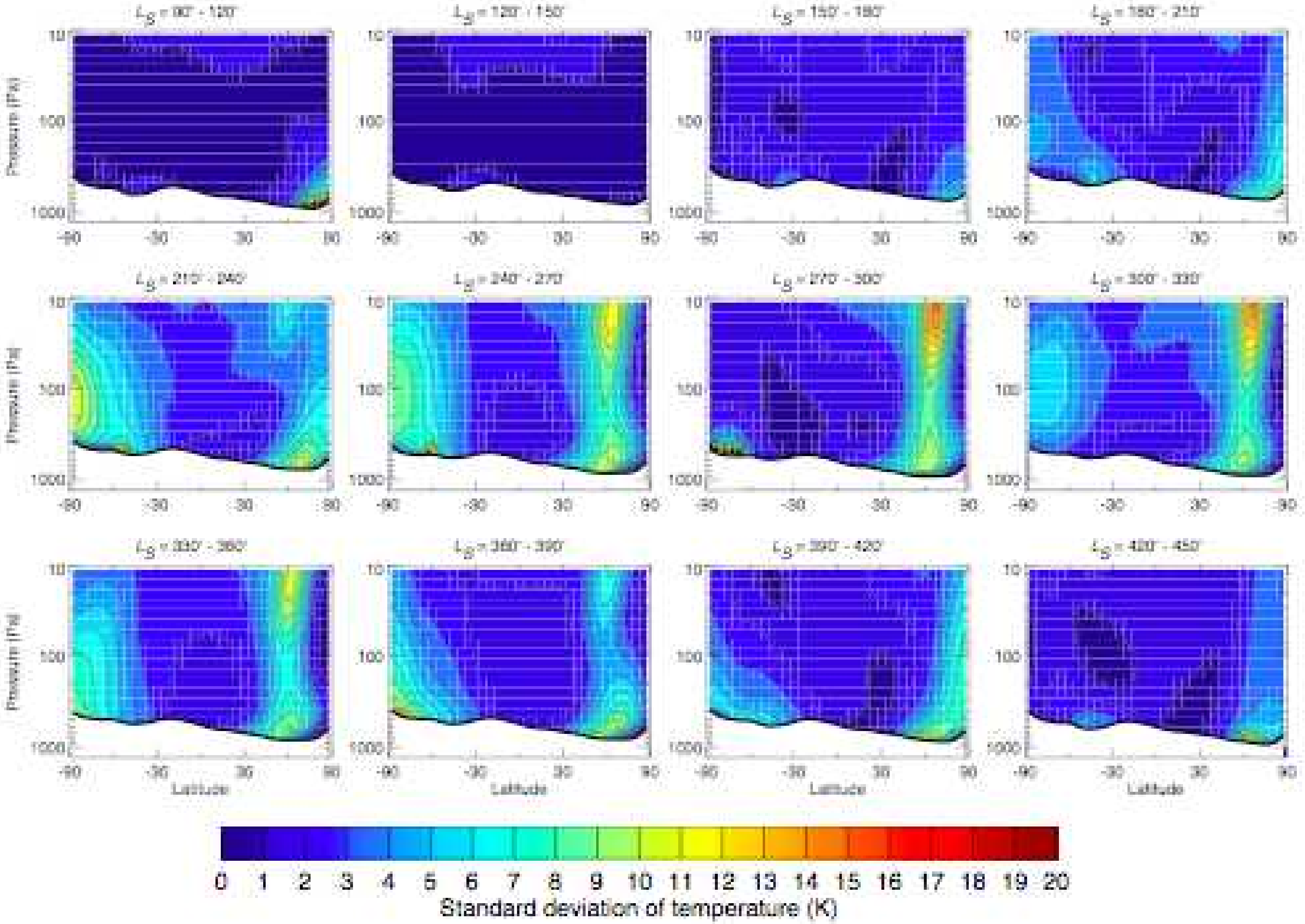
- p_s,u,v band-passed filtered (2-20 sol period)
- Spectral analysis of 60 sol records

Mars GCM: storm tracks

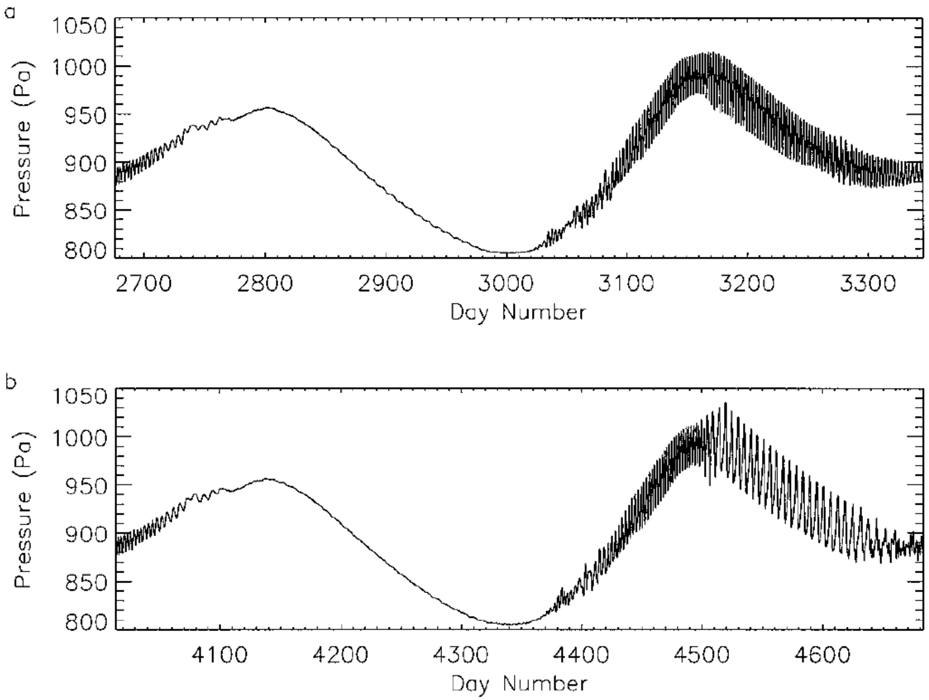


- Eddy heat fluxes, KE and variances concentrated into a band of latitudes
- Modulated by topography

Baroclinic $\langle T'^2 \rangle^{1/2}$ vs season

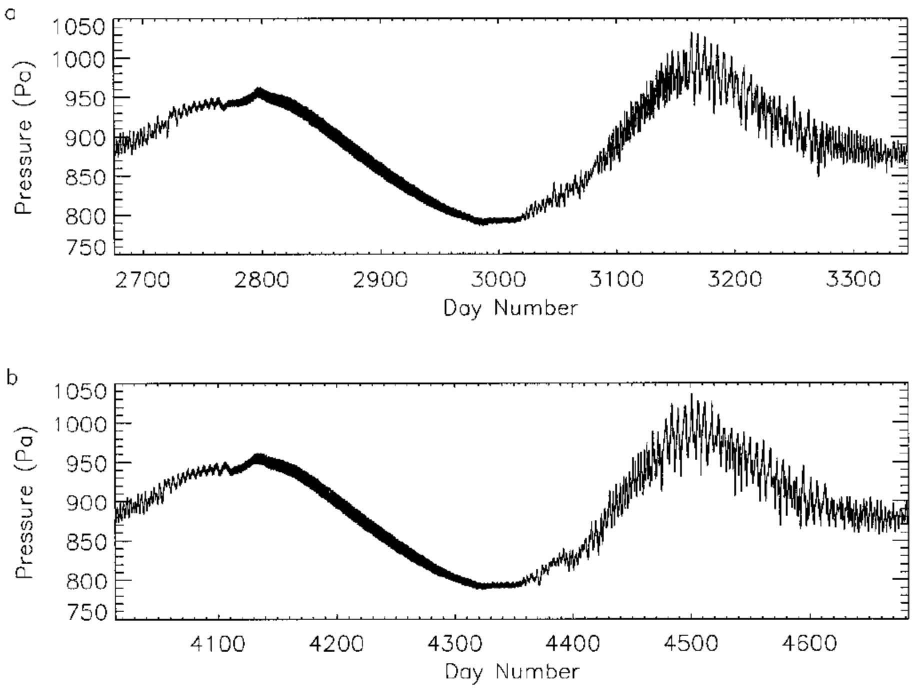


Low-dimensional dynamics?



- ‘Thought experiment’ using a GCM
  - Simulation of Martian circulation
    - WITH seasonal variations
    - WITHOUT diurnal variations
- Baroclinic instability absent in summer
- Baroclinic waves ~perfectly periodic in winter…

Low-dimensional dynamics?

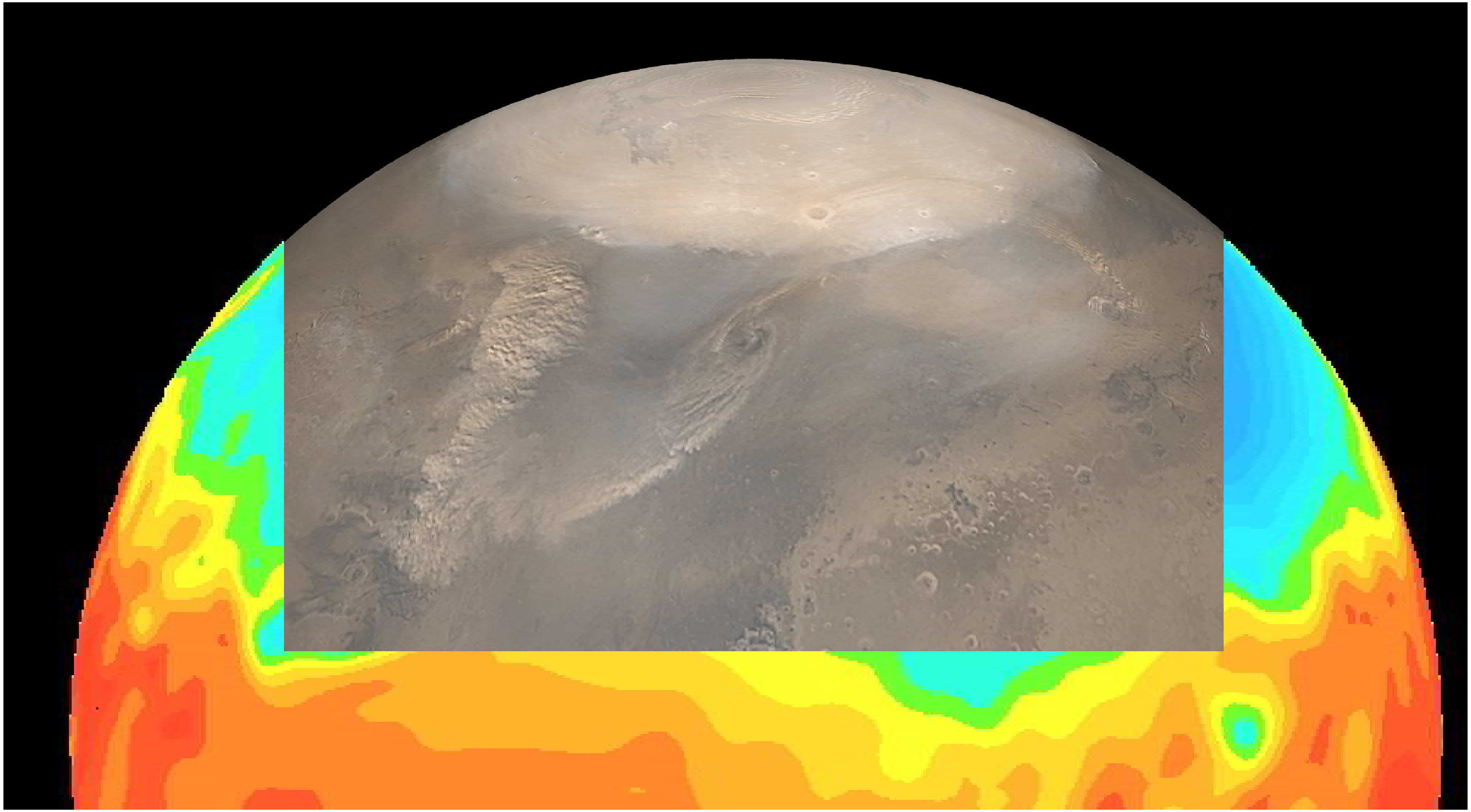


- ‘Thought experiment’ using a GCM
  - Simulation of Martian circulation
    - WITH seasonal variations
    - WITH diurnal variations
- Baroclinic instability absent in summer
- Baroclinic waves now CHAOTIC in winter…

Baroclinic storms on Mars

- Active and strong in autumn-winter-spring seasons
- Weak/shallow or absent in summer
- Dominated by planetary wavenumbers 1-3
  - Deep ‘internal’ baroclinic modes?
- Almost regular & persistent in time cf Earth
- Closer to marginal stability than Earth?

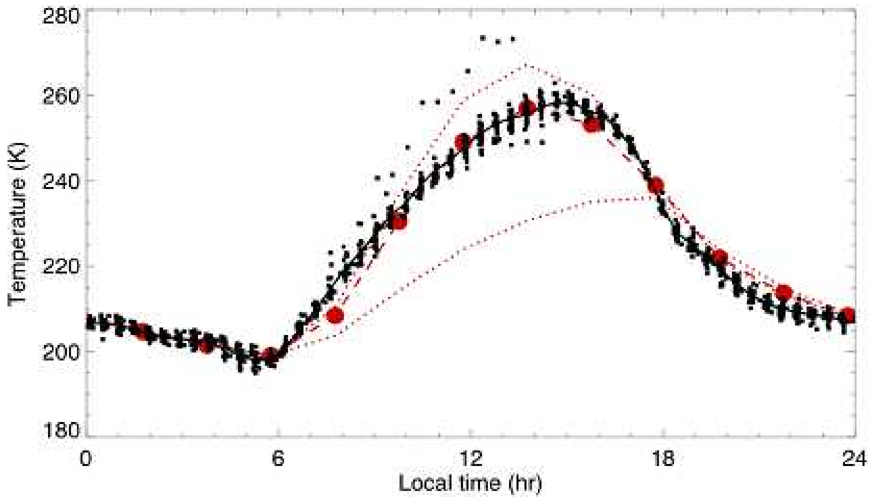
Fronts and cyclones

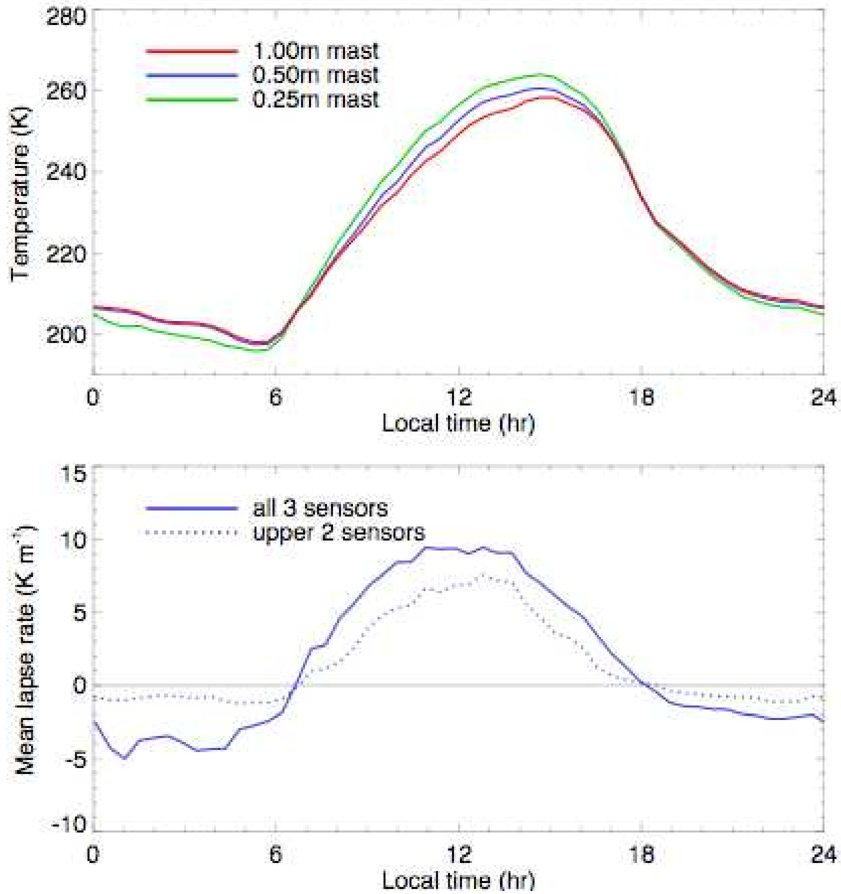


North polar dust storm (MOC)

N. hemisphere summer storm

Diurnal cycles (MPF)

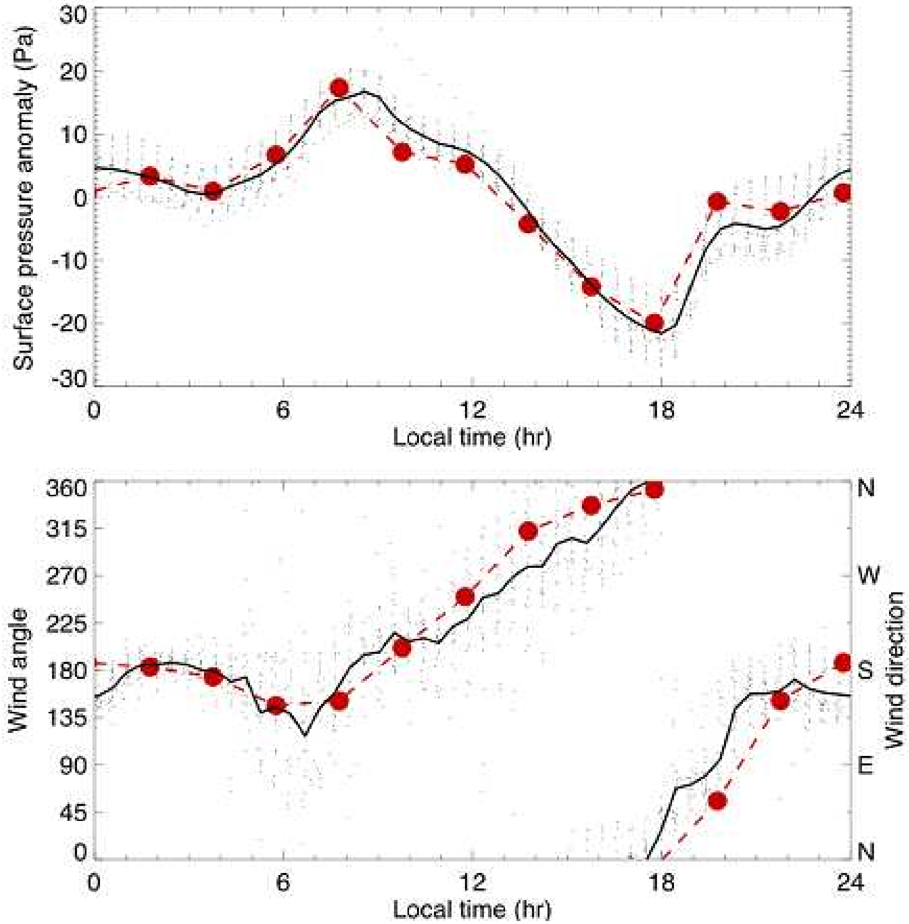




- Very repeatable variation of T(t) each day
- Diurnal tide dominant in NH summer

Mars - Thermal Tide

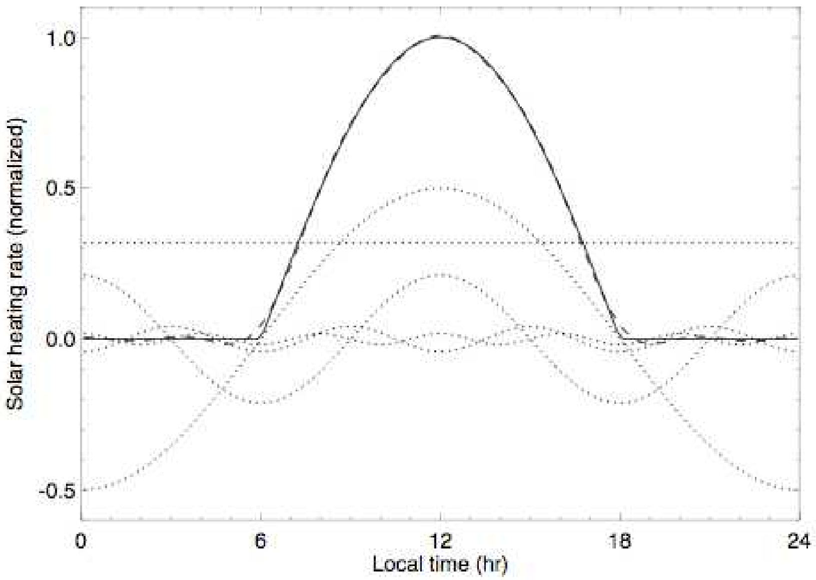
- Amplitude and phase of tide very repeatable
- Well predicted in Mars GCMs



QuickTime™ and a
Animation decompressor
are needed to see this picture.

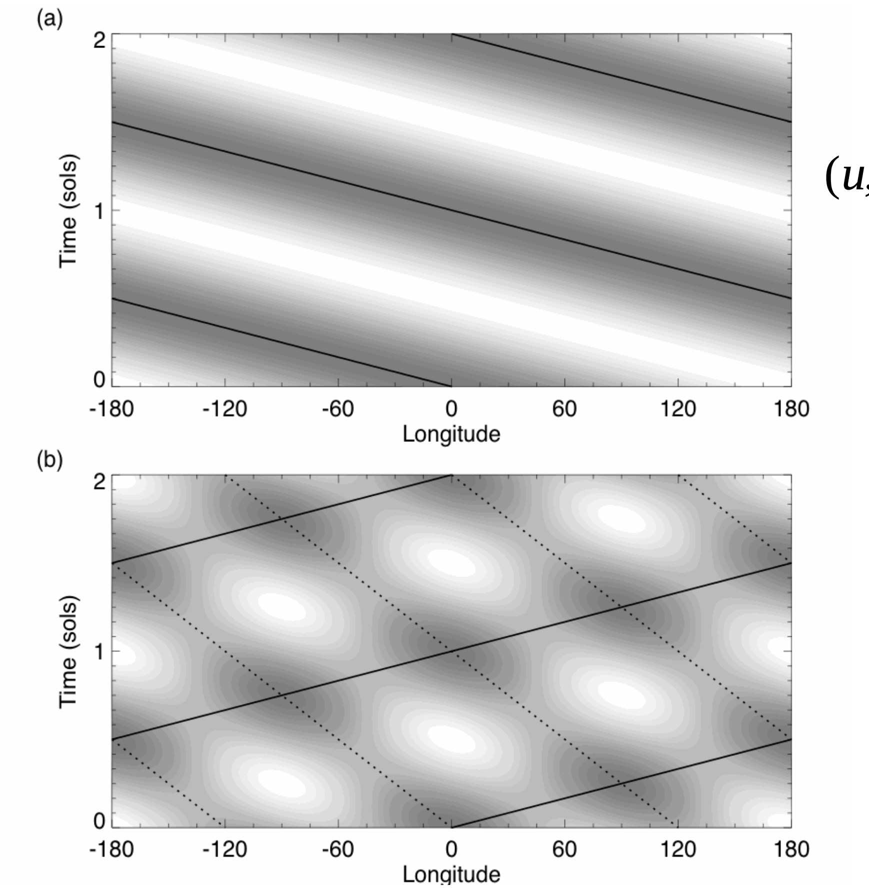
Migrating thermal tides

- Response to diurnal atmospheric heating
- Projects onto several zonal Fourier components
  - Diurnal tide
    - S=1 σ=-1/2
    - Vertical wavelength ~30 km
  - Semi-diurnal tide
    - S=2 σ=-1
    - Vertical wavelength >100 km



[Image source:
Read & Lewis 2004,
The Martian Climate Revisited]

Non-migrating tides & planetary wave resonance?



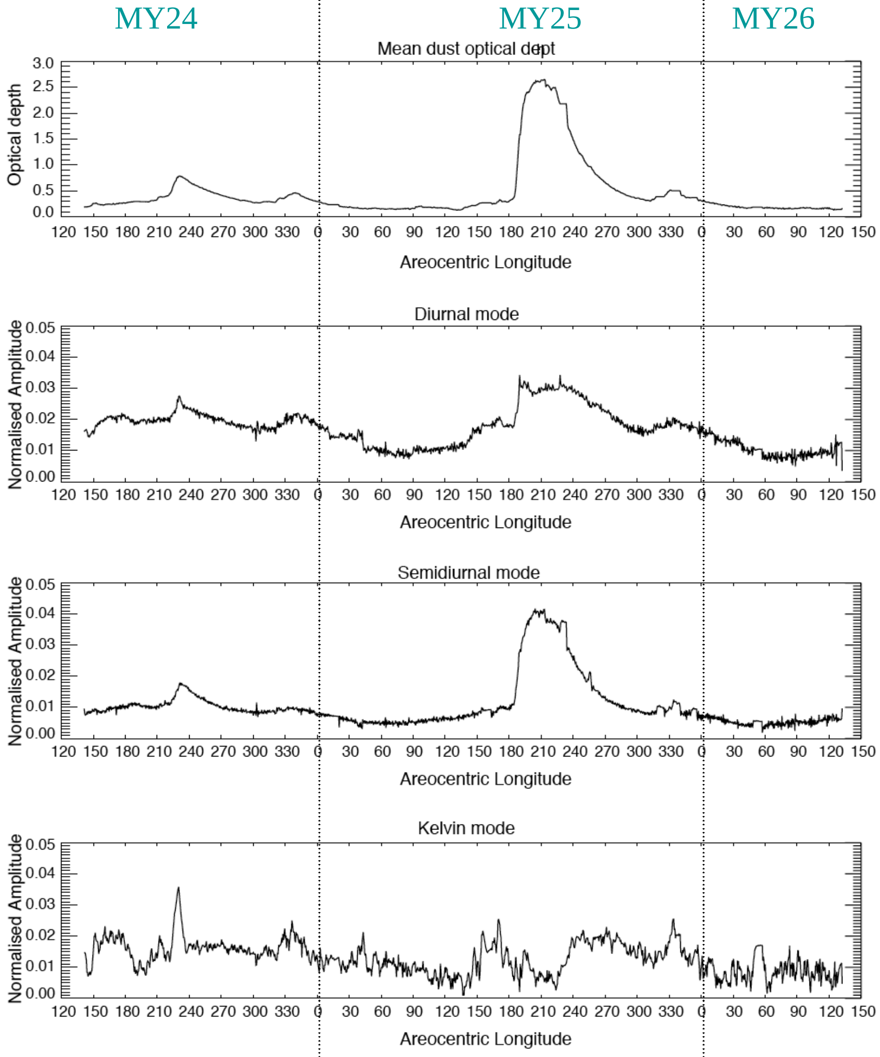
[Read & Lewis 2004,
The Martian Climate Revisited]

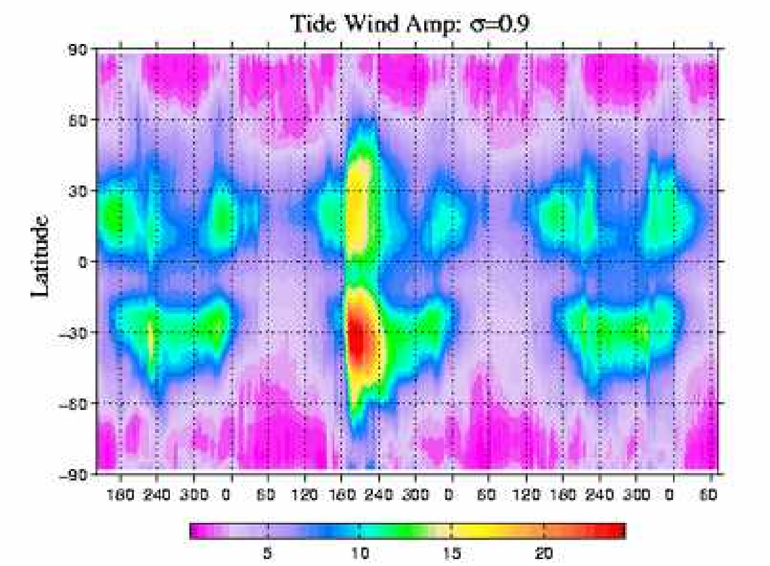
- Basic migrating tides of the form

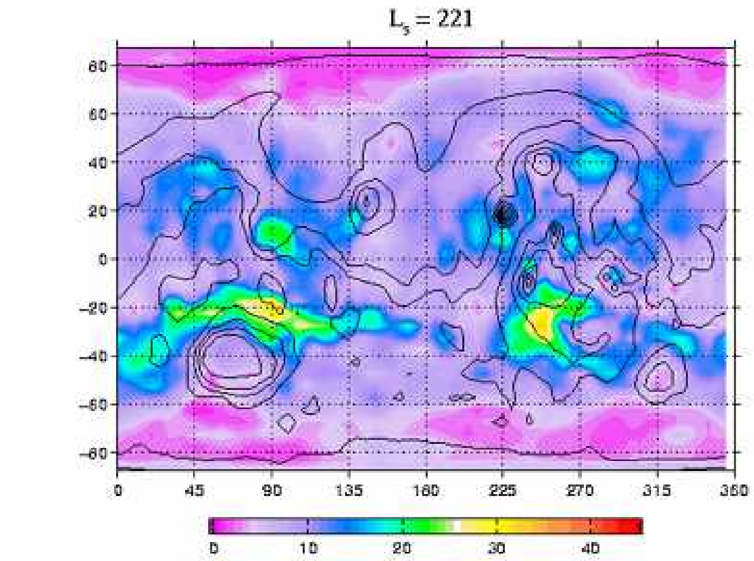
$$(u,v,\Phi) = \mathrm{Re}(u(\phi),v(\phi),\Phi(\phi))\exp[i(s\lambda - 2\Omega\sigma t)]$$

- Interaction/modulation by topography -> 'non-migrating' components
  - E.g. between diurnal tide *(s=1, σ=-1/2)* with *s = 2* topography, leads to
  - Westward (*s=3, σ=-1/2*) AND
  - Eastward (*s=1, σ=1/2*)
- Resonance with free *s=1* Kelvin mode…?

Thermal tides: dust & lifting?

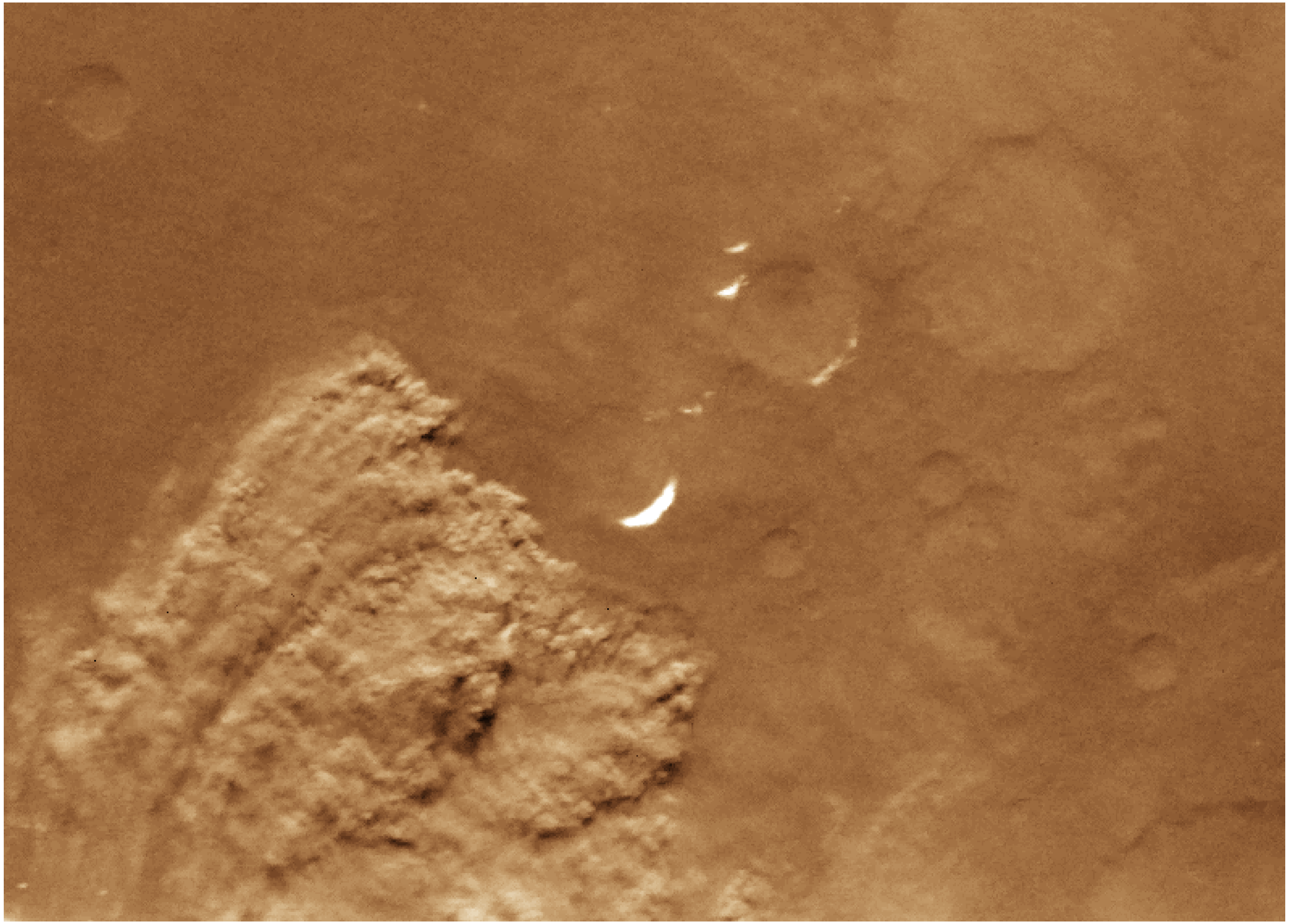




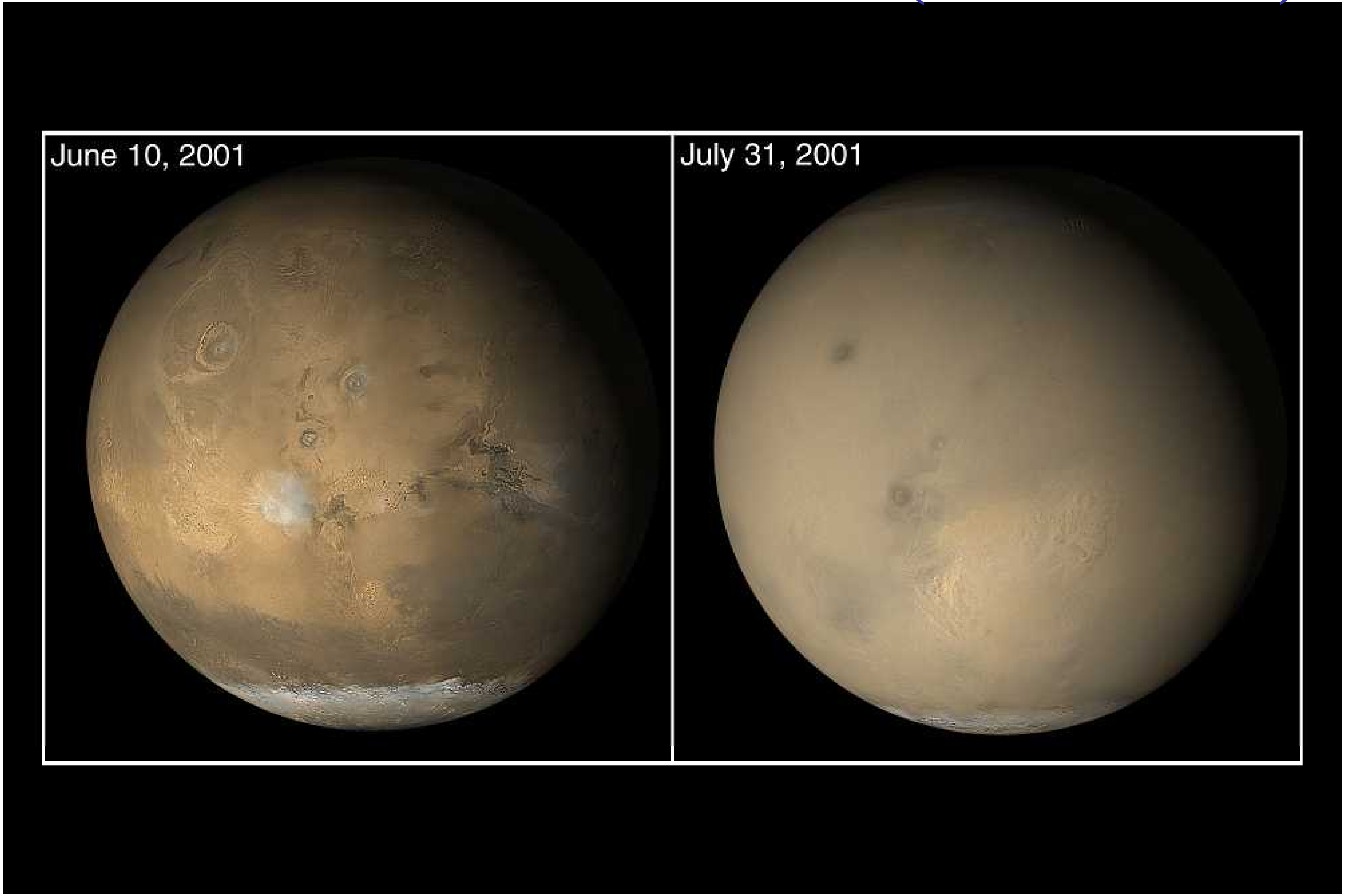


Lewis, S. R. & Barker, P. R. (2005, Adv. Space Res., 36, 2162
& Wilson, J., Lewis, S. R. & Montabone, L. (2008, 3rd Int Workshop on the Mars Atmosphere, Williamsburg, Va)
`

Local dust storms

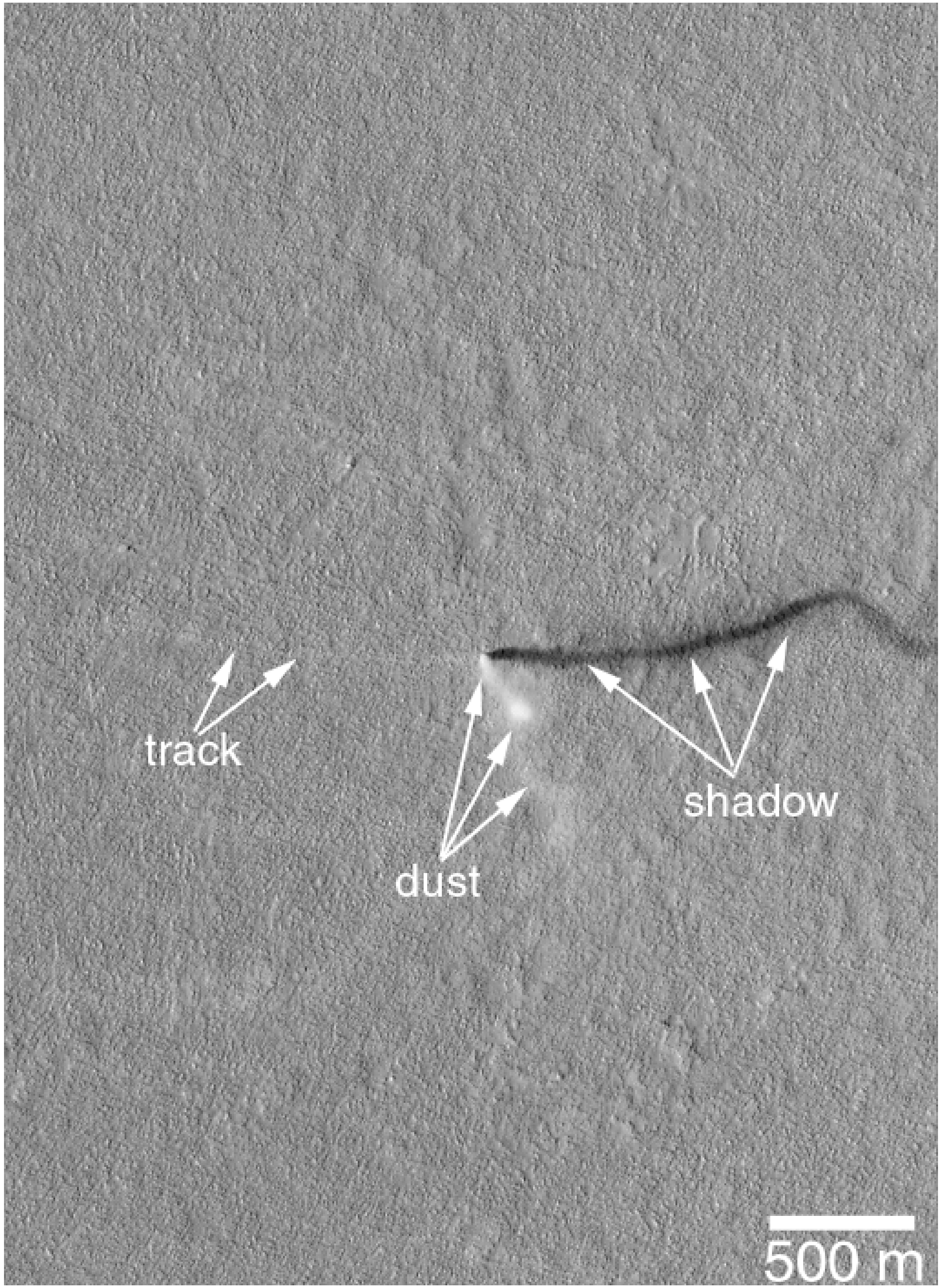


Global Dust Storm of 2001 (MGS/MOC)



Dust Devils on Mars (MGS/MOC)

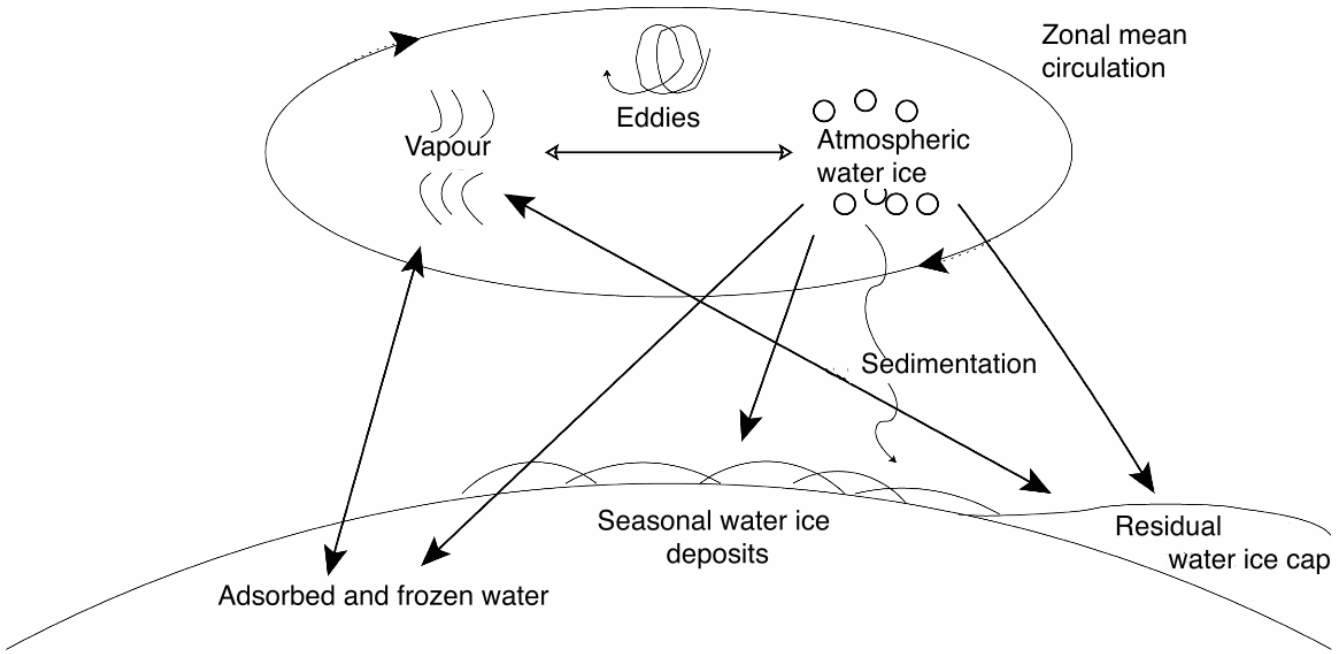
- Convective vortices
- Dust columns
- Streaks and tracks



Dust Devil seen from Spirit Rover

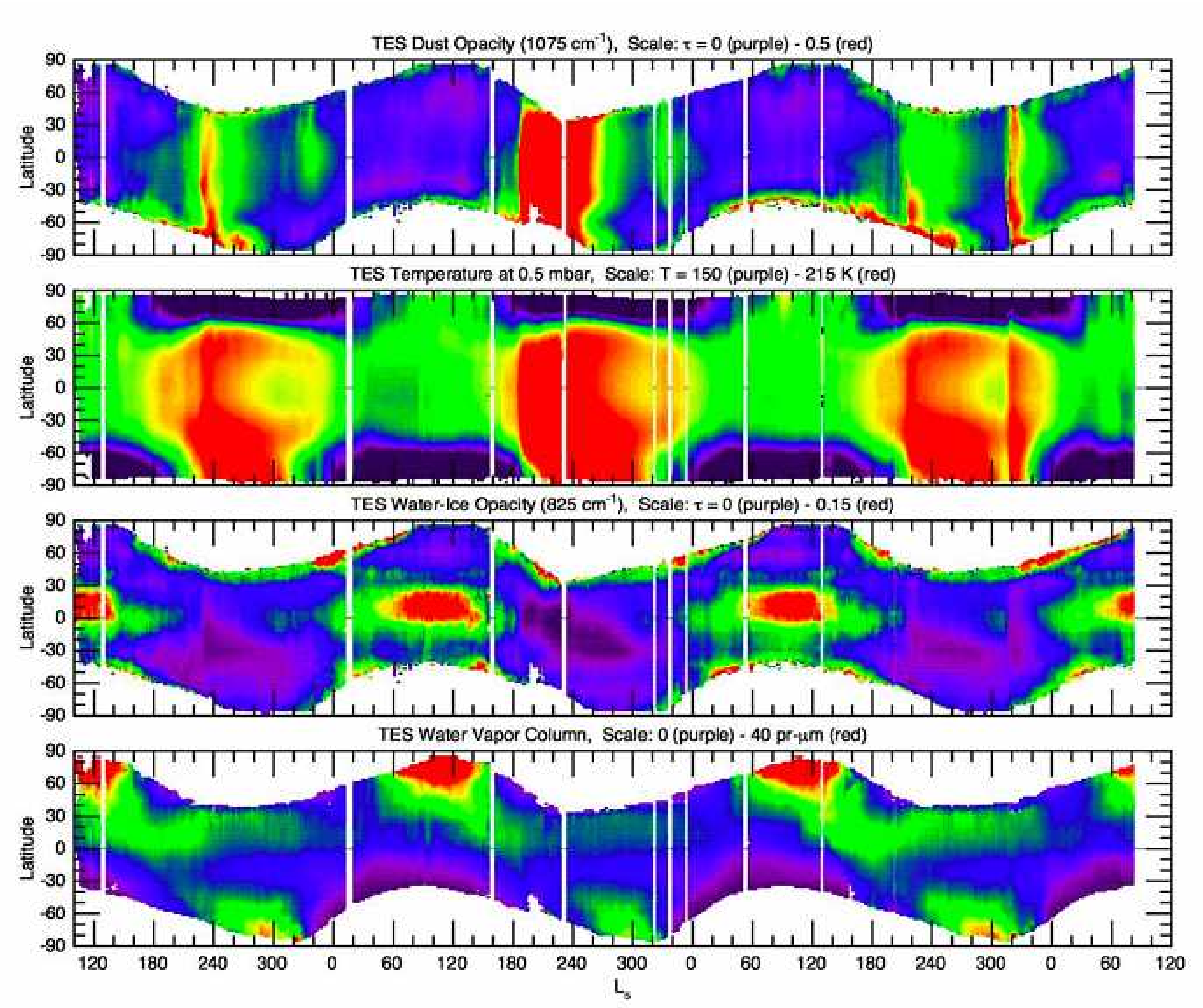
QuickTime™ and a
GIF decompressor
are needed to see this picture.

Mars Water Cycle



- Water mostly in frozen form at the surface
- Seasonal exchanges with the atmosphere
  - Water vapour (measured in precipitable microns!)
  - Ice clouds

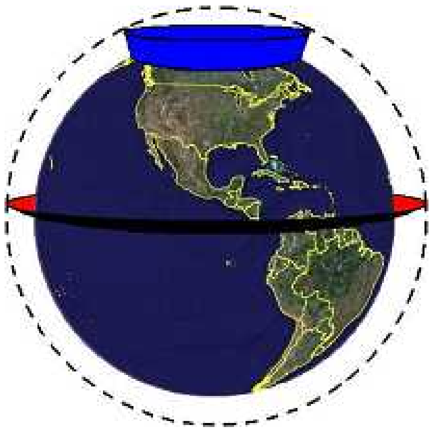
Mars dust and water cycles

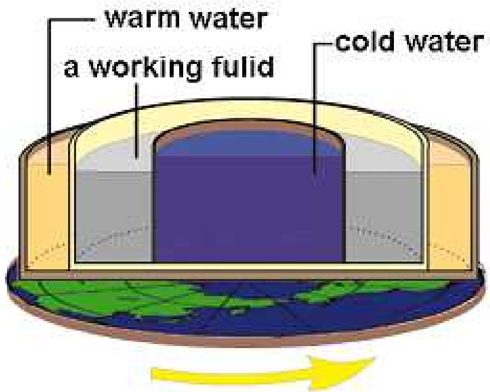


The story so far….

- Martian atmospheric structure determined largely by local radiative balance, modified by convection and transport
  - Hadley flow in tropics
  - Baroclinic storms in mid-high latitudes [but not throughout the year!]
  - Thermal tides very significant
  - Topography very significant
- Dust and water cycles
- Somewhat similar to Earth
  - Different emphases
  - Why are they different?
  - **part of a more systematic picture?**

Laboratory Analogues of Planetary Atmospheric Circulation Systems





- *Baroclinic instability*

- a potential energy releasing instability in the atmosphere and oceans

QuickTime™ and a
QuickDraw decompressor
are needed to see this picture.

Parameters to describe the operating conditions

- Force scaling
  - Coriolis to viscous

$$\frac{4\Omega^2 L^4}{\nu^2}$$

$$Ta = \frac{4\Omega^2 (b-a)^5}{\nu^2 \quad d}$$

- Taylor Number

  - Inertial to Coriolis

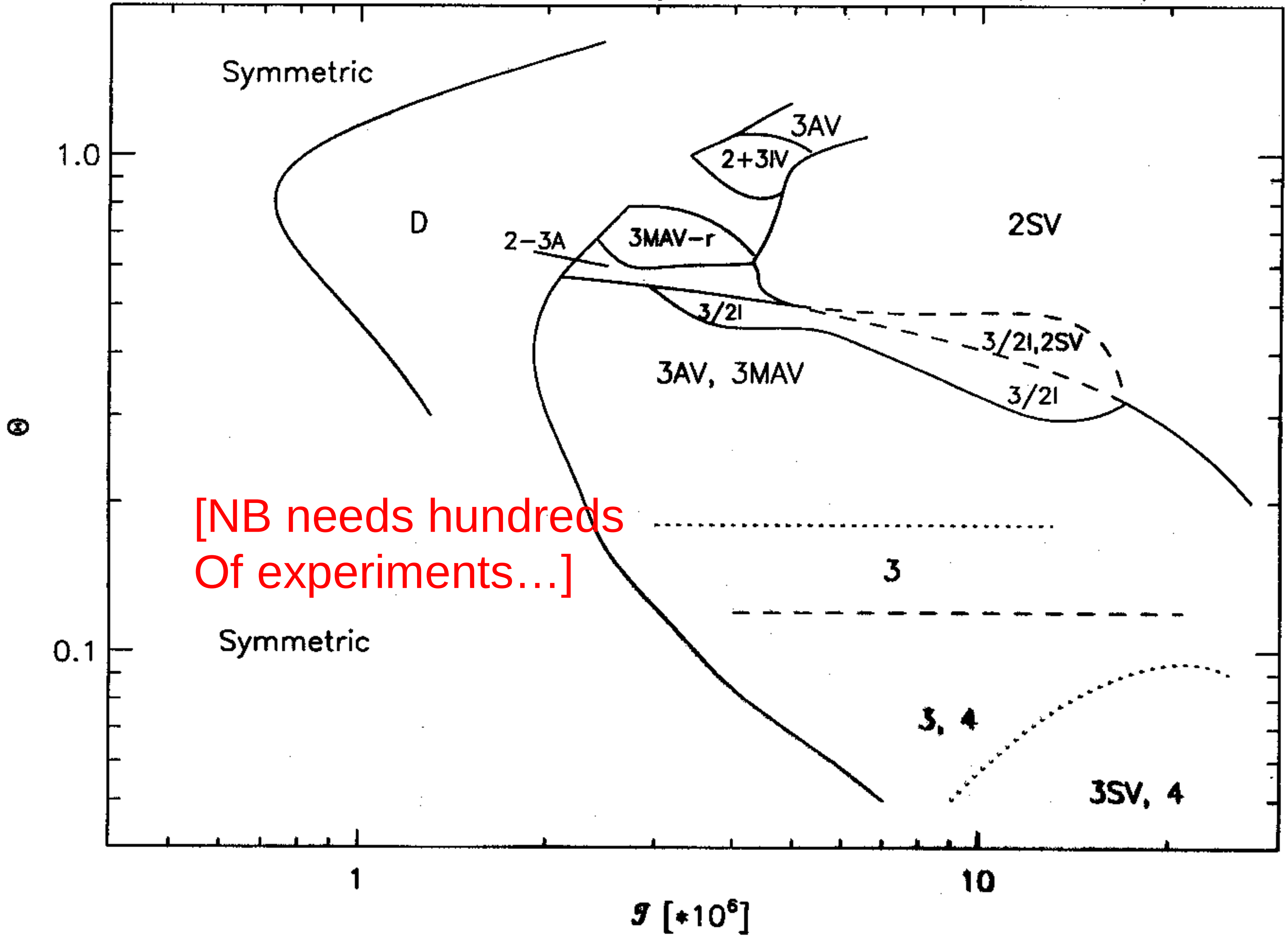
$$\frac{U}{2\Omega L}$$

- Using geometry and geostrophic thermal wind

$$\Theta = \frac{g\alpha \Delta T \, d}{\Omega^2 (b-a)^2}$$

- Θ (thermal Rossby number)

Regime diagram for high Prandtl number (Pr=26)



[NB needs hundreds
Of experiments…]

Planetary parameters

- Thermal Rossby and/or Burger number

$$\Theta = \frac{g\Delta\theta_y H}{\Omega^2 R^2 \theta_0} \quad \text{or} \quad Bu = \frac{N^2 H^2}{\Omega^2 R^2}; \ [N^2 = (g\partial\theta/\partial z)/\theta_0]$$

- Rhines lengthscale (based on thermal wind)

$$L_{Rh} = \pi \left(\frac{g\Delta\theta_y H}{2\Omega^2 \theta_0} \right)^{1/2} \quad \text{-> Jet number} \quad N_J \approx \frac{R\Omega}{\pi} \left(\frac{2\theta_0}{g\Delta\theta_y H} \right)^{1/2}$$

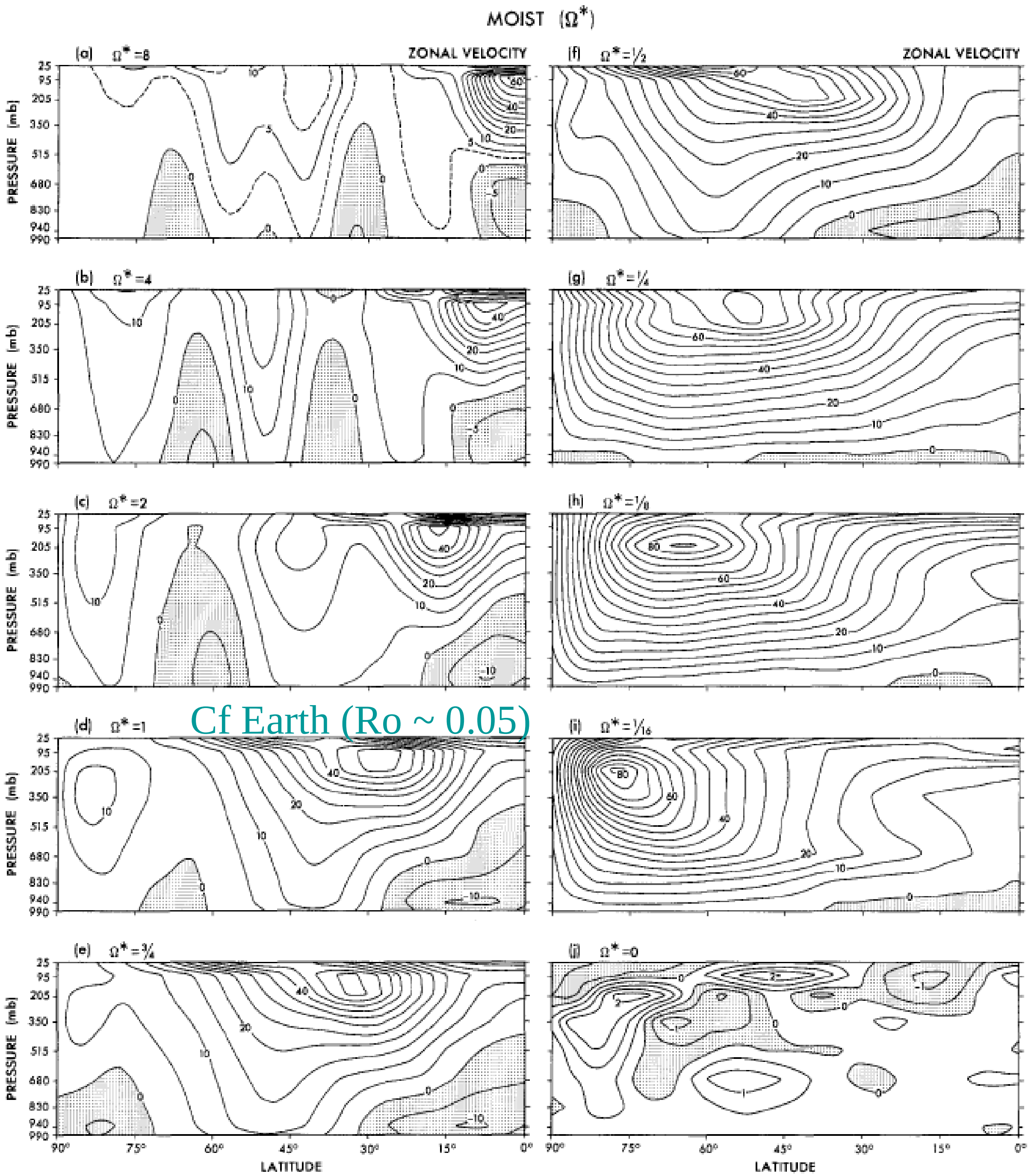
- Dissipation parameter[?]

$$F_r = 4\Omega^2 \min(\tau_{rad}^2, \tau_{fr}^2); \ [\text{cf } Ta = 4\Omega^2 \tau_{visc}^2]$$

NB - How to estimate/***predict*** $\Delta\theta_y$ & $\partial_z\theta$?

Planetary parameters

Planet	**Θ**	**Bu**	**N_J**	**$4\Omega^2\tau_R^2$**
Earth	0.06	0.04	1.77	155000
Mars	0.19	0.08	0.90	44
Venus	377	268	0.045	16450
Titan	18.5	23.6	0.17	75000



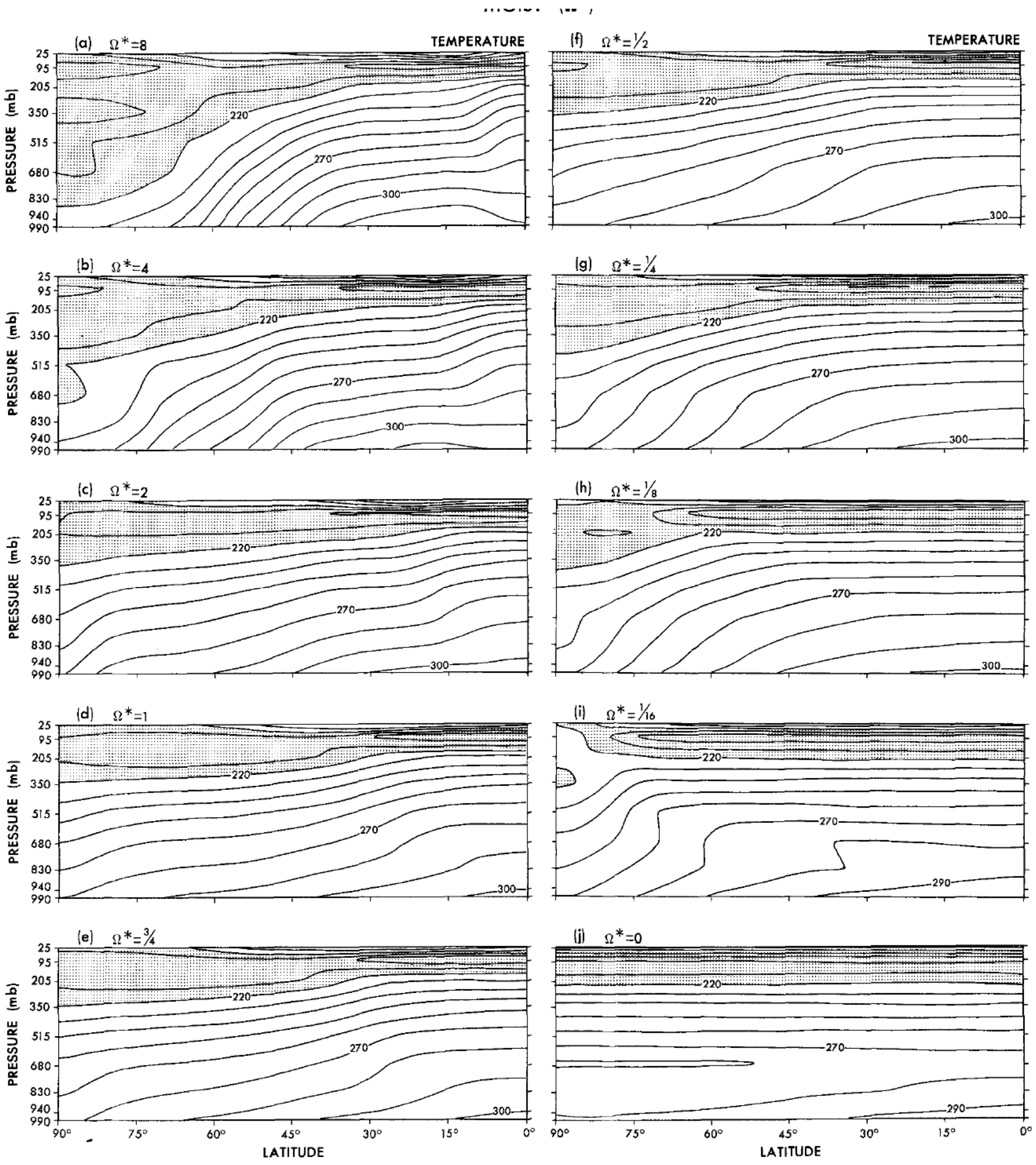
Cf Mars? (Ro ~ 0.15)

Varying Ω in a terrestrial GCM (Williams 1988)

(R42L9)

From previous considerations

- $N_J \sim R\Omega$ (if $\Delta\theta_y$~constant)
- Baroclinic instability shuts off at $\Omega < \Omega^*/4$

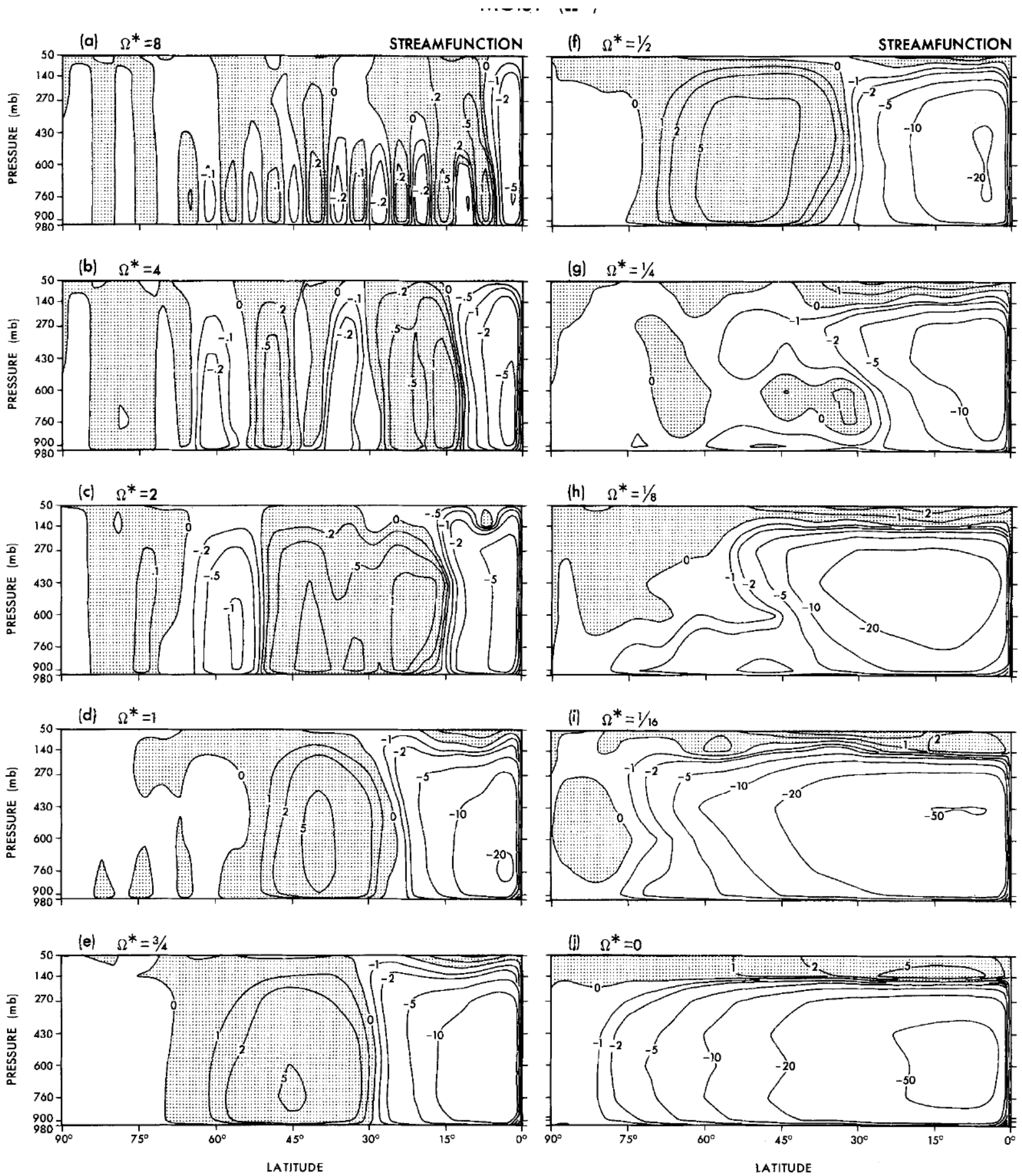


Varying Ω in a terrestrial GCM (Williams 1988)

(R42L9)

From previous considerations

- $N_J \sim R\Omega$ (if $\Delta\theta_y$~constant)
- Baroclinic instability shuts off at $\Omega < \Omega^*/4$
- $\Delta\theta_y$ increases sharply as $\Omega\uparrow$



Varying Ω in a terrestrial GCM (Williams 1988)

(R42L9)

From previous considerations

- $N_J \sim R\Omega$ (if $\Delta\theta_y$~constant)
- Baroclinic instability shuts off at $\Omega < \Omega^*/4$

"Closure" for $\Delta\theta_y$ & $\partial_z\theta$

- a 'macroturbulent' approach?

- Baroclinic 'adjustment' (e.g. Stone 1978)?
  - Flow adjusts to 'critical stability' limit…? [see also Schneider & Walker 2004, 2006]
- Mixing length/eddy diffusion parameterization (e.g. Held 1999)?

$$\Delta\theta_y \approx \frac{\Delta\theta_{Ry}}{1+6\left(\frac{cD}{Ba^2}\right)}; \quad \text{where } \Delta\theta_{Ry} \text{ is in radiative equilibrium}$$

  - c = specific heat capacity
  - D = 'eddy diffusion' coefficient **[How to parameterize?]**
  - $B = \partial F_R / \partial T$
  - a = planetary radius

Perspectives/Outlook

- Mars exhibits a substantially Earth-like atmospheric circulation, with some key differences:
  - Thinner, less dense atmosphere -> more radiatively dominated than Earth
    - Strong thermal tides near the surface
    - Strongly super-adiabatic convection in summer
  - No oceans or liquid water at surface -> surface temperature more seasonally variable
  - Baroclinically active, though not much during summer
    - ~Regular/persistent wave structures - more predictable?
  - Strong topographical modulation of dynamical activity
    - Western boundary currents, interactions with tides…..
  - Dust cycle a major source of interannual variability
    - Strong radiative feedbacks
  - Water cycle active, though energetically not very significant [in present climate…?]
    - Water ice clouds radiatively active

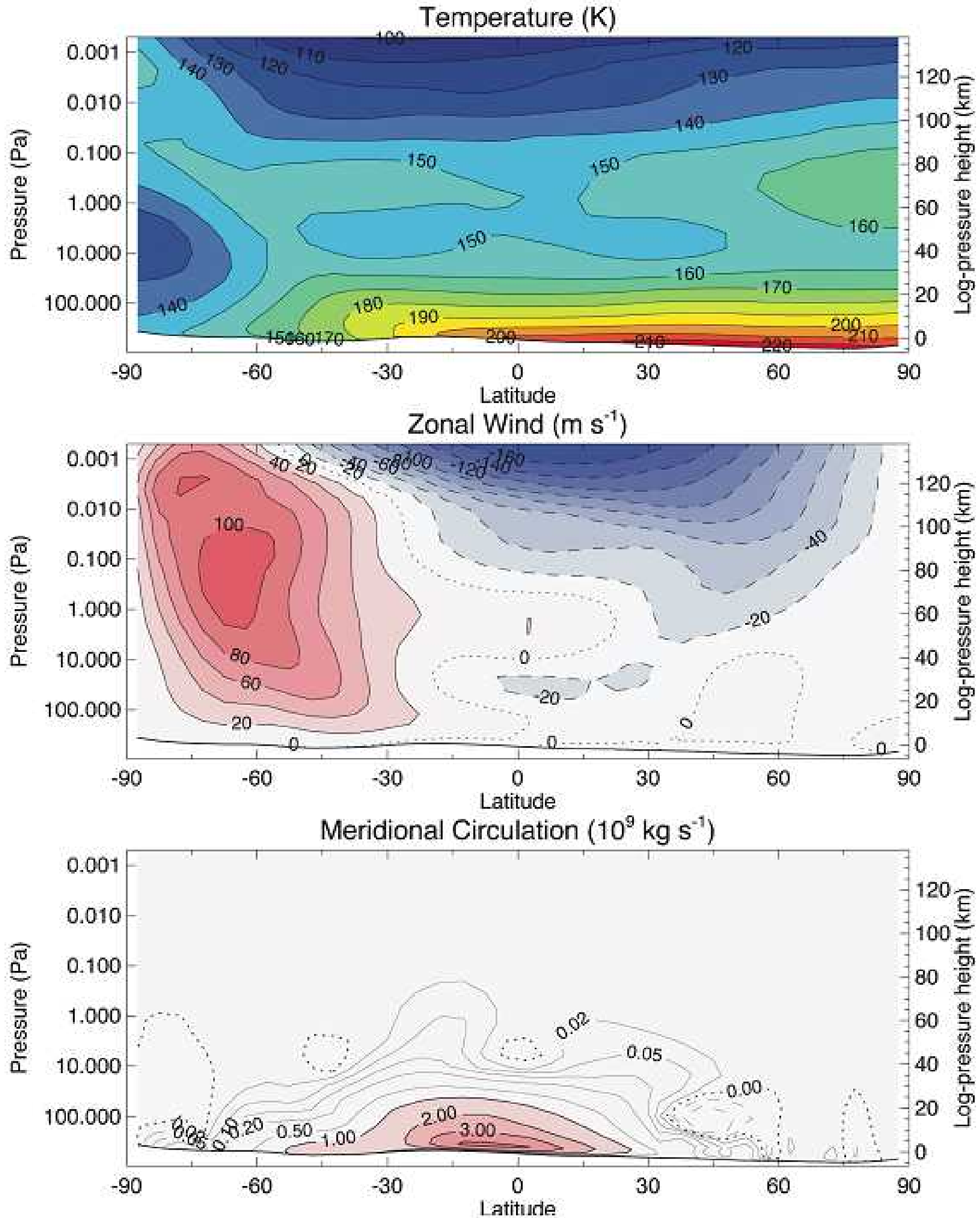
Perspectives/Outlook

- Planet encircling dust storms - how do they work?
  - Initiation AND decay?
- Is Mars' present climate static or in transition?
  - Water cycle - transferring water from N - S?
  - Cyclic climate changes…….? [See lectures by Francois Forget….]
- Can we understand Mars's climate and circulation (and that of other planets) as a shift in dynamical circulation regime with parameters?
  - Dynamics of rotating, stratified fluid systems governed by *at least* 3-4 principal dimensionless parameters
    - especially thermal Rossby and Burger numbers
  - Ro/Bu for Mars ~ 2 x Earth -> consistent with more regular baroclinic activity?
  - ***Scaling behaviour*** of large-scale motions….development of a 'macroturbulent' approach?
- Other 'Big Questions'?
  - Origin of atmospheric methane?
  - Ice and liquid water at, or below, the surface?
  - Etc etc!

Thanks for your attention!
2111

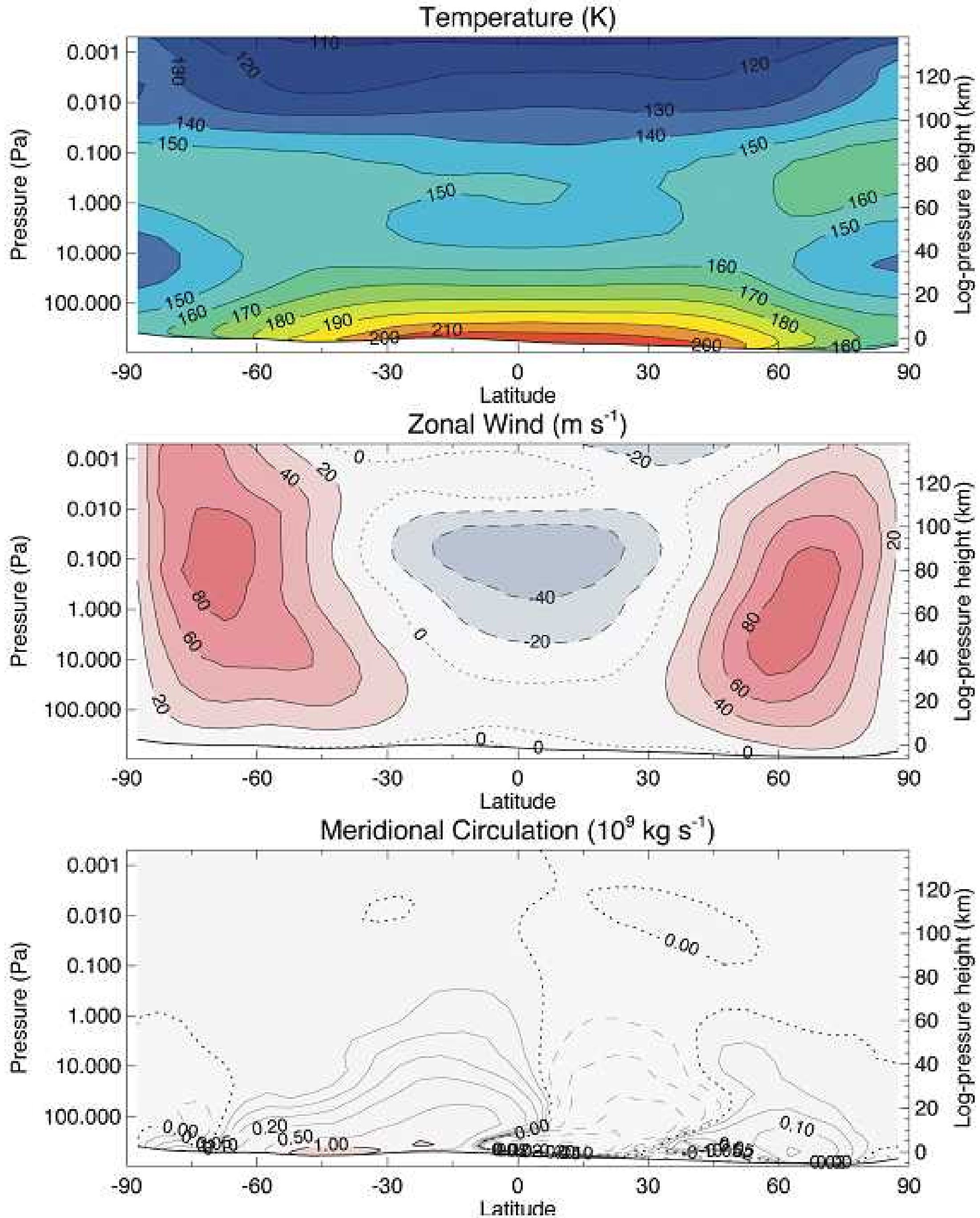
MGS dust, NH summer

(L_S = 90-120^o)

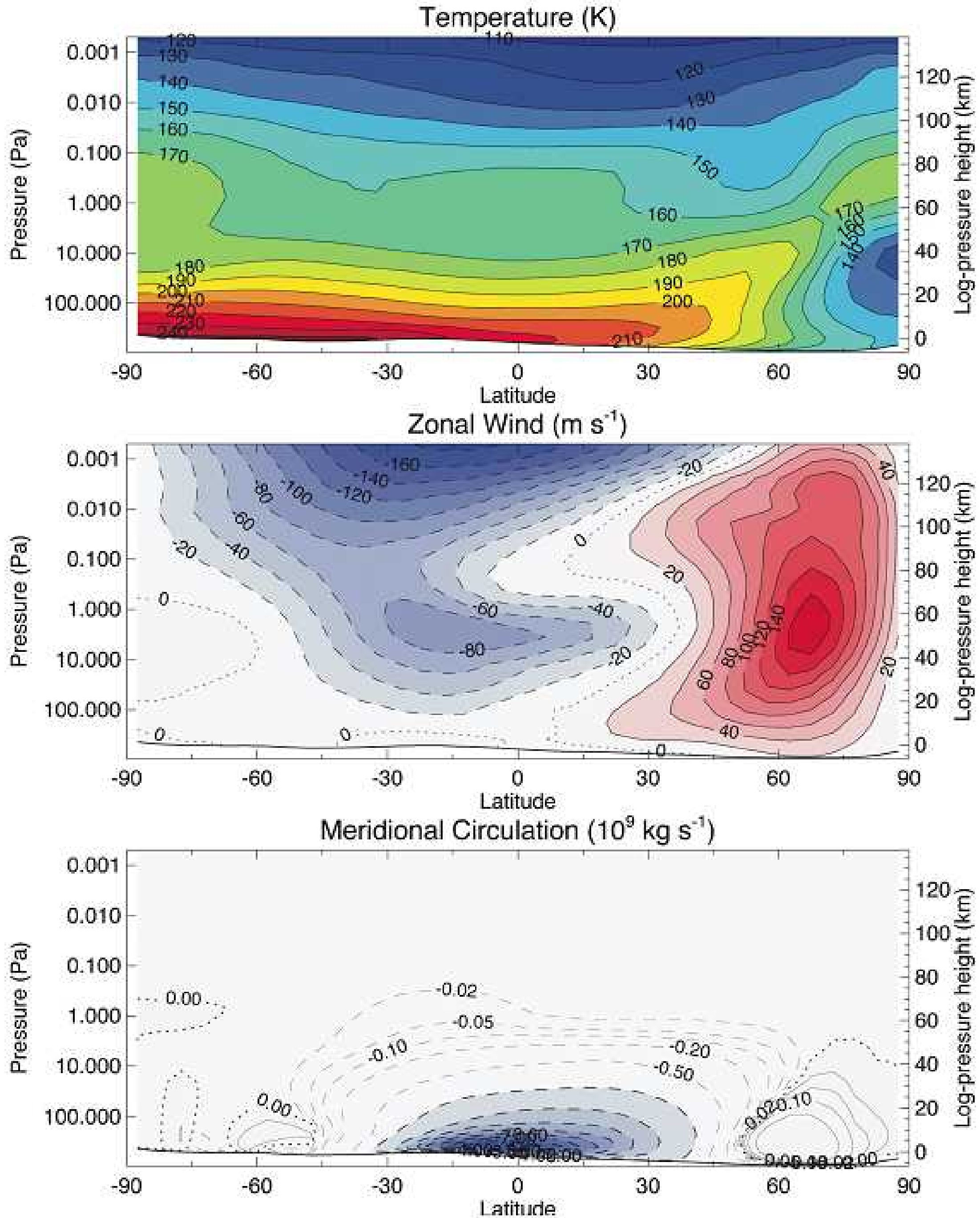


MGS dust, Equinox

(L_S = 150-180^o)



MGS dust, NH winter
(L_S = 240-270^o)



references (1)

- Andrews, D. G., 2000: An Introduction to Atmospheric Physics. *Cambridge University Press*, p.240.
- Barnes,J. R., 1984: Linear baroclinic instability un the Martian atmosphere. *J. Atmos. Sci.*, **41**, 1536-1550.
- Findlater, J., 1969: A major low-level air current near the Indian Ocean during the northern summer. *Quart. J. R. Meteorol. Soc.*, **95**, 362-380.
- Held, Issac M., Hou, Arthur Y., 1980: Nonlinear Axially Symmetric Circulations in a Nearly Inviscid Atmosphere. *J. Atmos. Sci.*, **37**, 515-533.
- Held, Isaac M., 1999: The macroturbulence of the troposphere. *Tellus. A.*, **51**, 59-70.
- Houghton. J. T., 2002: The Physics of Atmospheres. *Cambridge University Press*, p.336.
- James. I. N., 1995: Introduction to Circulating Atmospheres. *Cambridge University Press*, p.444.
- Lewis, S. R., Barker, P. R., 2005: Atmospheric tides in a Mars general circulation model with data assimilation. *Adv. Space Res.*, **36**, 2162-2168.
- Lindzen, Richard S., Hou, Arthur Y., 1988: Hadley Circulations for Zonally Averaged Heating Centered off the Equator. *J. Atmos. Sci.*, **45**, 2416-2427.
- Read, P. L., Lewis, S. R., Bingham, S. J., Newman, C. E., 2004: Predicting Weather Condition and Climate for Mars Expeditons. *Martian Expedition Planning.*, **107**, p.3.

references (2)

- Read. P. L., Lewis. S. R., 2004: The Martian Climate Revisited: atmosphere and environment of a desert planet. *Springer/Praxis*, p.375.
- Schneider, T., Walker, C. C.,2004: Stratification-turbulence feedbacks limit nonlinear interactions between large-scale eddies in the atmosphere. AGU, Fall Meeting, abstract#A13C-05.
- Schneider, Tapio, Walker, Christopher C.,2006: Self-organization of atmospheric macroturbulence into critical state of weak nonlinear eddy eddy interactions. *J. Atmos. Sci*., **63**, 1569-1586.
- Smith, Michael D., Pearl, John C., Conrath, Barney J., Christensen, Philip R., 2000: Mars Global Surveyor Thermal Emission Spectrometer (TES) observations of dust opacity during aerobraking and science phasing. *J. Geophys. Res*., **105**, 9539-9552.
- Stone, Peter H., 1978: Baroclinic Adjustment. *J. Atmos. Sci*., **35**, 561-571.
- Tanaka, H. L., Arai, M., 1999: Linear baroclinic instability in the Martian atmosphere: Primitive equation calculations. *Earth Plan. Space*, **51**, 225-232.
- Williams, Gareth P., 1988: The dynamical range of global circulations-1. *Climate Dynamics*, **2**, 205-260.
- Wilson, R. J., Lewis , S. R., Montabone, L., 2008: Thermal tides in an assimilation of three years of thermal emission spectrometer data from Mars global surveyor. *3rd Int Workshop on the Mars Atmosphere*, **1447**, 9022.