Martian Dynamic Meteorology

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Martian Dynamic Meteorology

“The Diversity of Planets”:

A Comparison of the Atmospheres of Earth and Mars

Outline

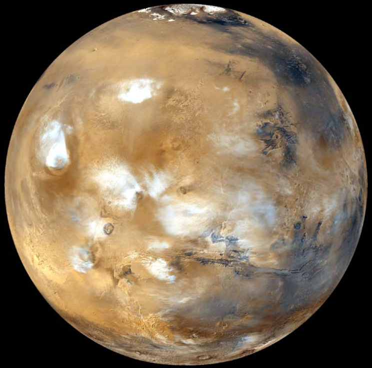
- Overview of Comparative Planetology
  - Only considers terrestrial planets
  - Mostly examines atmospheres
  - Focus on Mars and Earth
- Brief Introduction to Atmospheric Dynamics
- Intermission (includes movies)
- Mars vs. Earth: A Comparative Planetology Study with respect to Atmospheres
  - Important similarities to help guide us
  - Important differences to understand

Part 1:

Overview of Inner Planet Atmospheres (especially Earth and Mars)

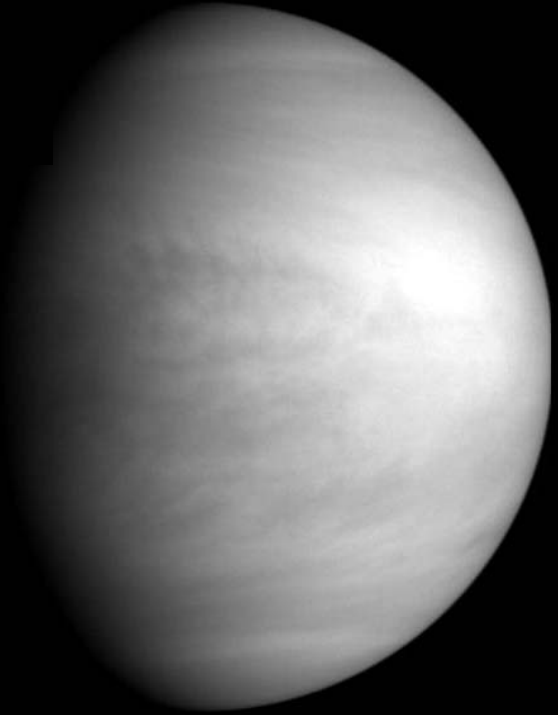
The Inner Planets

Earth



Mars

Mercury

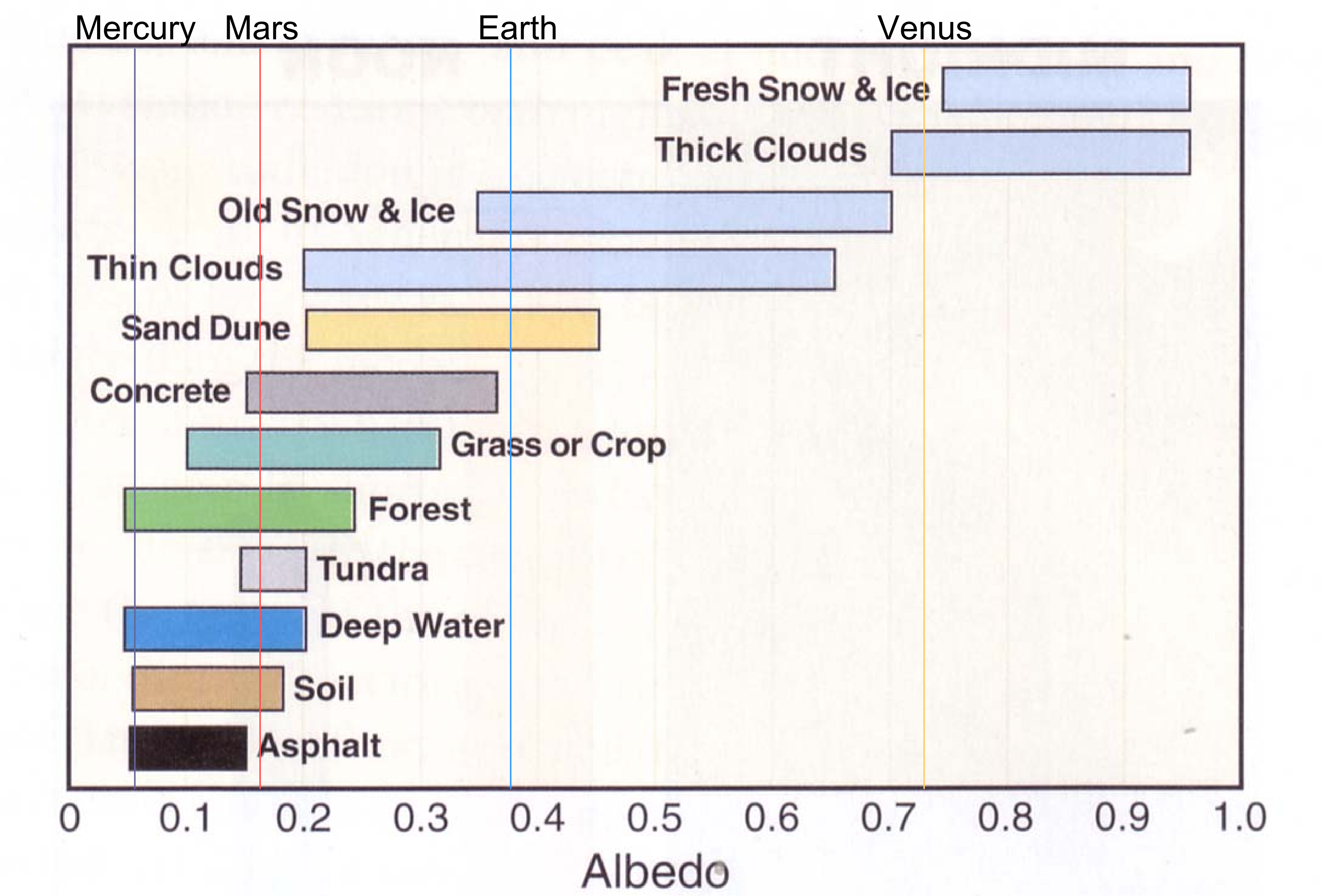


Venus

Terrestrial Planets in General

Planet	d (AU)	g (m/s^2)	albedo	T (K)	P (fraction of Earth)	Composition
Mercury	0.39	3.71	0.056	100 (night) 590-725 (day)	10^{-15}	He, H_2
Venus	0.72	8.90	0.72	737	91	CO_2, N_2, SO_2
Earth	1.00	9.82	0.385	283-293 (day)	1	N_2, O_2, CO_2, Ar, H_2O
Mars	1.52	3.73	0.16	184-242 (day)	0.007-0.009	CO_2, N_2, Ar, O_2, CO, NO

Albedo examples



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Particles on ballistic trajectories do not constitute an atmosphere

Planet Characteristics

Property	Earth	Mars
Radius (km)	6371	3390
g (m s^{-2})	9.82	3.73
Length of year (⊕ day)	365	687
Length of day	24 h	24 h 39.6 m
a (AU)	1.00	1.52
Obliquity	23.45	25.19
Eccentricity	0.017	0.093

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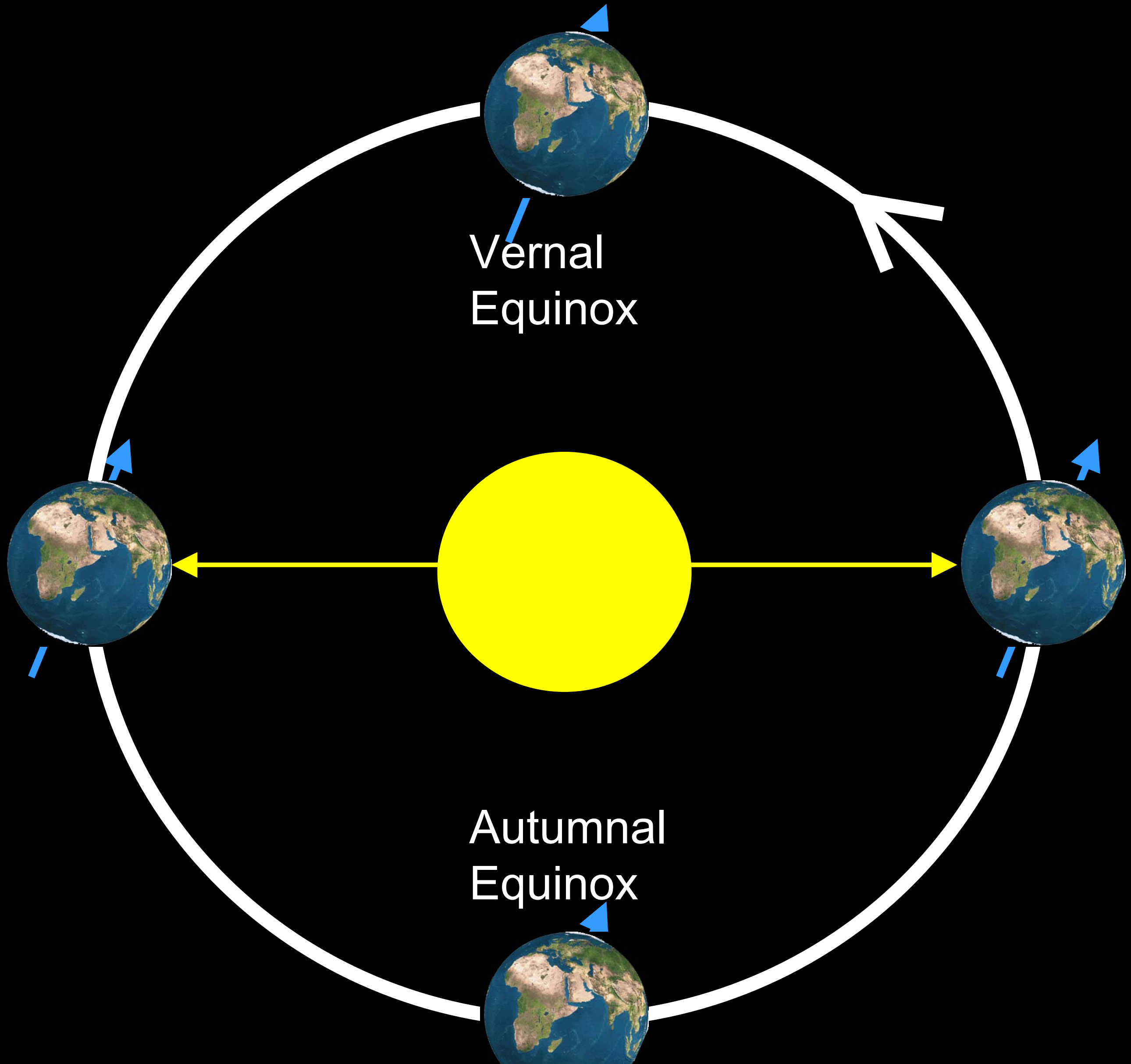
Earth’s Circular Orbit



Vernal Equinox

Summer Solstice

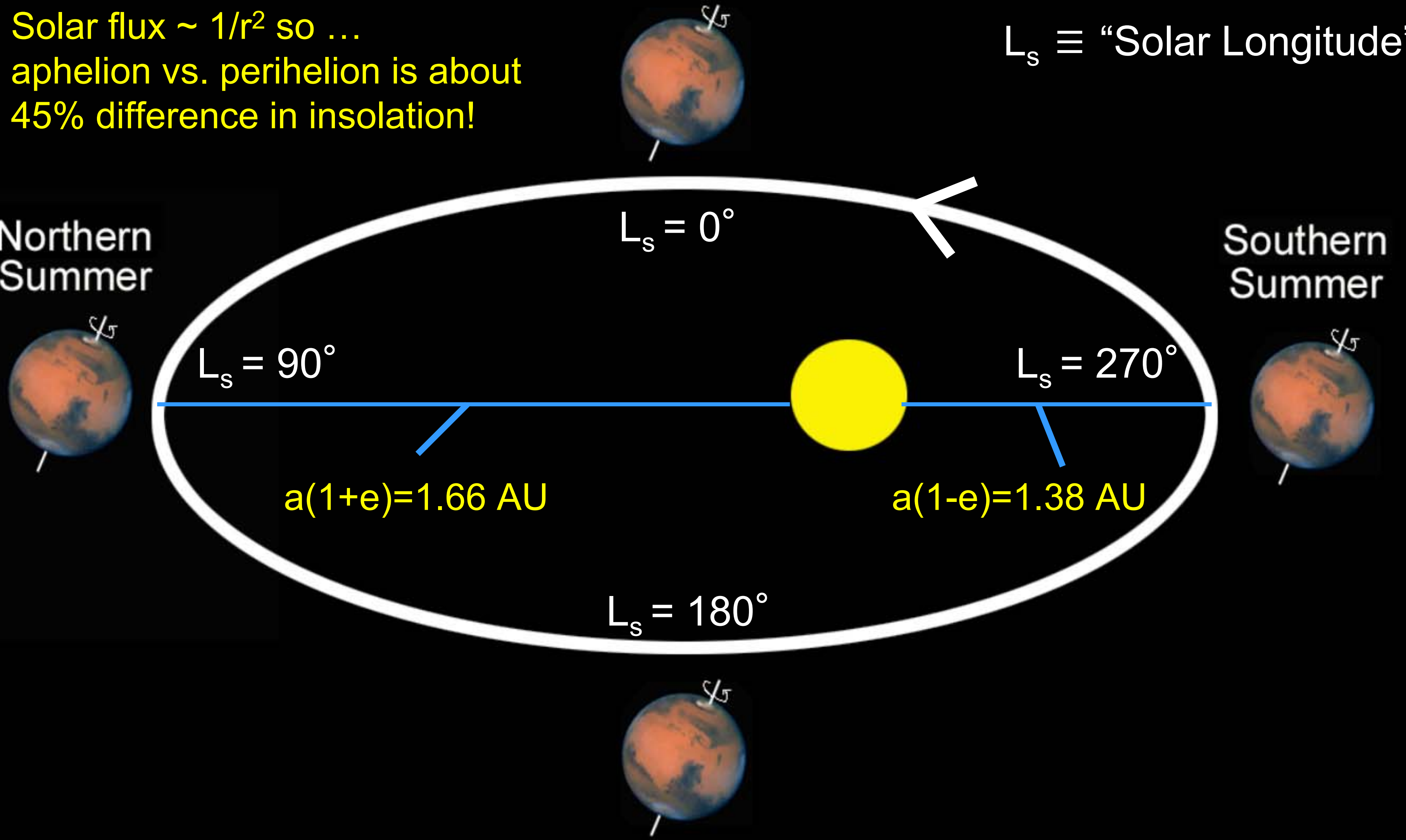
Winter Solstice

Autumnal Equinox

Mars' Highly Eccentric Orbit

Solar flux ~ $1/r^2$ so …
aphelion vs. perihelion is about
45% difference in insolation!

$L_s \equiv$ "Solar Longitude



Northern Summer

Southern Summer

$L_s = 0^\circ$

$L_s = 90^\circ$

$L_s = 270^\circ$

$L_s = 180^\circ$

$a(1+e)=1.66$ AU

$a(1-e)=1.38$ AU

Atmospheric Composition

Constituent	Earth	Mars
N_2	78.08%	2.7%
O_2	20.95%	0.13%
Ar	0.93%	1.6%
CO_2	0.035%	95.32%
H_2O	<4%	<0.03%
CO	.00001%	0.08%

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Atmosphere Characteristics

Property	Earth	Mars
$T_{surface}$ (K)	~288	~214
$P_{surface}$ (Pa) [bar]	10133 [1.0133]	636 [0.00636]
m (g/mol)	28.97 (mostly **N_2**)	43.34 (mostly **CO_2**)
H (km) “scale height”	8.42	11.07

Part 2:

Brief Introduction to Atmospheric Dynamics

Part 2: Table of Contents

Ideal Gas Law

$$PV = NkT$$

$$n = \frac{N}{V}, \quad \rho = nm, \quad R = \frac{k}{m}$$

$$\boxed{P = \rho RT}$$

P = Pressure, V = Volume, T = Temperature

N =# of molecules

k = Boltzmann's constant, R = gas constant

n = number density, ρ = mass density

Hydrostatic Balance

Equate pressure balance with gravitational force

$$\left(p(z)-p(z+\Delta z)\right)\Delta A = mg$$

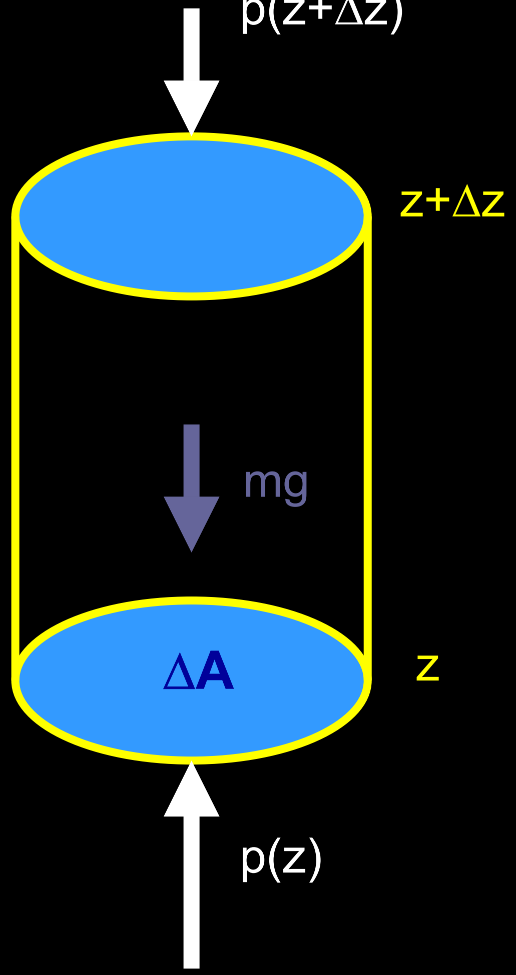
$$m=\rho V,\quad V=\Delta A\times\Delta z$$

$$p(z+\Delta z)\approx p(z)+\frac{dP}{dz}\Delta z$$

$$\therefore\ p(z)-p(z+\Delta z)=-\frac{dP}{dz}\Delta z$$

$$-\frac{dP}{dz}\Delta z\Delta A=\rho(\Delta A\Delta z)g$$

$$\rightarrow\boxed{\frac{dP}{dz}=-\rho g}$$



Combine Ideal Gas Law and Hydrostatic Balance (1)

$$\boxed{P = \rho R T} \quad \text{and} \quad \boxed{\frac{dP}{dz} = -\rho g}$$

$$\rho = \frac{P}{RT} \rightarrow \frac{dP}{dz} = -\frac{Pg}{RT} \rightarrow \frac{dP}{P} = -\frac{g}{RT}dz$$

$$\int \frac{dP}{P} = -\int \frac{g}{RT}dz \rightarrow \boxed{\ln P = -\frac{g}{R}\int \frac{dz}{T}}$$

Combine Ideal Gas Law and Hydrostatic Balance (2)

$$\boxed{\ln P = -\frac{g}{R}\int \frac{dz}{T}}$$

Assuming T is constant (for now):

$$\ln P = -\frac{g}{RT}z + \text{constant}$$

$$P(z=0) \equiv P_0 \quad \rightarrow \quad \text{constant} = \ln P_0$$

$$\boxed{P = P_0 e^{-\frac{gz}{RT}}}$$

Scale Height

$$\boxed{P = P_0 e^{-\frac{gz}{RT}}}$$

$$\text{if } \boxed{H \equiv \frac{RT}{g}}, \text{ then } P = P_0 e^{-\frac{z}{H}}$$

H is the “scale height,” the height over which the pressure reduces by a factor of 1/e.

The scale height can also be used to conveniently describe a “typical length scale” in the vertical for an atmosphere.

Potential Temperature and the First Law of Thermodynamics

Potential Temperature, θ, is another convenient variable used in atmospheric dynamics, and it can be derived from the 1st Law of Thermodynamics and the Ideal Gas Law.

Potential Temperature and Entropy (1)

$$\boxed{\text{First Law}: \quad \delta U = \delta Q + \delta W}$$

$$\delta U = c_v \delta T, \quad \delta Q = T \delta S, \quad \delta W = -P \delta V$$

$$c_v \delta T = T \delta S - P \delta V$$

Differentiating ideal gas law:

$$P \delta V + V \delta P = R \delta T$$

Combine with 1st Law and

use ideal gas law again to remove V:

$$c_v \delta T = T \delta S + \frac{RT}{P} \delta P - R \delta T$$

Potential Temperature and Entropy (2)

$$c_v \delta T = T\delta S + \frac{RT}{P}\delta P - R\delta T$$

$$(c_v + R)\delta T = T\delta S + \frac{RT}{P}\delta P$$

$$c_p = c_v + R$$

$$\boxed{c_p \delta T = T\delta S + \frac{RT}{P}\delta P}$$

For an adiabatic process, $\delta Q \equiv 0$ (or $T\delta S = 0$) :

$$\delta \to d$$

$$c_p \frac{dT}{T} = R\frac{dP}{P}$$

Potential Temperature and Entropy (3)

$$c_p \frac{dT}{T} = R \frac{dP}{P}$$

$$\text{Integrating}: \ \ln T = \frac{R}{c_p} \ln P + \text{constant}$$

$$\text{To find constant, use } \theta = T \text{ when } P = P_0$$

$$\ln \frac{\theta}{T} = \frac{R}{c_p} \ln \frac{P_0}{P} \quad \rightarrow \quad \boxed{\theta \equiv T\left(\frac{P_0}{P}\right)^{\frac{R}{c_p}}}$$

Potential Temperature and Entropy (4)

$$\theta \equiv T\left(\frac{P_0}{P}\right)^{\frac{R}{c_p}}$$

θ is the "potential temperature."

It is the temperature that an air parcel would have if it was moved from P to P_0 adiabatically (no heat exchanged with surroundings).

Potential Temperature and Entropy (5)

Now go back to earlier equation and use definition of θ

$$\boxed{c_p dT = TdS + \frac{RT}{P} dP}$$

$$dS = c_p \frac{dT}{T} - R \frac{dP}{P}$$

$$S = c_p \ln T - R \ln P + \text{constant}$$

$$\theta = T\left(\frac{P_0}{P}\right)^{\frac{R}{c_p}} \quad or \quad T = \theta\left(\frac{P}{P_0}\right)^{\frac{R}{c_p}}$$

$$\ln T = \ln \theta + \frac{R}{c_p} \ln P$$

Potential Temperature and Entropy (6)

$$S = c_p \ln T - R \ln P + \text{constant}$$

$$\ln T = \ln \theta + \frac{R}{c_p} \ln P$$

$$S = c_p \left(\ln \theta + \frac{R}{c_p} \ln P \right) - R \ln P + \text{constant}$$

$$S = c_p \ln \theta + \text{constant}$$

Potential Temperature and Entropy (7)

$$S = c_p \ln \theta + \text{constant}$$

So, θ and S are directly related, and potential temperature is also a measure of the entropy of the parcel of air

Dry Adiabatic Lapse Rate

- If an air parcel is raised or lowered adiabatically:
  - its potential temperature will remain the same
  - but its (regular) temperature will change.
  - What is the change in temperature for adiabatic ($dQ=0$) processes?
- Can answer by starting with a rewritten form of 1st Law of Thermodynamics again

Dry Adiabatic Lapse Rate

$$\boxed{c_p dT = TdS + \frac{RT}{P} dP}, \quad dQ = TdS = 0$$

$$c_p dT = \frac{RT}{P} dP, \quad \text{and divide by } dz:$$

$$c_p \frac{dT}{dz} = \frac{RT}{P}\frac{dP}{dz}, \text{ but } \frac{dP}{dz} = -\rho g, \text{ and } \rho = \frac{P}{RT}$$

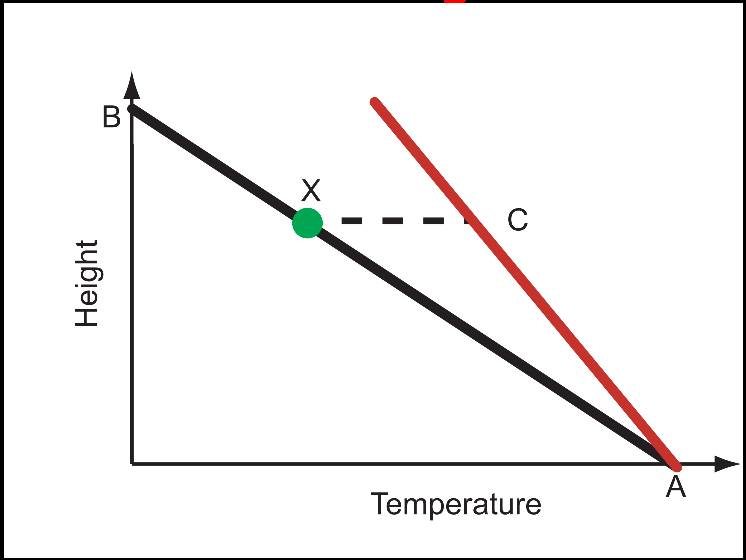
$$c_p \frac{dT}{dz} = \frac{1}{\rho}\left(-\rho g\right) \quad \rightarrow \quad c_p \frac{dT}{dz} = -g$$

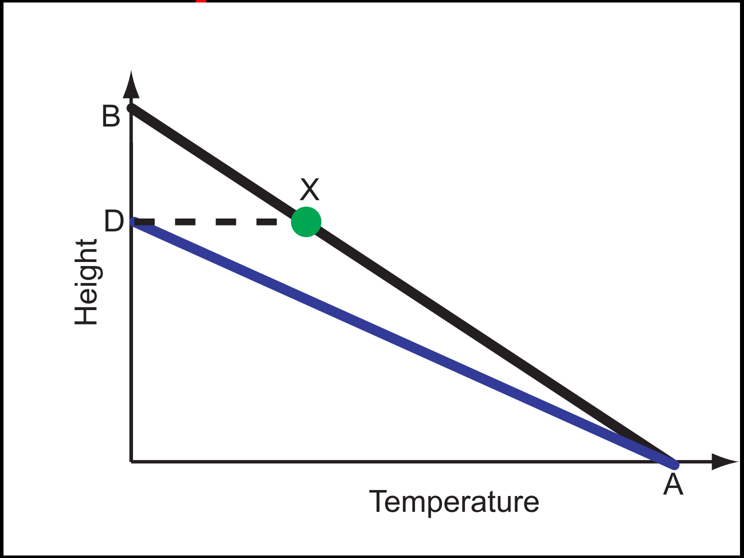
$$\boxed{\frac{dT}{dz} = -\frac{g}{c_p}}$$

Values of Lapse Rates on Earth and Mars

	Earth	Mars
g (m/s^2)	9.81	3.72
c_p ($J\ K^{-1}\ kg^{-1}$)	1005	770
Dry Adiabatic Lapse Rate (dT/dz) (K/km)	9.76	4.83

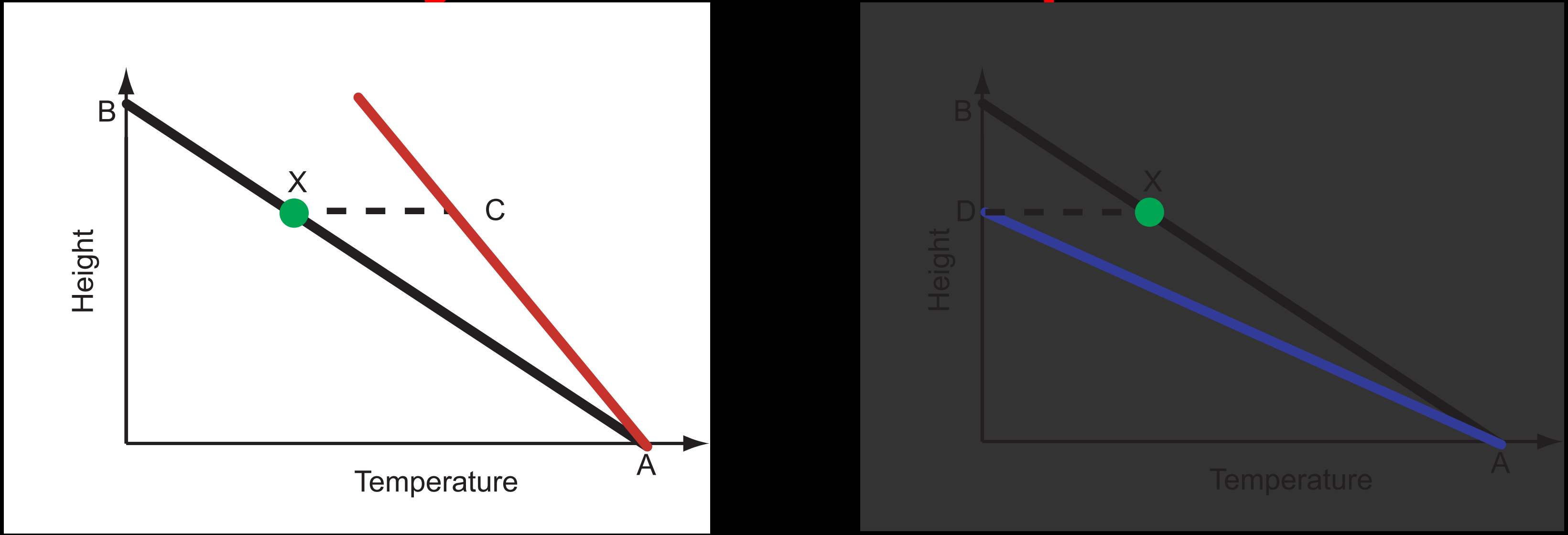
Stability and the Lapse Rate





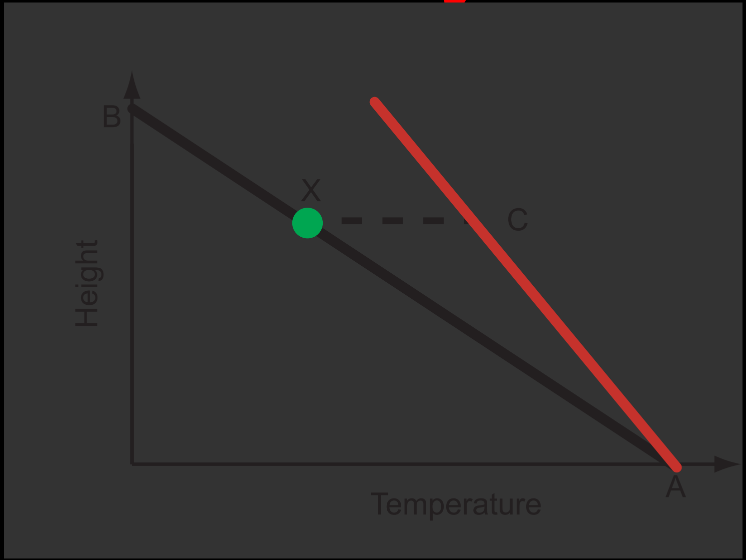
- The dry adiabatic lapse rate (DALR) is the line A-B above
- Let's move a parcel of air from the ground at point A to a height X

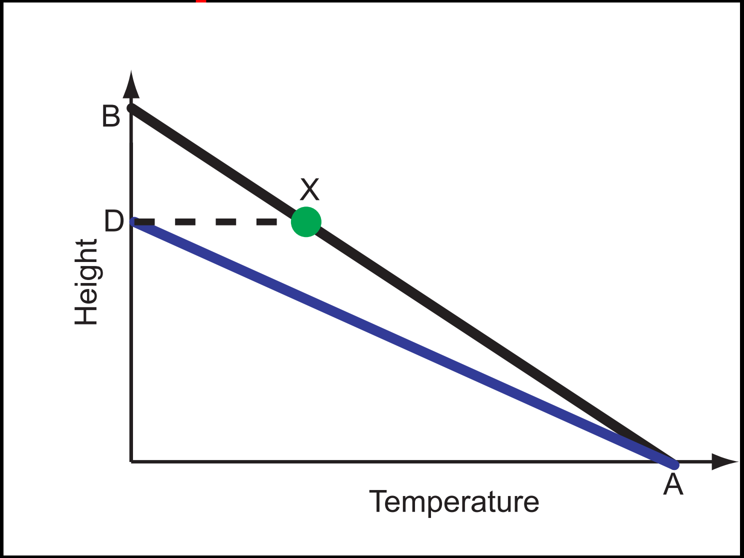
Stability and the Lapse Rate



- If the real lapse rate is A-C (due to radiative heating, conduction, etc.) then a parcel raised to a height X will be colder than the surroundings, and thus denser, and will fall back to the ground.
- This condition is said to be “stable” … a parcel will want to return where it came from.

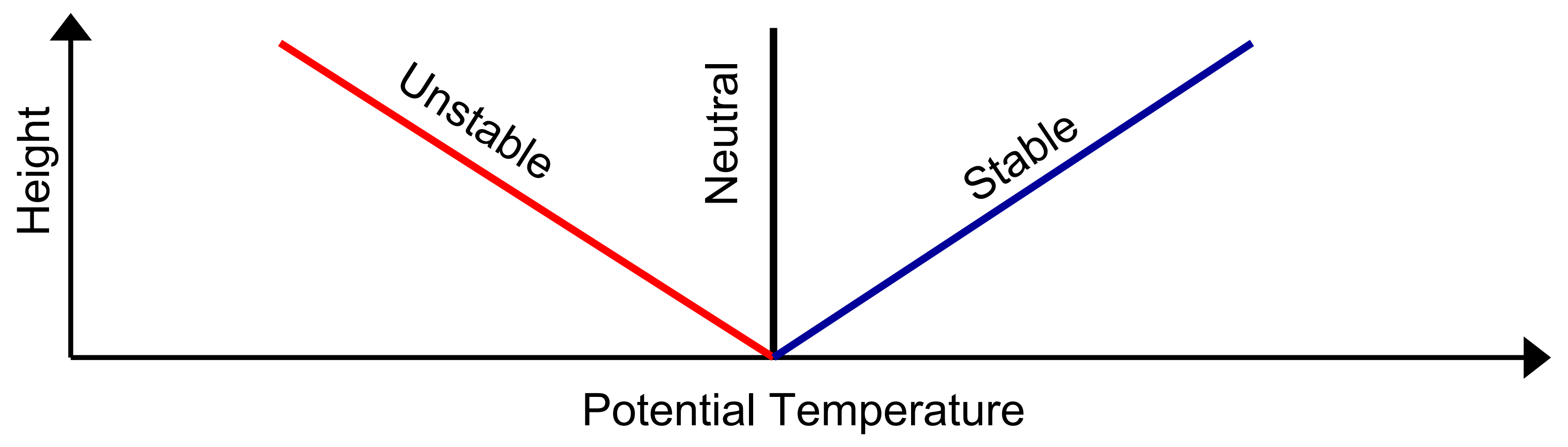
Stability and the Lapse Rate





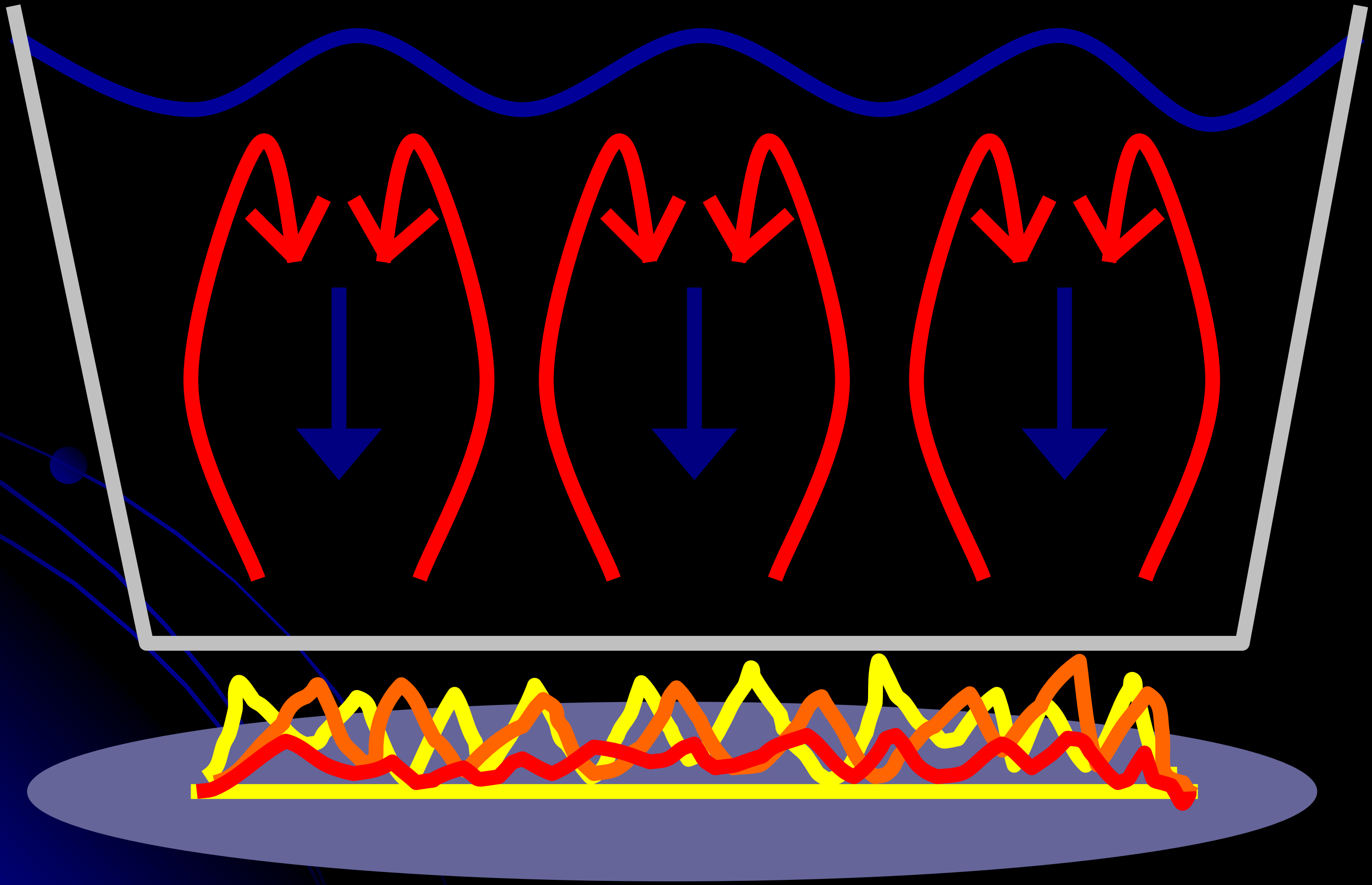
- If the real lapse rate is A-D, then a parcel at height X will be warmer than the surroundings, and less dense, and will want to continue rising.
- This condition is said to be “unstable” … a parcel that rises will want to continue rising

Potential Temperature

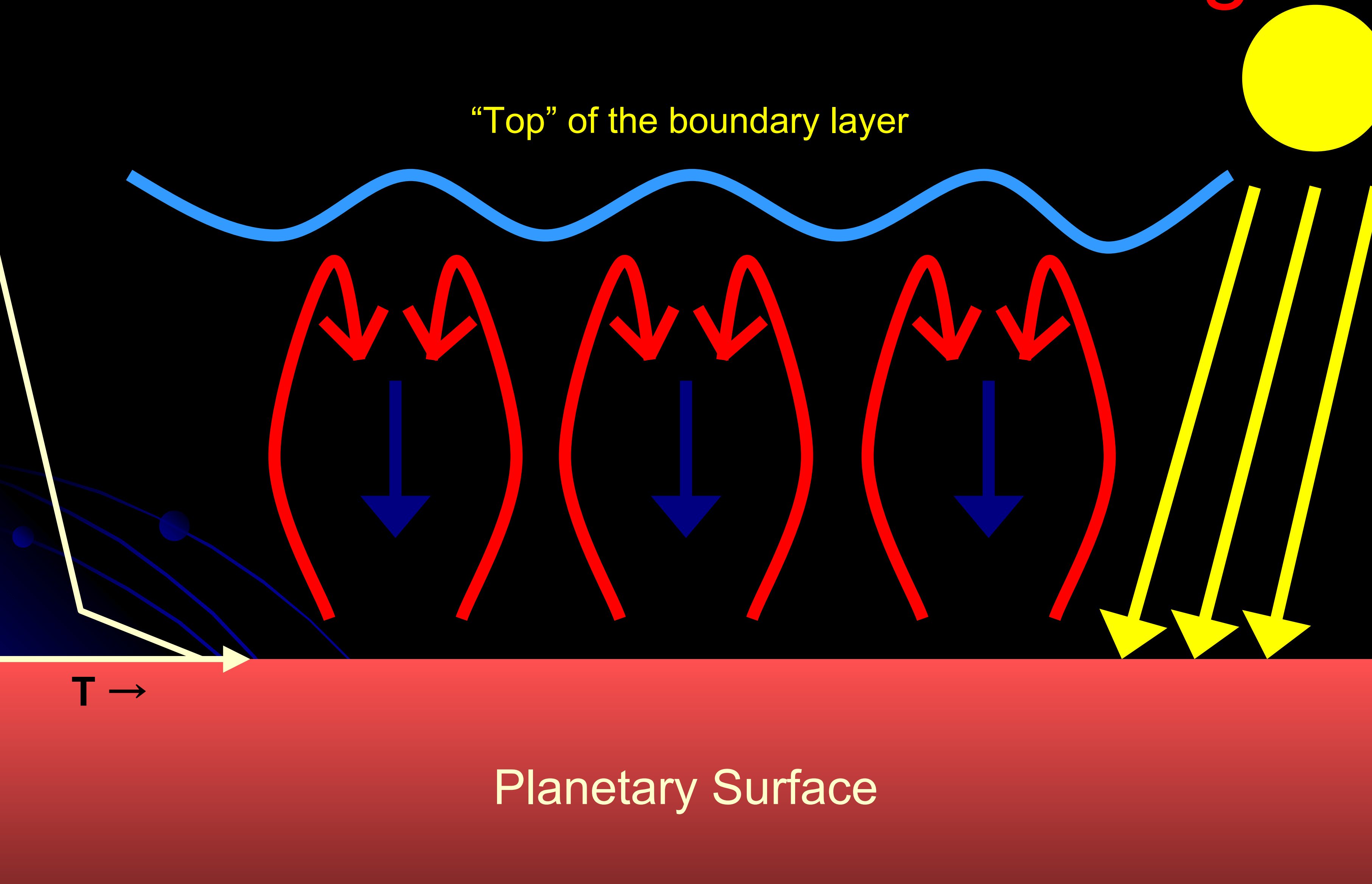


- It’s much easier to see using potential temperature.
- A vertical line is neutral, a positive slope is stable and a negative slope is unstable

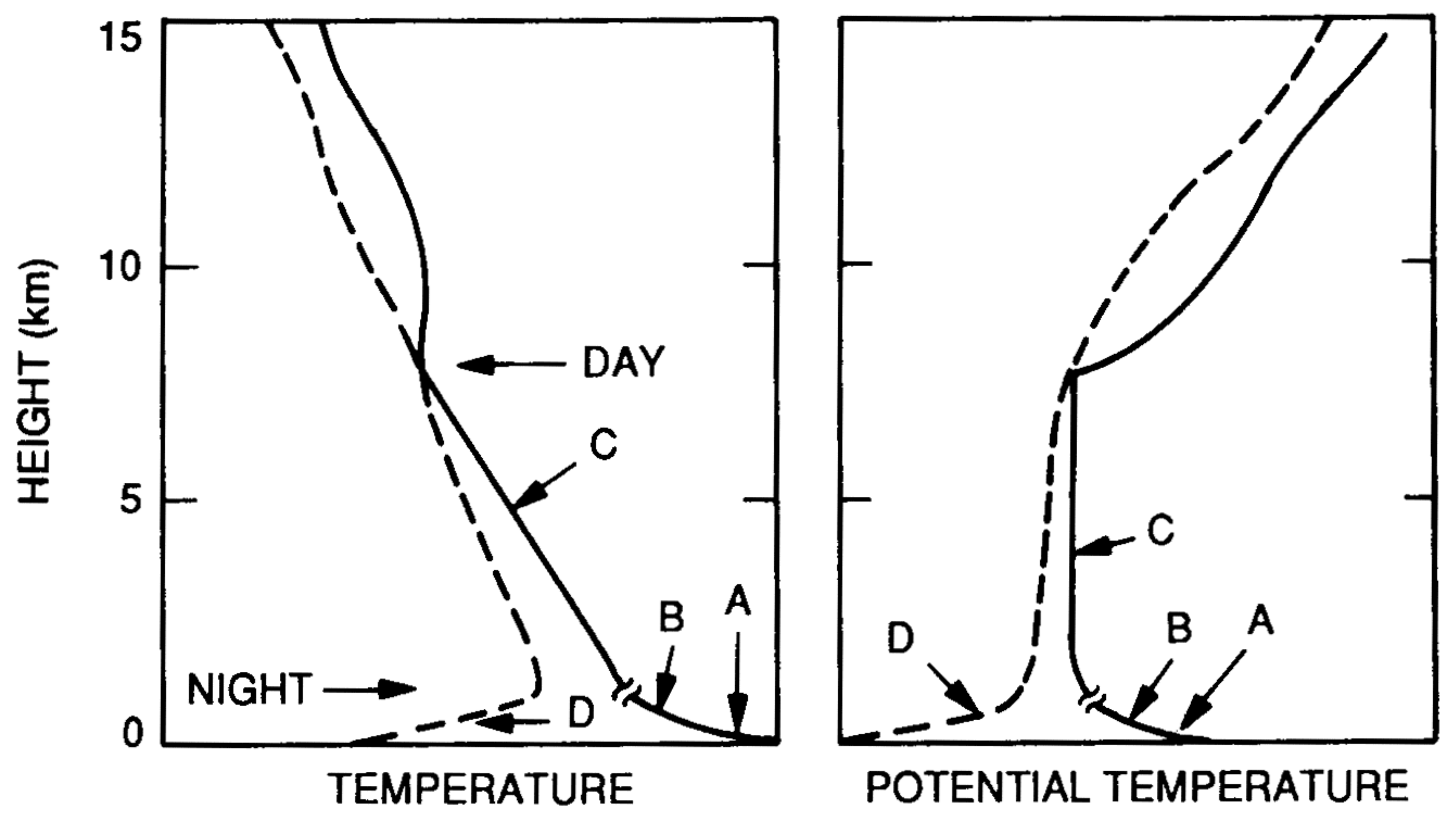
Convection: Boiling Water



Convection: Surface Heating

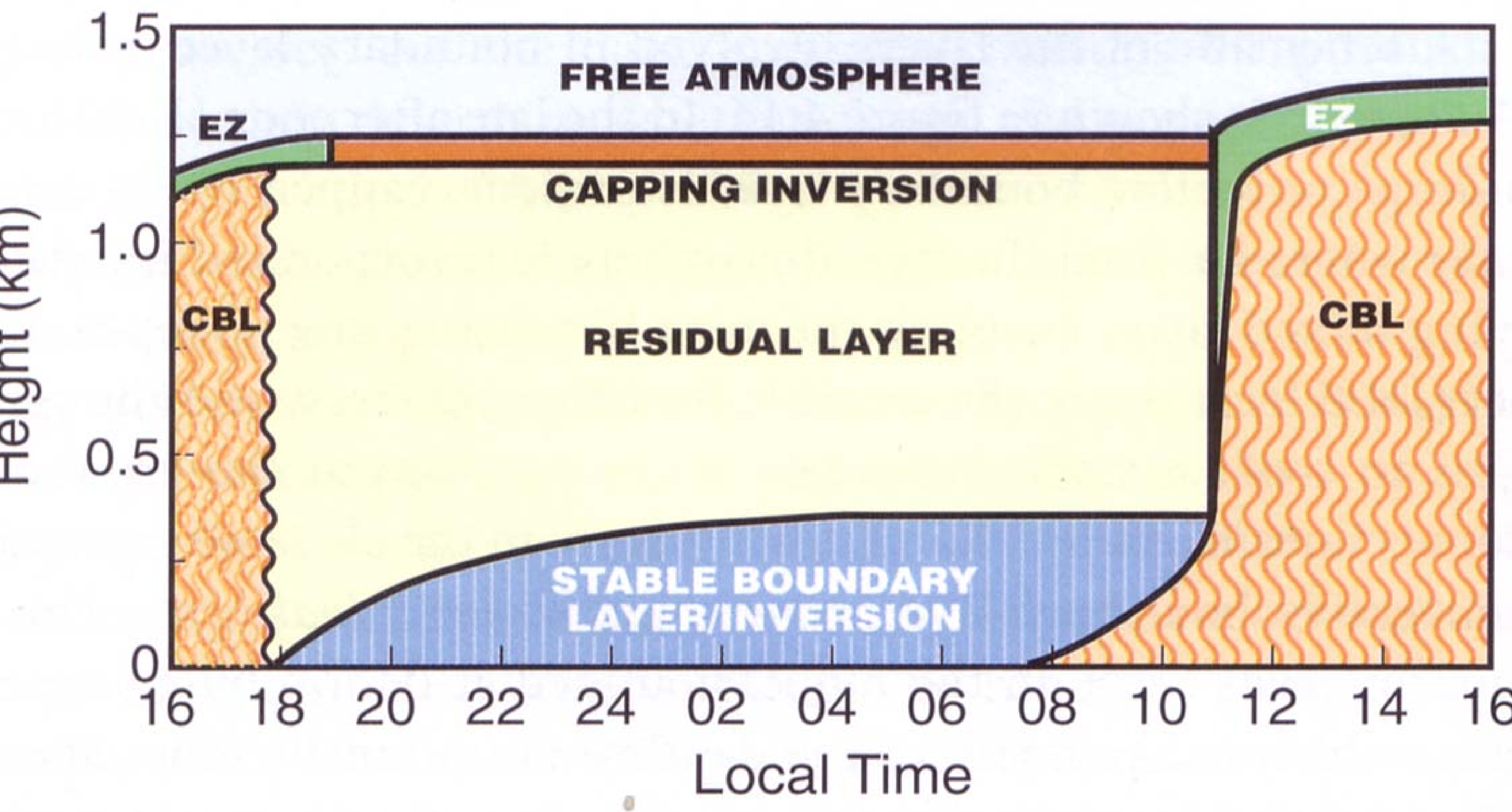


Martian Daytime T profile

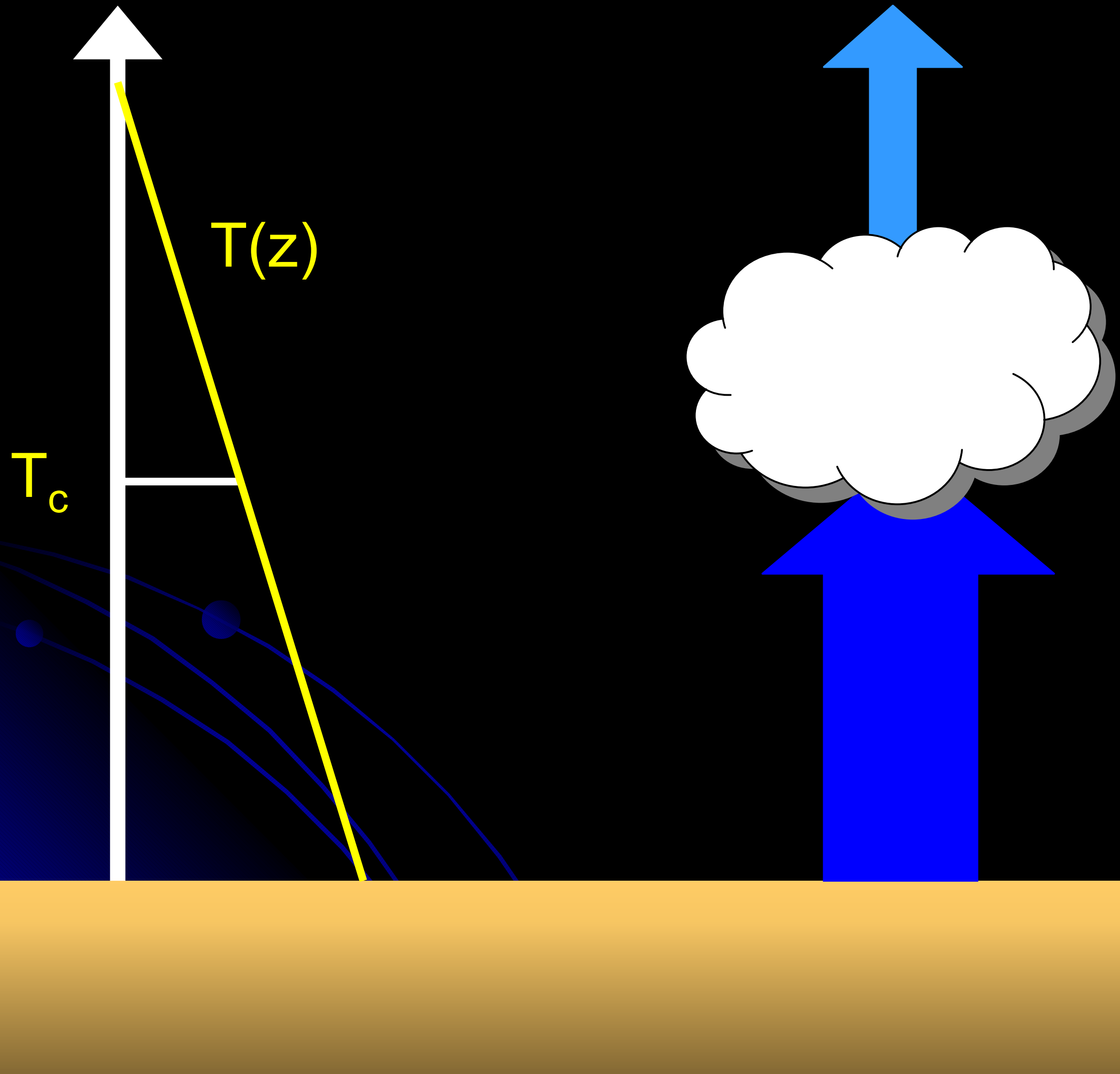


- A-B: “Superadiabatic” conduction layer, C: Convecting zone, D: Nighttime radiative-cooling inversion layer

Boundary Layers



Convective Cloud Formation



Less moist air

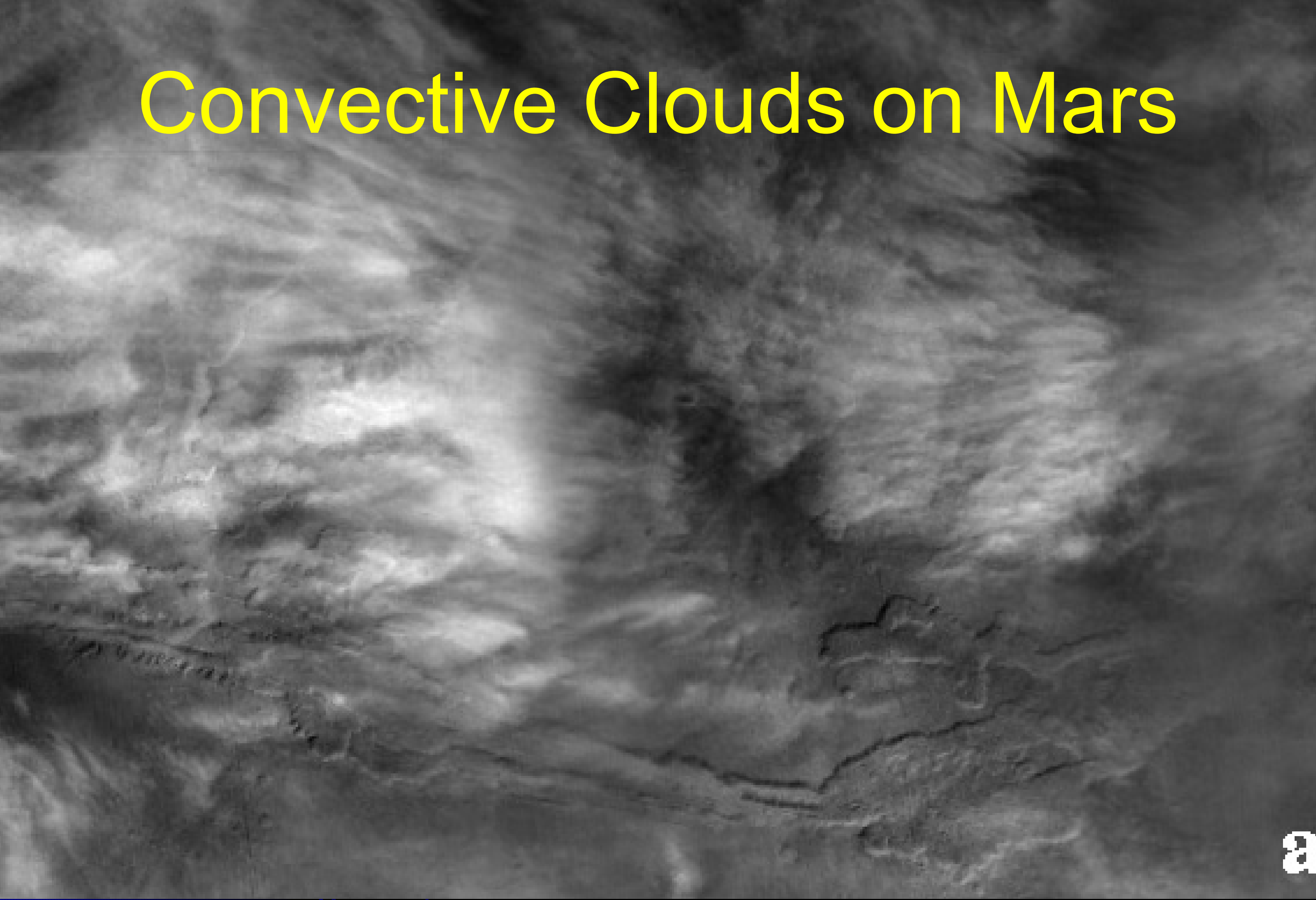
Condensation occurs when air can no longer hold all vapor at a certain temperature

Moist air rises and cools

Convection and Cloud Formation

Open cellular convection over the oceans

Convective Clouds on Mars



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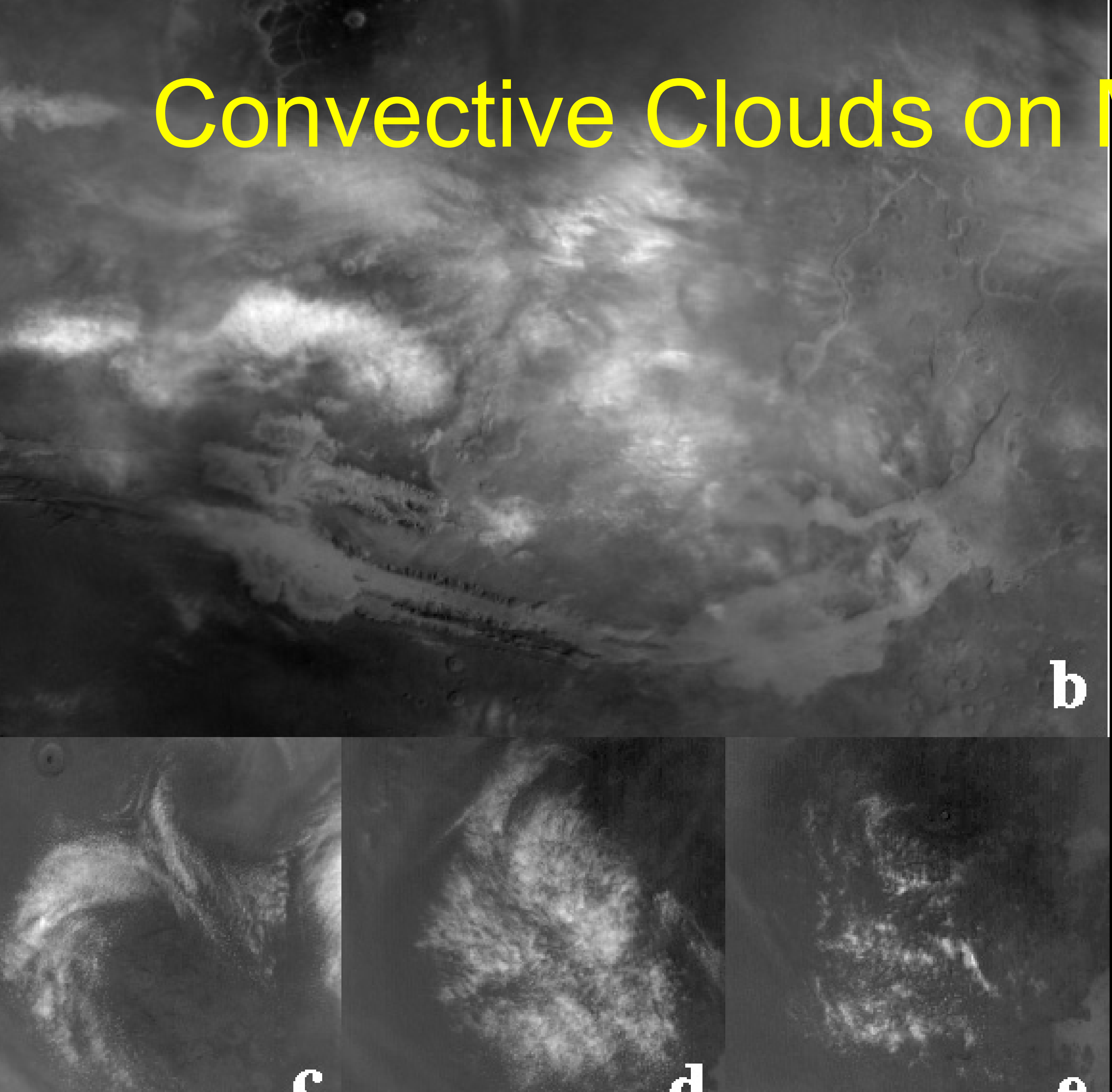
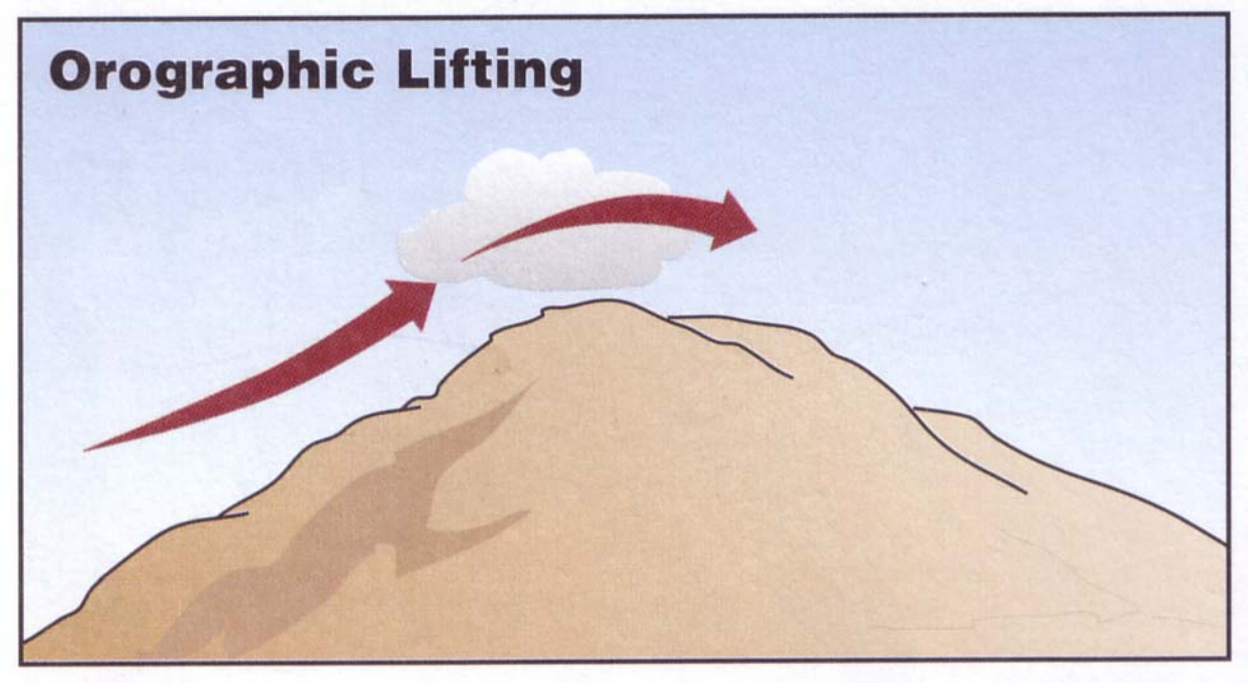
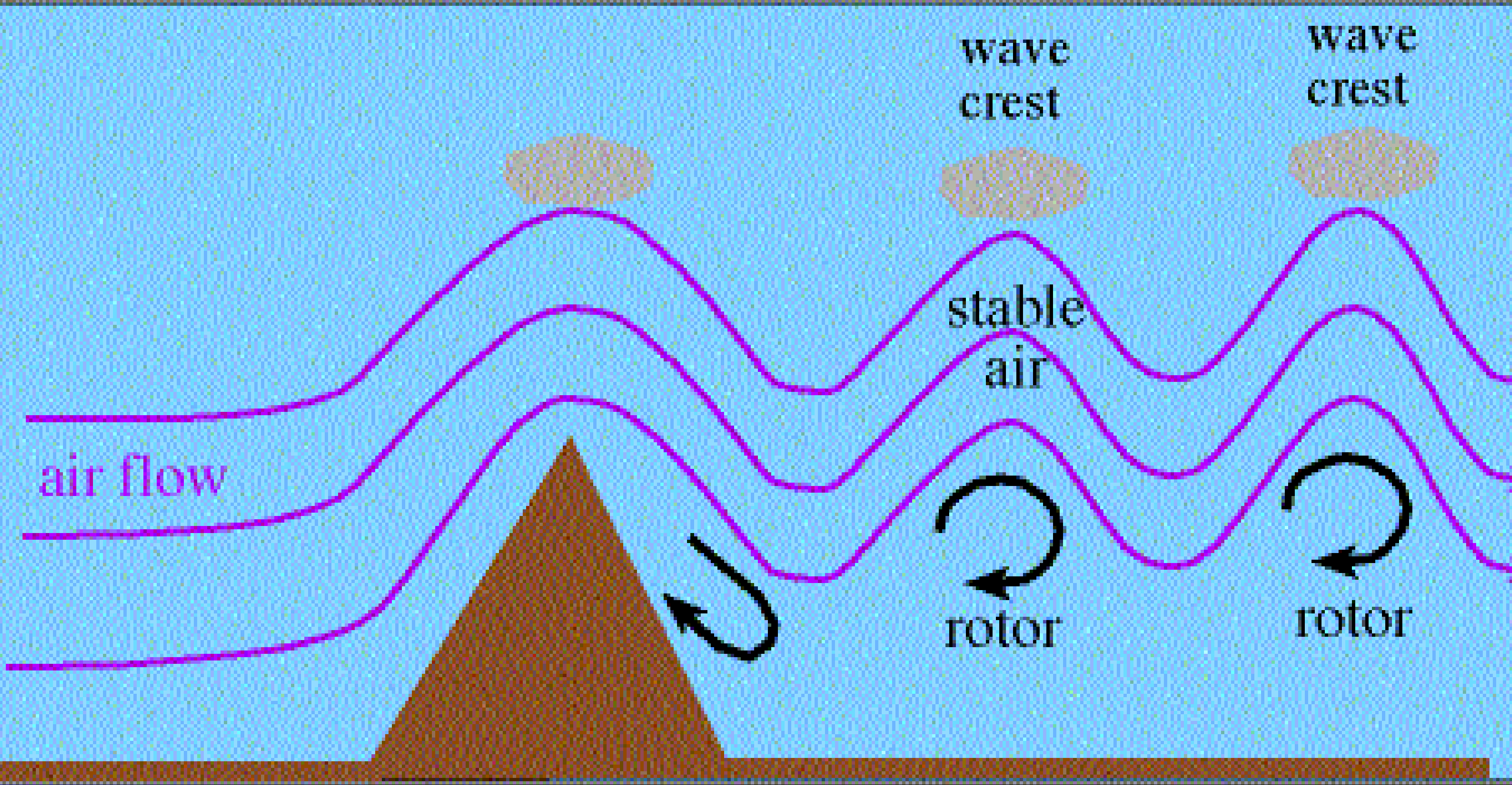


Topographically Forced Clouds



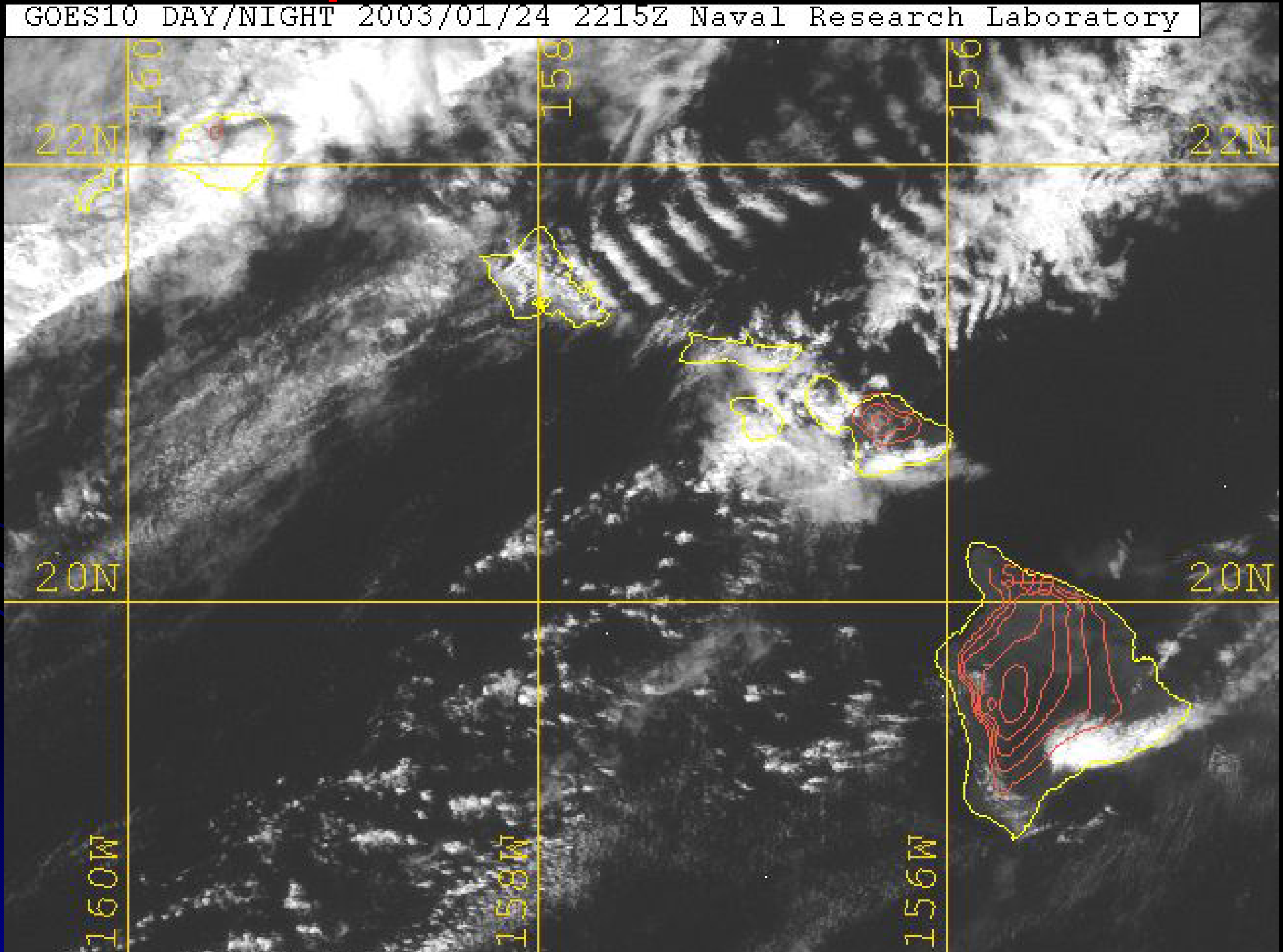
- “Moist” air rises (due to convective instability) over a mountain, cools as it rises, and can’t hold as much water vapor as it gets colder.
- When the temperature gets cold enough, the vapor condenses and a cloud forms

Topography and Lee Waves



- Rotor circulations on the leeward side of the mountain: bad for airplanes
- Rotors can have strong vertical motions

Examples of Wave Clouds



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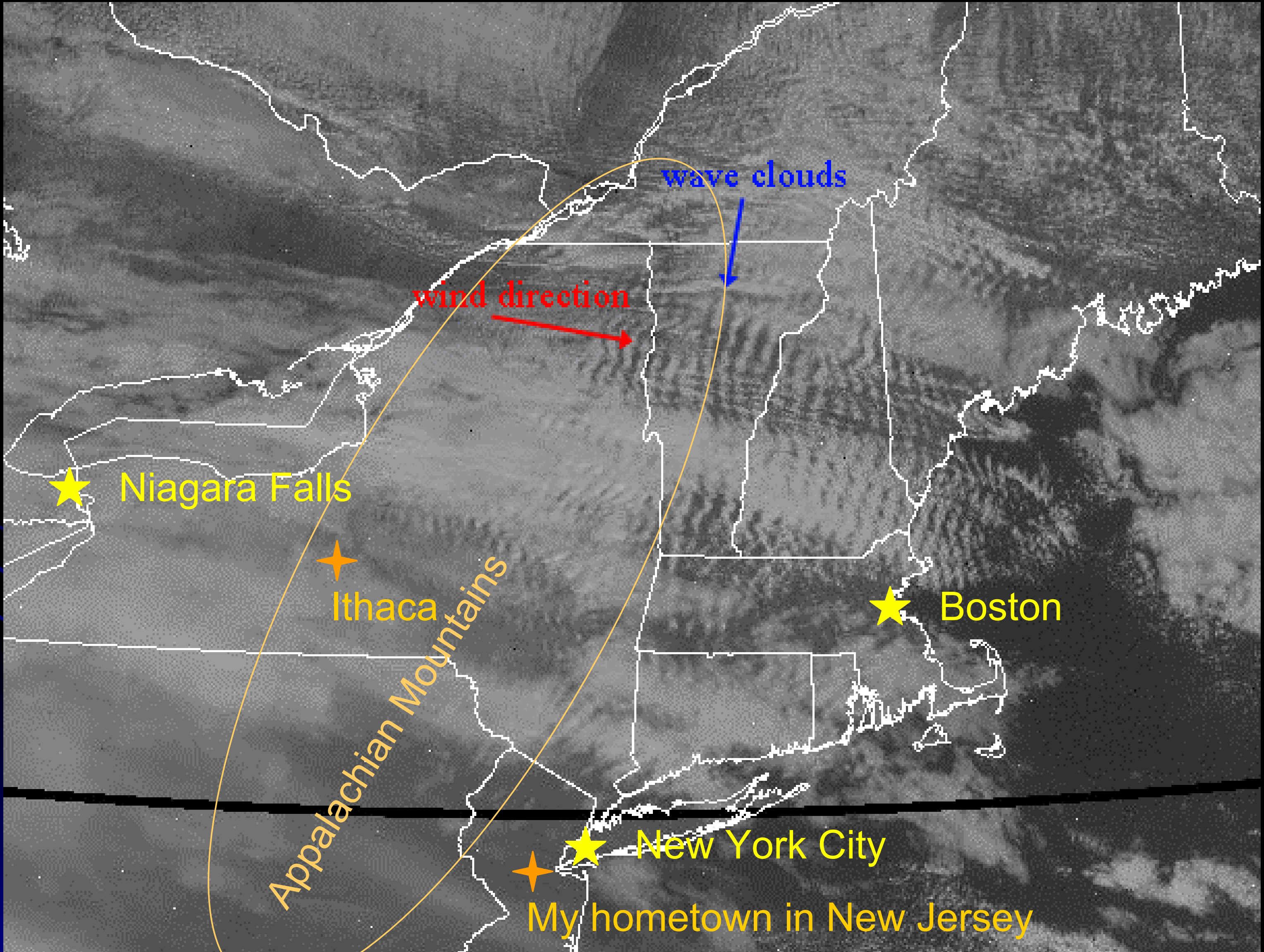


Newton's Equation for an Atmosphere

$$\boxed{\vec{F}} = \boxed{m\vec{a}}$$

$$\vec{a} = \frac{D\vec{v}}{Dt}, \quad \vec{v} = (u, v, w)$$

$$\frac{D\vec{v}}{Dt} \equiv \frac{\partial \vec{v}}{\partial t} + \left(\vec{v} \cdot \vec{\nabla}\right)\vec{v}$$

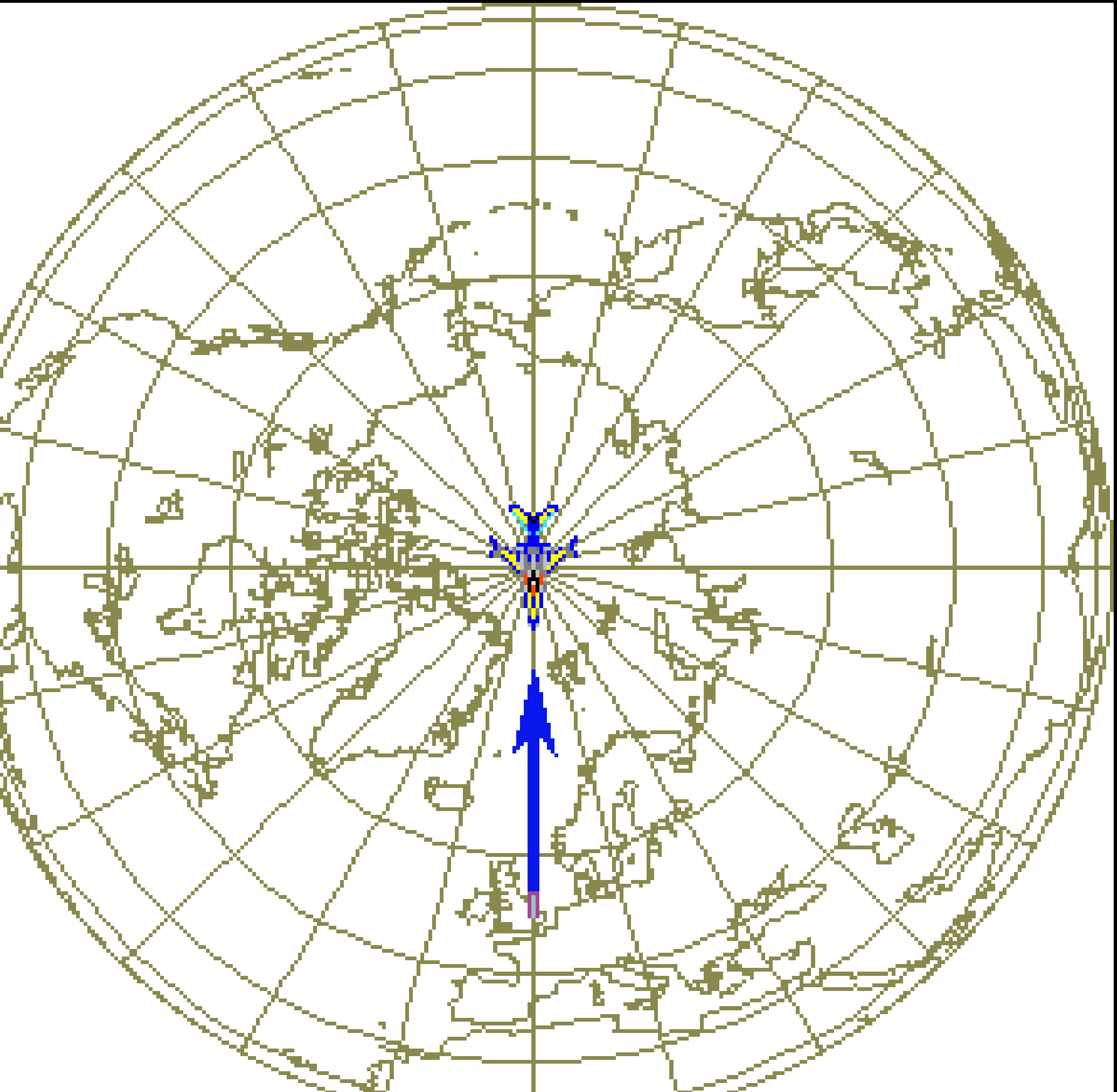
Taking in to account rotating reference frame, and gravity, pressure, and friction forces:

$$\boxed{\frac{\partial \vec{v}}{\partial t} + \left(\vec{v} \cdot \vec{\nabla}\right)\vec{v} + 2\vec{\Omega} \times \vec{v}} = \boxed{-g\hat{\mathrm{k}} - \frac{1}{\rho}\vec{\nabla}P + F_r}$$

What is Coriolis “Force”?

- The *coriolis force* arises due to the fact that the earth is rotating
- Always acts to deflect an object to the right (left) of it's direction of motion in the northern (southern) hemisphere
- Magnitude is zero at the equator, maximum at the poles
- Magnitude depends on the rotation rate of the earth
  - Magnitude would increase if the earths rotation rate increased
- If the earth were not rotating, the coriolis force would be zero

Coriolis Force



- We are observing in inertial frame
  - Plane is flying straight
- Yellow dots show what observer in rotating frame (the Earth) sees
  - Path of plane forms a curve
- Observer on Earth explains curving path with some “extra force”
- We call it the “Coriolis Force”

Newton's Equation for an Atmosphere

$$\boxed{\vec{F}} = \boxed{m\vec{a}}$$

$$\boxed{\frac{\partial \vec{v}}{\partial t} + \left(\vec{v} \cdot \vec{\nabla}\right)\vec{v} + 2\vec{\Omega} \times \vec{v}} = \boxed{-g\hat{k} - \frac{1}{\rho}\vec{\nabla}P + F_r}$$

$\vec{\Omega} \equiv$ Rotation vector of Earth's spin (axis)

magnitude is Earth's rotation rate (1/s)

The equations are usual written with only

the time derivative on the left:

$$\frac{\partial \vec{v}}{\partial t} = -\left(\vec{v} \cdot \vec{\nabla}\right)\vec{v} - 2\vec{\Omega} \times \vec{v} - g\hat{k} - \frac{1}{\rho}\vec{\nabla}P + F_r$$

Vertical Momentum Equation for Large Scale Motions

$$\frac{\partial w}{\partial t} = -\left(\vec{v} \cdot \vec{\nabla}\right) w - 2\vec{\Omega} \times w\hat{\mathrm{k}} - g - \frac{1}{\rho}\frac{dP}{dz} + F_r$$

We can assume (trust me!) that the time derivative, advection, coriolis, and friction forces are small compared to what remains:

$$0 = -0 - 0 - g - \frac{1}{\rho}\frac{dP}{dz} + 0$$

$$\frac{dP}{dz} = -\rho g$$

Our hydrostatic equation again!

Horizontal Momentum Equation for Large Scale Motions

$$\frac{\partial \vec{v}}{\partial t} = -(\vec{v} \cdot \vec{\nabla})\vec{v} - 2\vec{\Omega} \times \vec{v} - g\hat{\mathrm{k}} - \frac{1}{\rho}\vec{\nabla}P + F_r$$

This time biggest terms are coriolis and pressure force :

$$0 = 0 - 2\vec{\Omega} \times \vec{v}_h - 0 - \frac{1}{\rho}\vec{\nabla}_h P + 0$$

In rotating frame (Earth observer) we write :

$$\vec{\Omega} \times \vec{v}_h = -\Omega v \sin\phi\ \hat{\mathrm{i}} + \Omega u \sin\phi\ \hat{\mathrm{j}}$$

ϕ = latitude, $\hat{\mathrm{i}}$ is East, $\hat{\mathrm{j}}$ is north

$$f \equiv 2\Omega \sin\phi$$

$$2\vec{\Omega} \times \vec{v}_h = -fv\ \hat{\mathrm{i}} + fu\ \hat{\mathrm{j}}$$

Horizontal Momentum Equation for Large Scale Motions

$$-2\vec{\Omega}\times\vec{v}_h = \frac{1}{\rho}\vec{\nabla}_h P$$

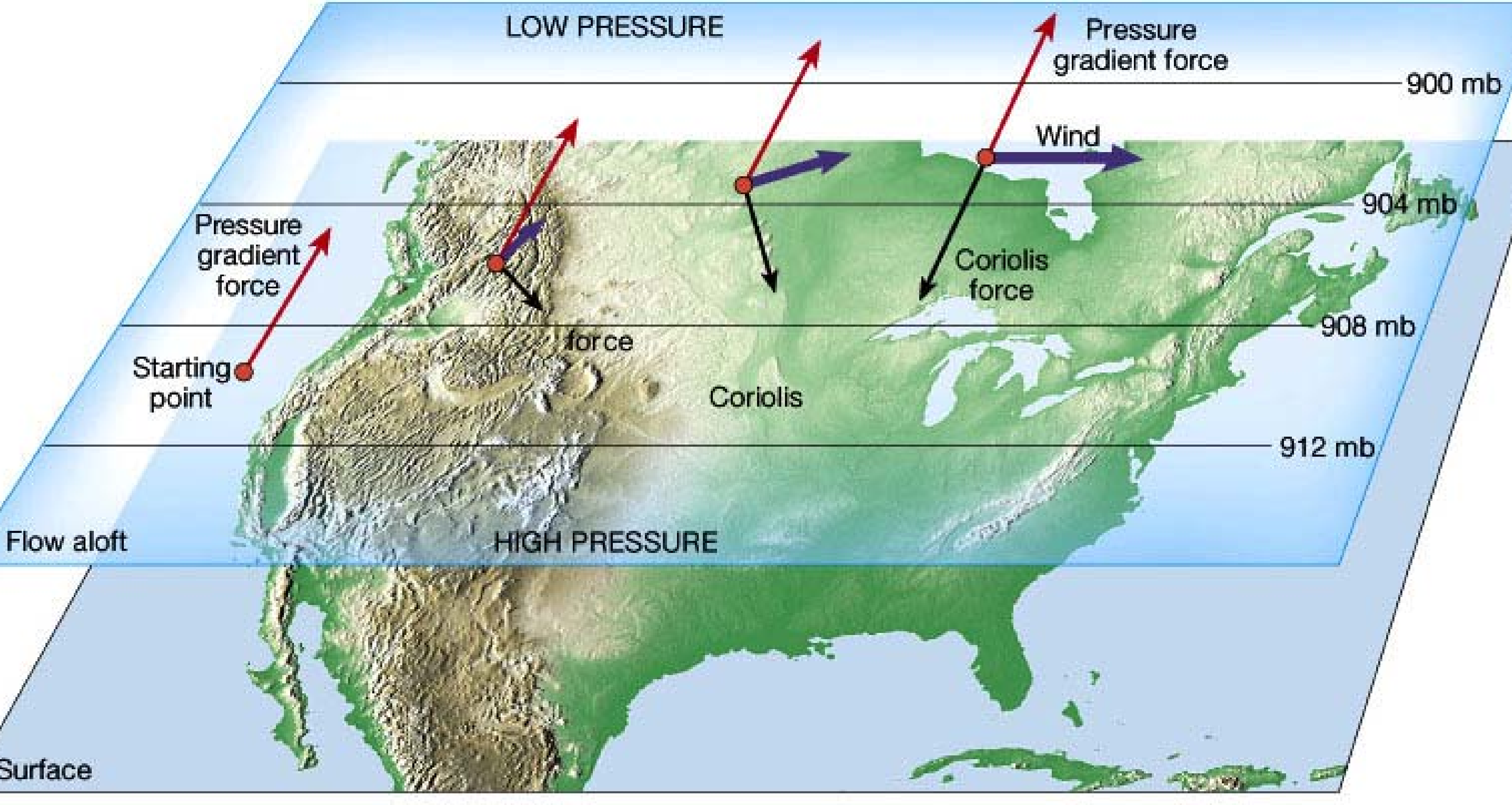
$$2\vec{\Omega}\times\vec{v}_h = -fv\,\hat{\mathrm{i}} + fu\,\hat{\mathrm{j}}$$

Rewriting for each vector direction :

$$fv = \frac{1}{\rho}\frac{\partial P}{\partial x}, \qquad -fu = \frac{1}{\rho}\frac{\partial P}{\partial y}$$

This is called the "Geostrophic Approximation"

What does geostrophy mean?



Combine Geostrophic Approximation and Hydrostatic Balance

$$\boxed{fu = -\frac{1}{\rho}\frac{\partial P}{\partial y}}, \qquad \boxed{-\rho g = \frac{\partial P}{\partial z},} \qquad \rho = \frac{P}{RT}$$

$$fu = -RT\frac{\partial \ln P}{\partial y}, \qquad -\frac{g}{RT} = \frac{\partial \ln P}{\partial z}$$

take $\frac{\partial}{\partial z}$ of left equation, and $\frac{\partial}{\partial y}$ of right equation and assume $\mathrm{T} \equiv \mathrm{T(y)}$ only

$$f\frac{\partial u}{\partial z} = -RT\frac{\partial^2 \ln P}{\partial y \partial z}, \qquad \frac{g}{RT^2}\frac{\partial T}{\partial y} = \frac{\partial^2 \ln P}{\partial y \partial z}$$

The Thermal Wind Equation

$$f\frac{\partial u}{\partial z} = -RT\frac{\partial^2 \ln P}{\partial y \partial z}, \qquad \frac{g}{RT^2}\frac{\partial T}{\partial y} = \frac{\partial^2 \ln P}{\partial y \partial z}$$

$$\frac{f}{RT}\frac{\partial u}{\partial z} = -\frac{g}{RT^2}\frac{\partial T}{\partial y} \quad \rightarrow \quad \boxed{f\frac{\partial u}{\partial z} = -\frac{g}{T}\frac{\partial T}{\partial y}}$$

and for other direction (not shown) :

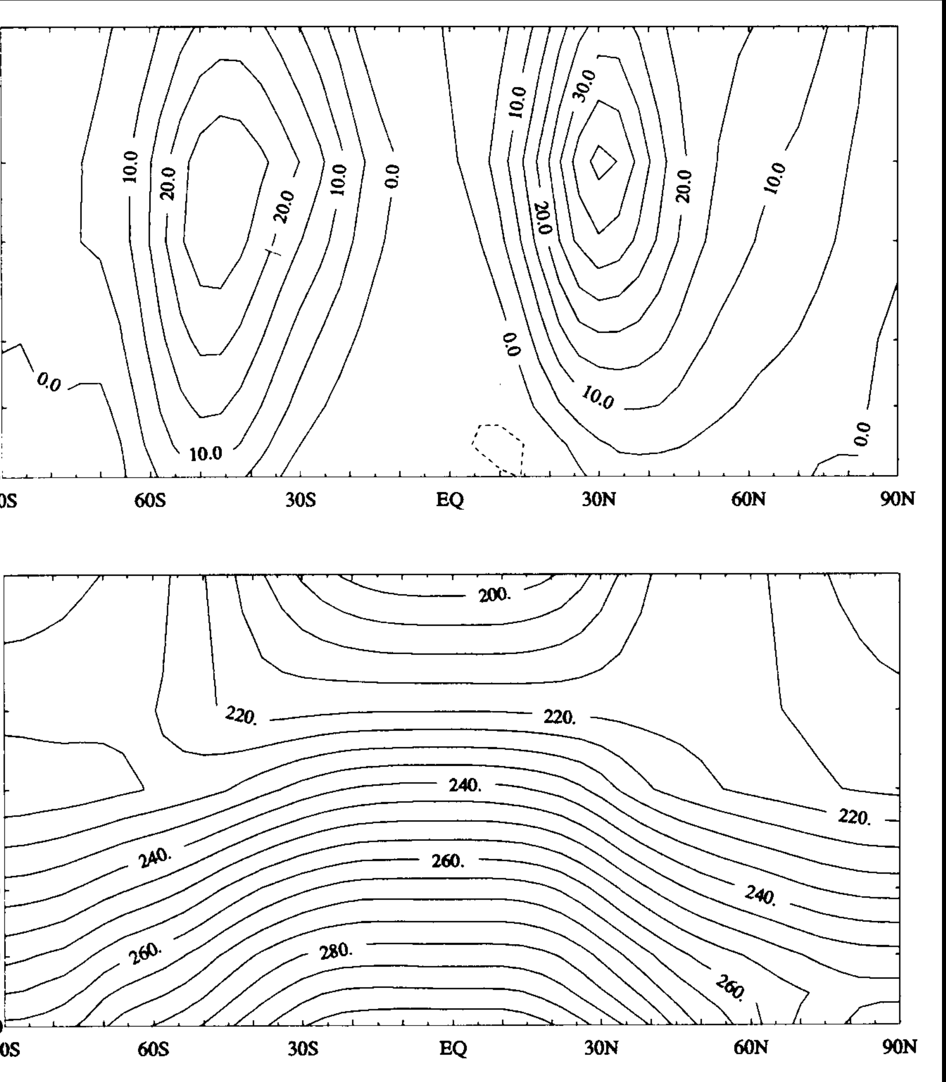
$$\boxed{f\frac{\partial v}{\partial z} = \frac{g}{T}\frac{\partial T}{\partial x}}$$

These are the "thermal wind equations"

What does thermal wind mean?

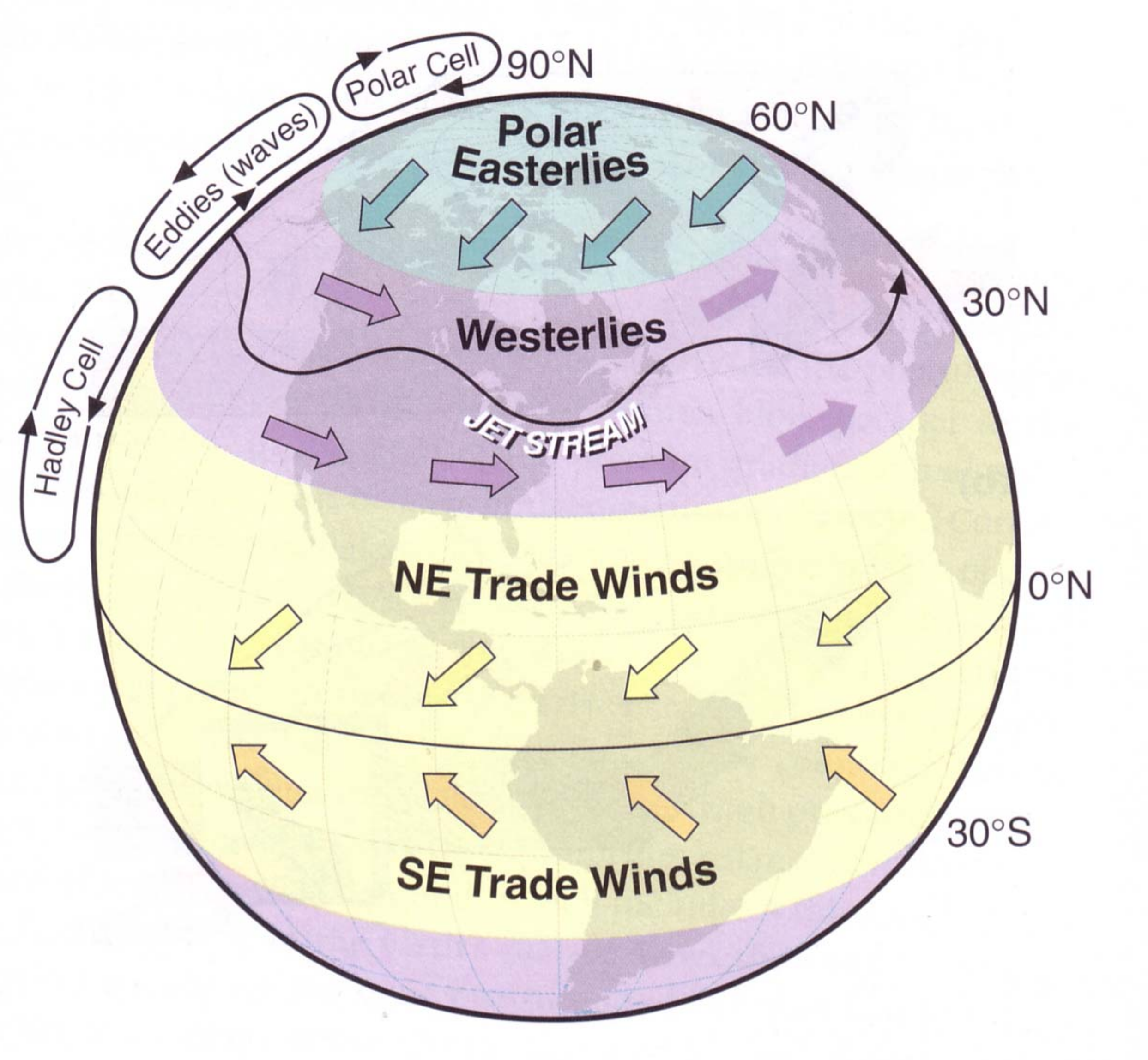
- Let’s take one equation: $$f\frac{\partial u}{\partial z} = -\frac{g}{T}\frac{\partial T}{\partial y}$$
- Temperature decreases from equator to pole due to insolation, so dT/dy < 0 (NH)
- f (NH) and g are positive and constant, and T is positive
- So du/dz > 0, meaning eastward winds increase with height!
- Where the temperature gradient is strongest, the wind increase will be greatest, creating a “jet” that blows from west to east

Thermal Wind Equation and Jet Stream



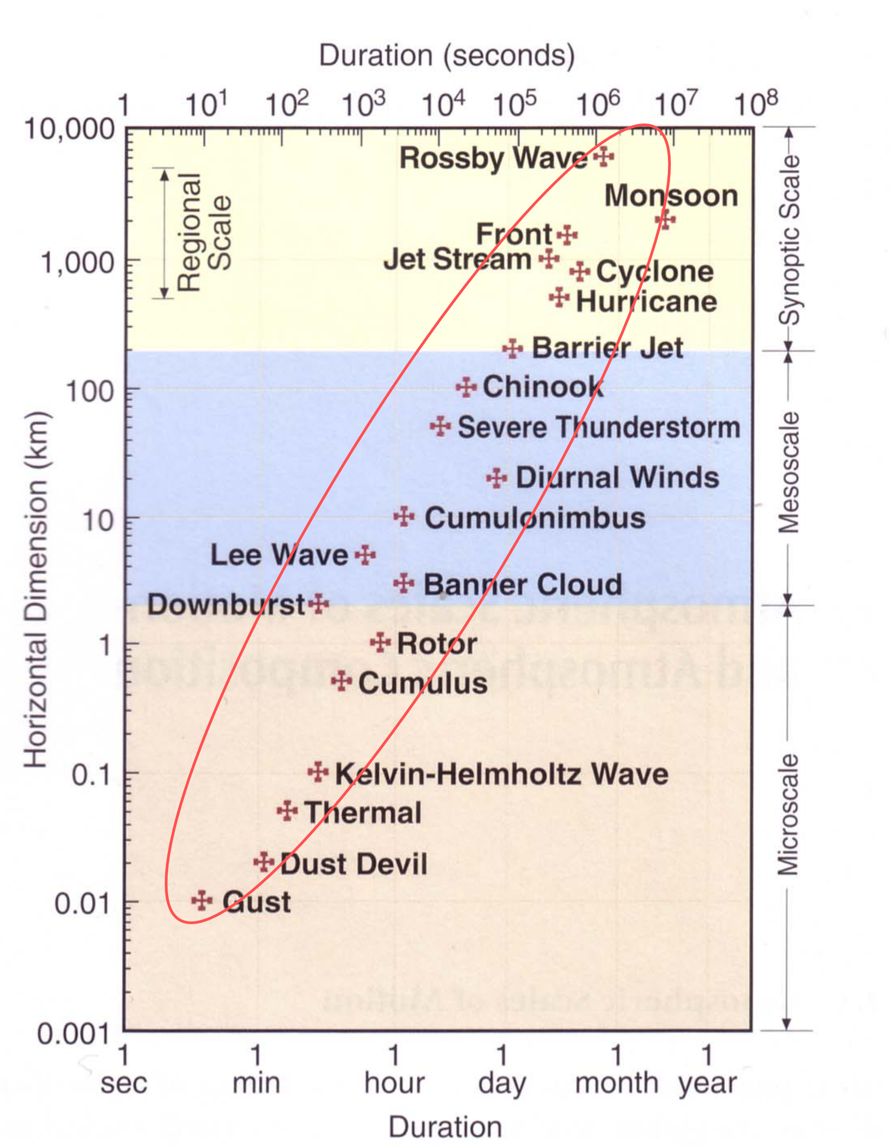
- Pole-to-equator temperature differenc generates eastward wind
- Temperature gradient is greatest at mid-latitudes
  - Jet forms at mid-latitudes

Mid-latitude jet-stream



In the mid-latitudes, where Japan, America, and Europe are located, weather systems generally comes from the west

Types of Weather

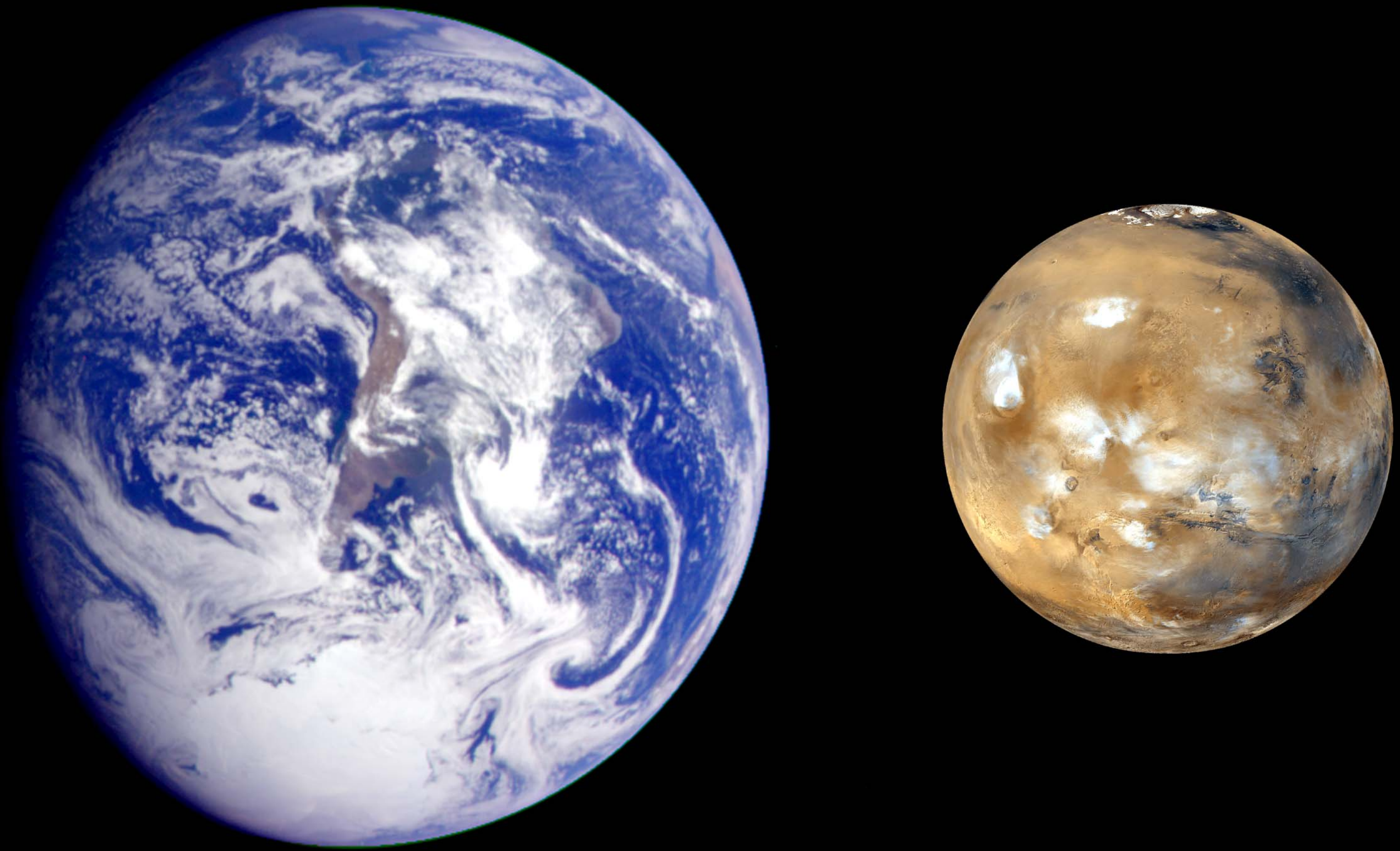


- The smaller the weather type, generally the shorter it lasts
- Three main categories of length scales that weather is divided into: Synoptic, Mesoscale, Microscale
- Mars shares some, but not all of these weather types.
- Rossby radius of deformation determines upper limit of size of a weather system (several 1000's of km)

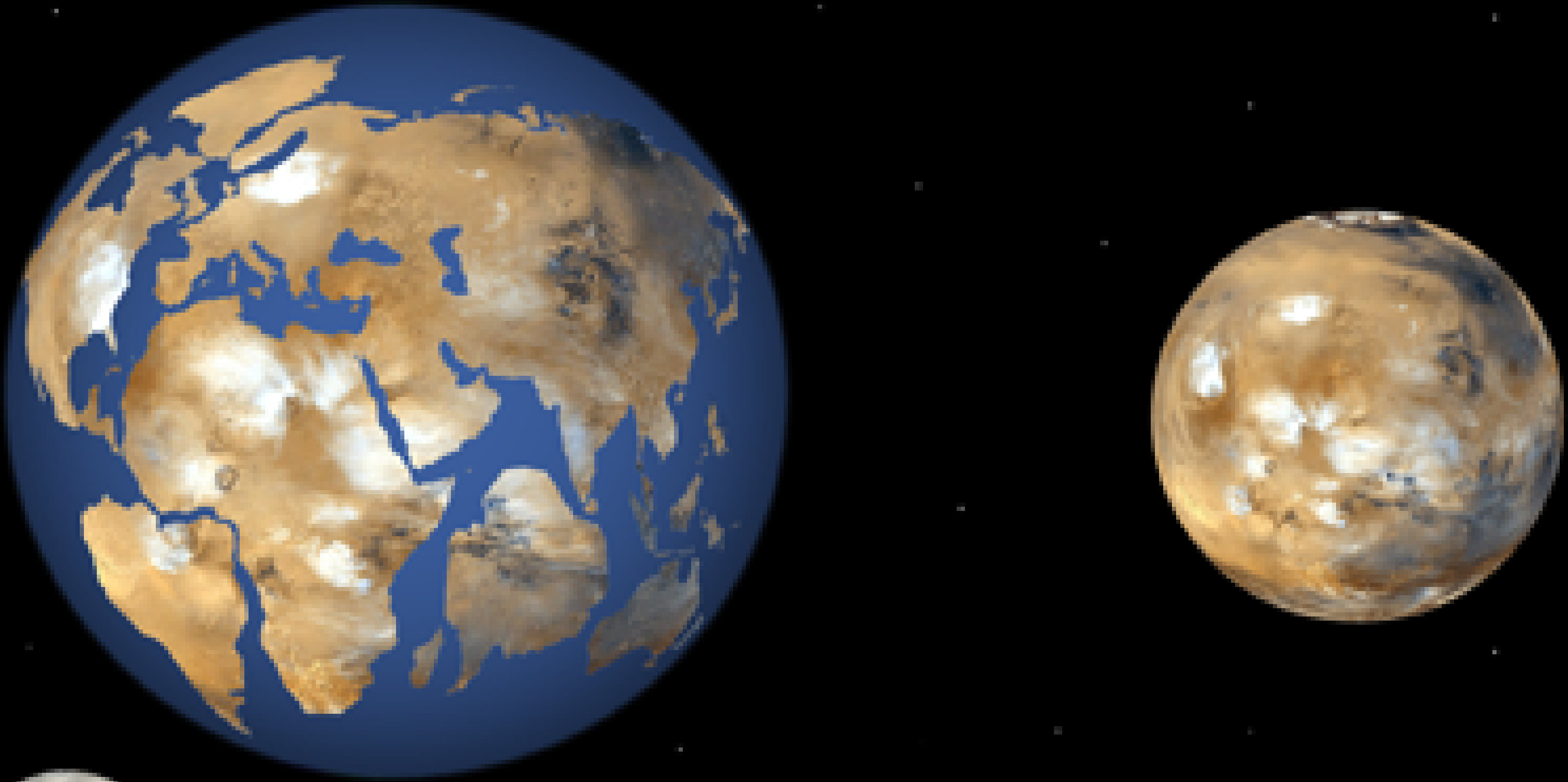
First Half Summary

- Weather involves the transport of heat
- Uneven heating of the atmosphere by the sun is the ultimate cause for all weather
- Weather can be thought of as the chaotic motions of heat transport from one place to another

Part 3:
Mars vs. Earth



The land area of the Earth is approximately equal to the total surface of Mars.



The land area of Africa is about the same as the total surface of the Moon.

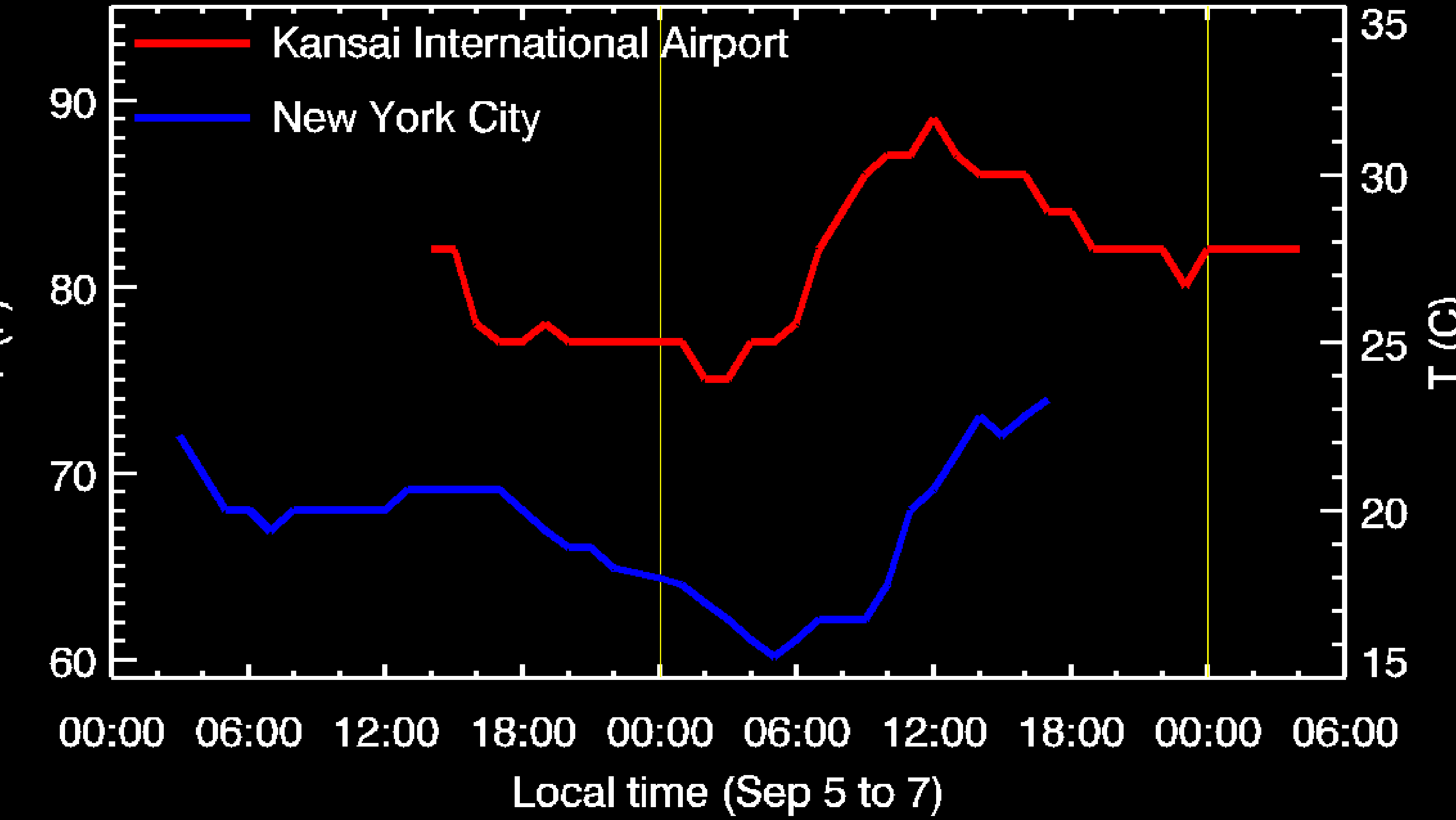
Part 3: Table of Contents

- Temperature
- Hadley Circulation
- Pressure
- Cycles
  - CO_2
  - H_2O
  - Dust
    - Dust Storms
    - Dust Lifting
    - Dust Devils

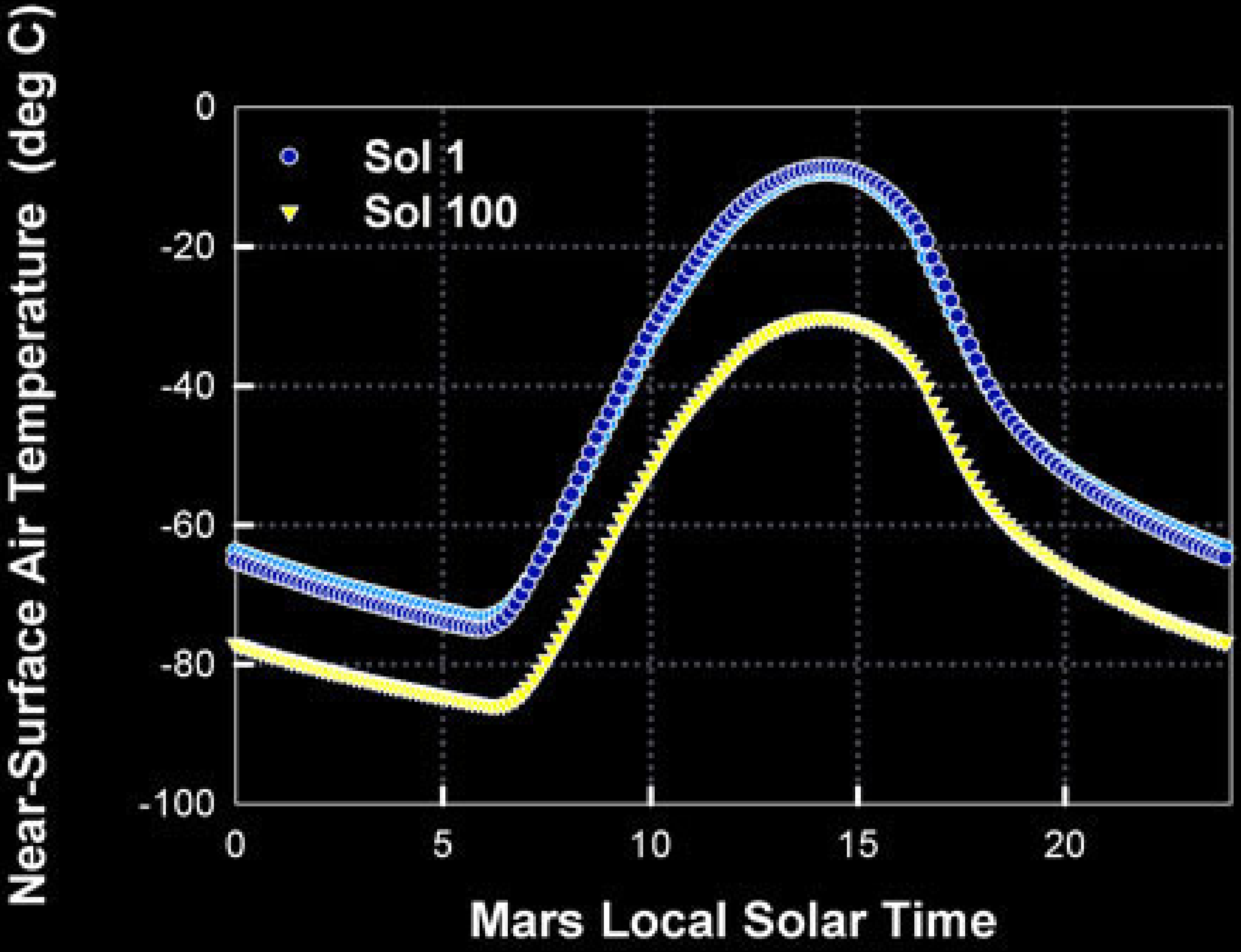
Mars vs. Earth

Temperature

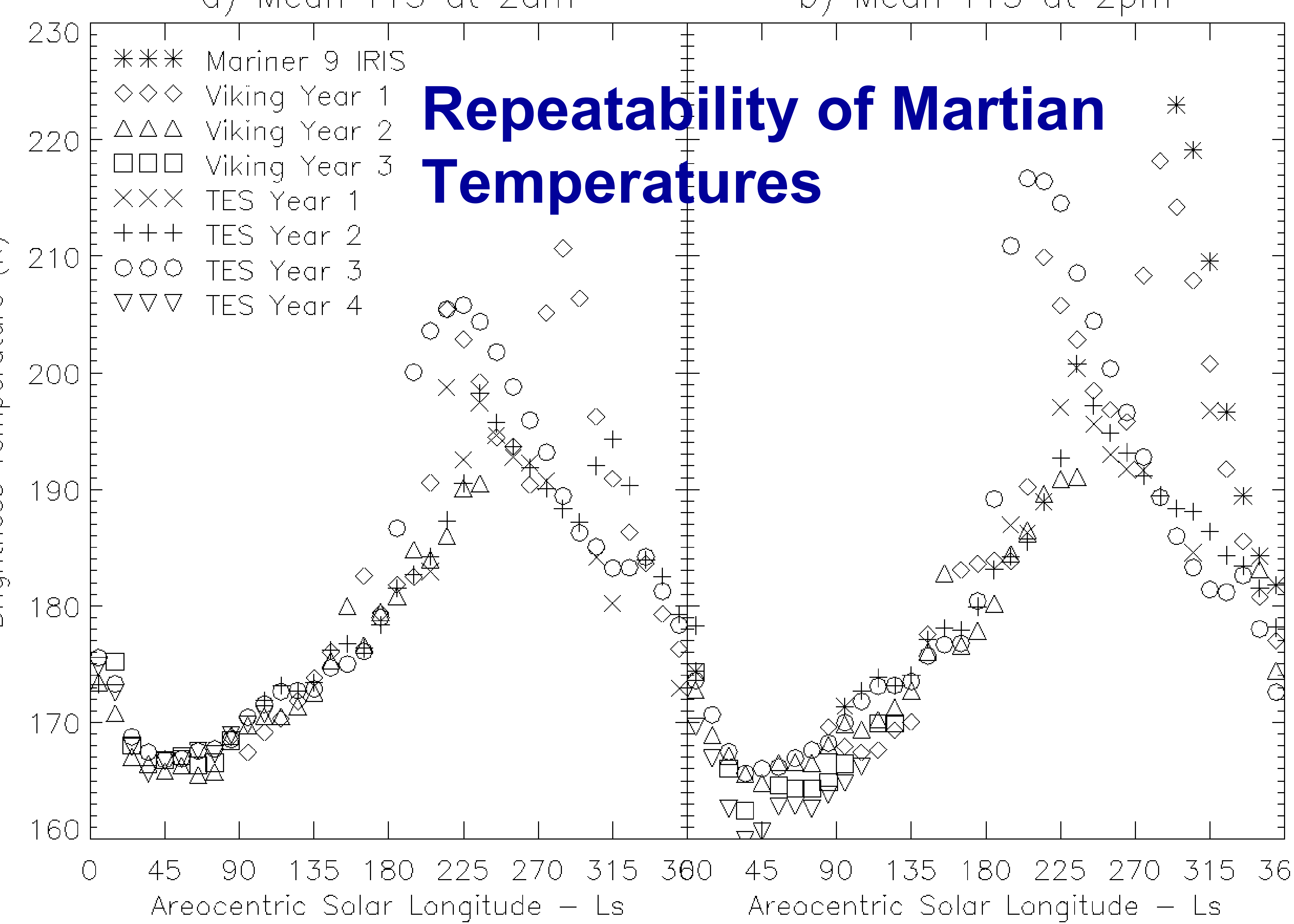
Earth Air Temperatures



Martian Air Temperatures



Repeatability of Martian Temperatures



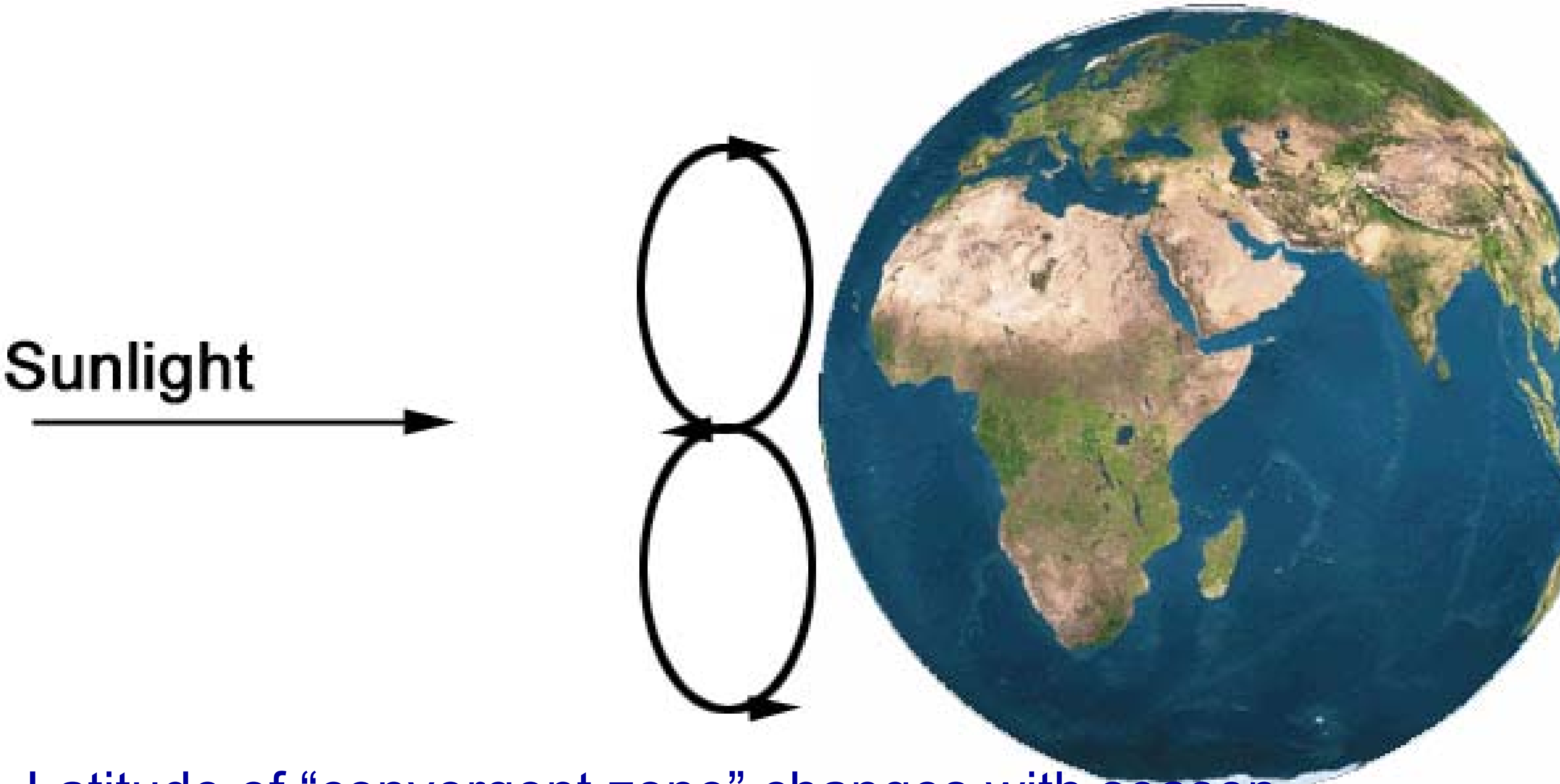
Mars vs. Earth

Hadley Circulation

What is “Hadley Circulation”?

- Theoretical Definition
  - Axisymmetric thermally forced direct atmospheric circulation
- Operational Definition
  - Zonal-mean (averaged along a latitude line) meridional (along a longitude line) overturning atmospheric circulation

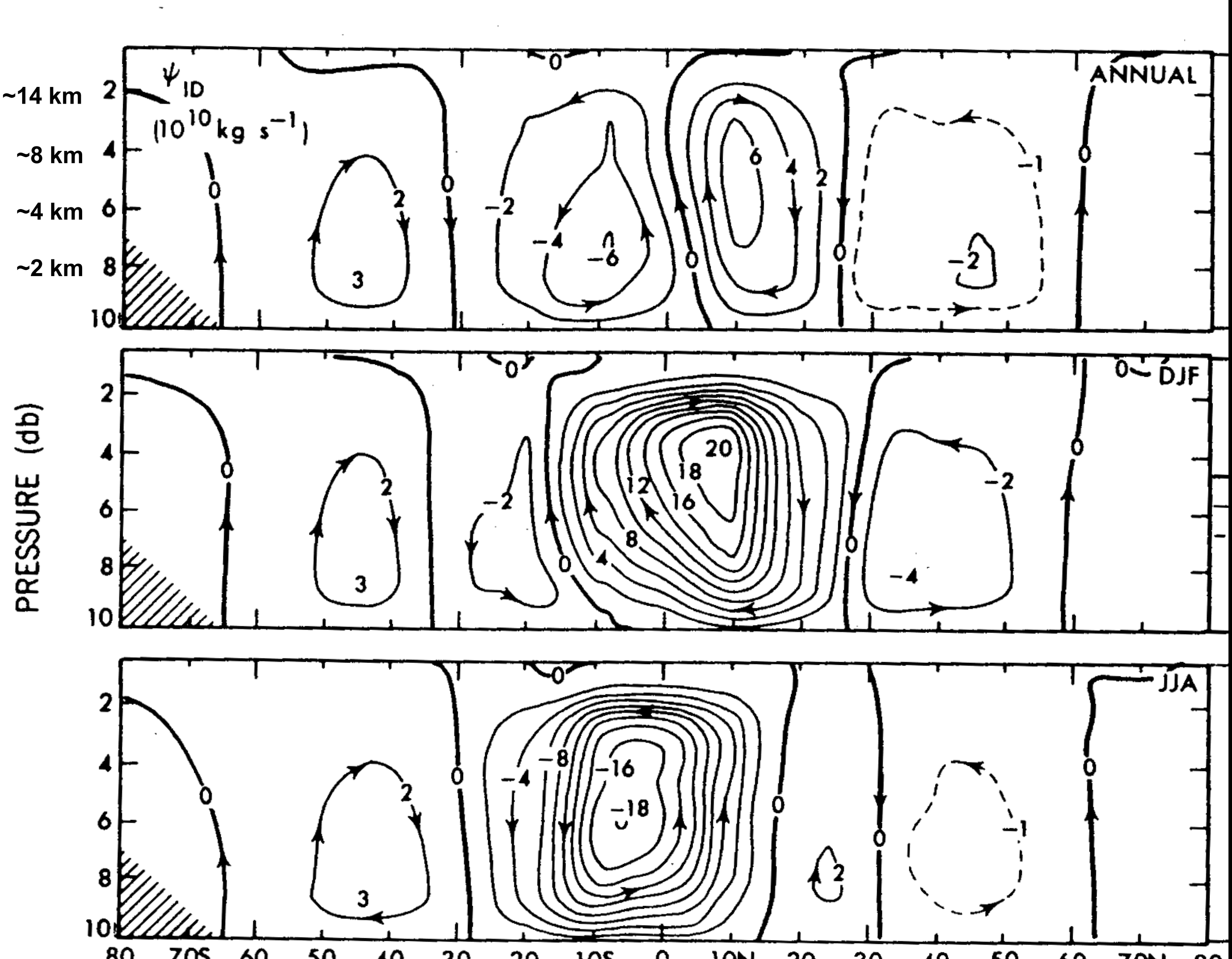
Annual-average Hadley Circulation



Latitude of “convergent zone” changes with season

- Moves north during northern summer
- Moves south during southern summer

Terrestrial Hadley Circulation

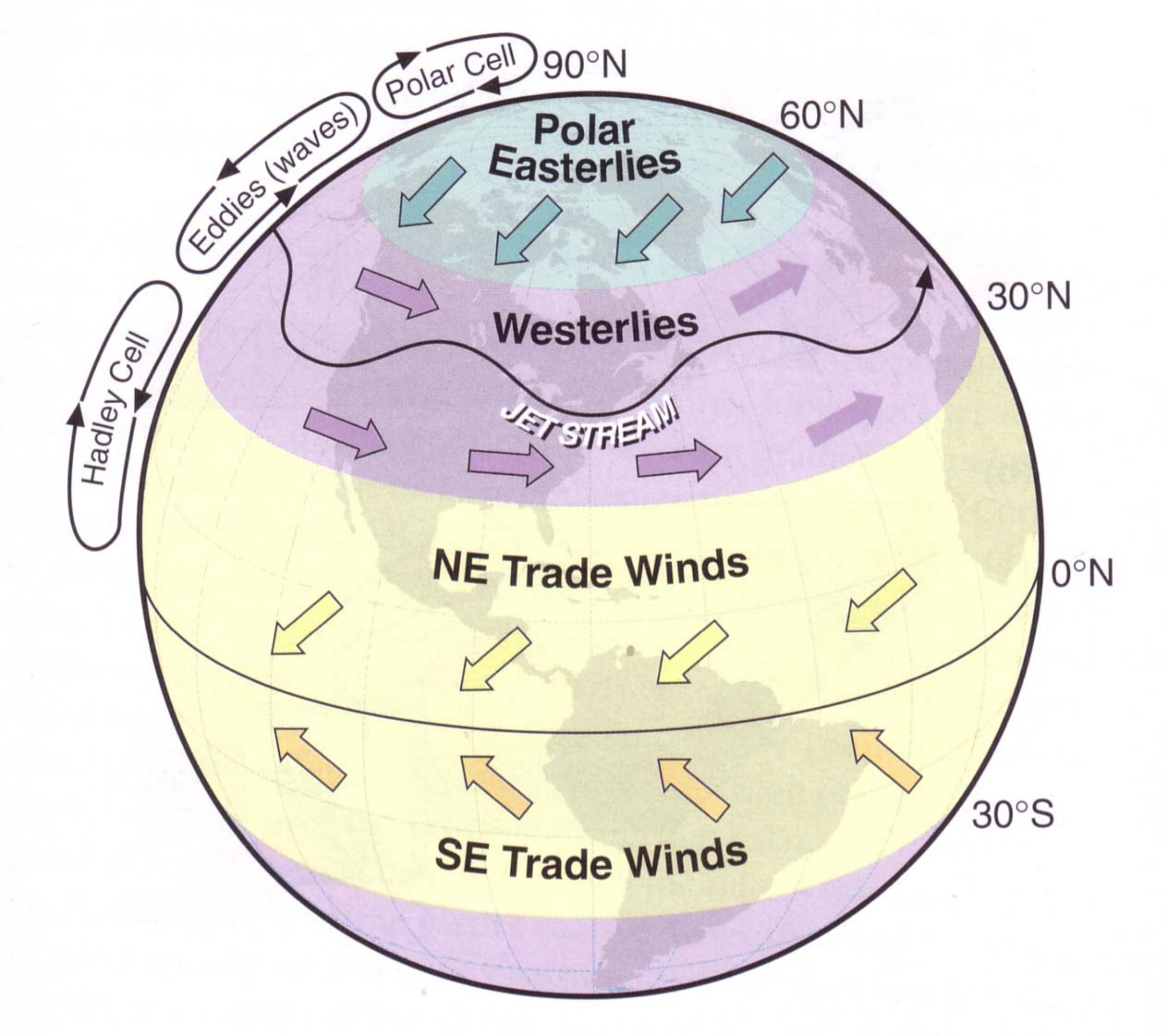


Annual average (but also like equinox)

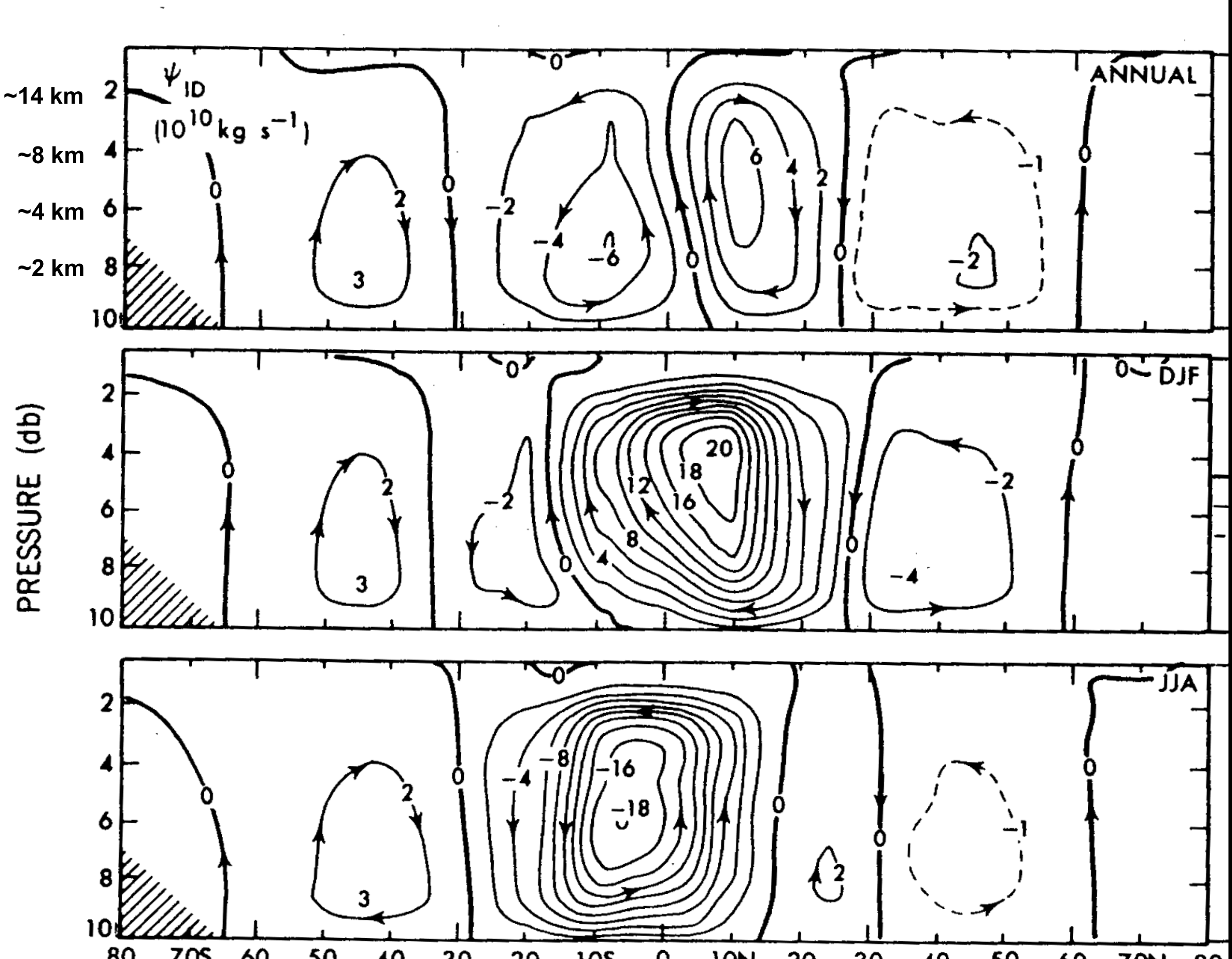
Northern Winter

Northern Summe

Earth Atmospheric Circulation



Terrestrial Hadley Circulation

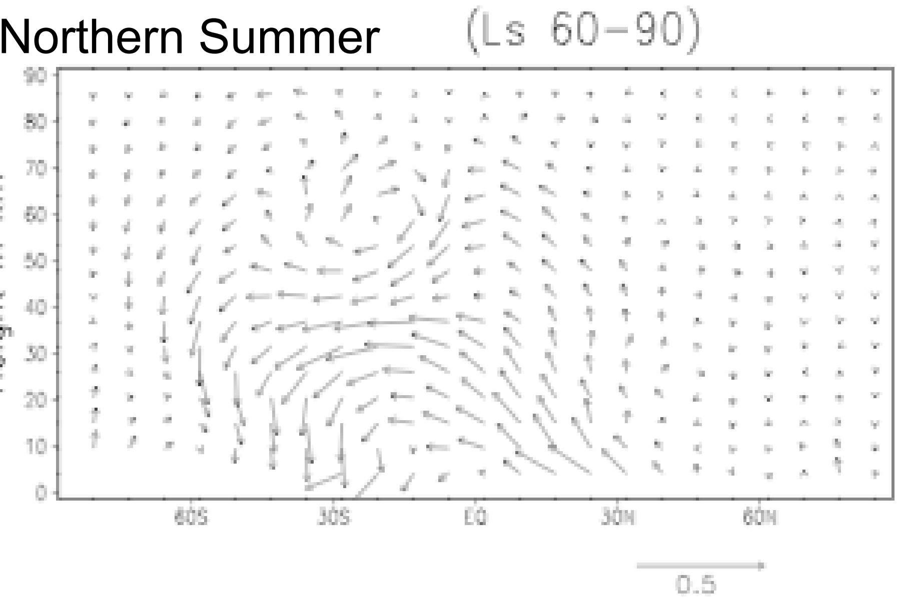


Annual average (but also like equinox)

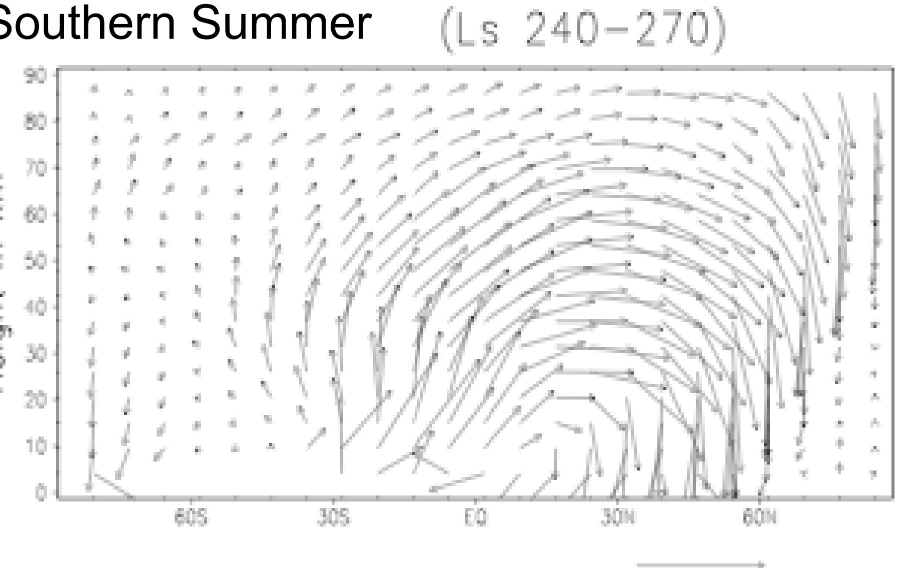
Northern Winter

Northern Summe

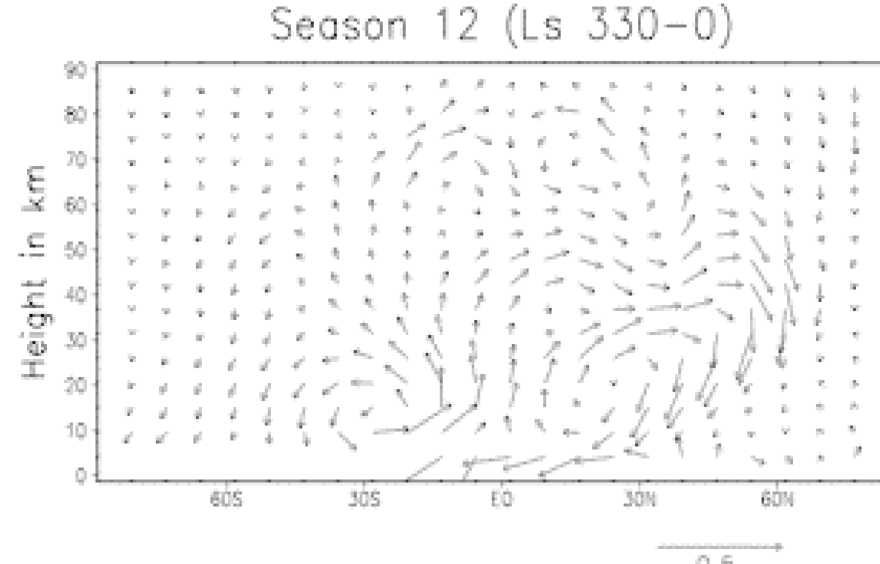
Martian Hadley Circulation

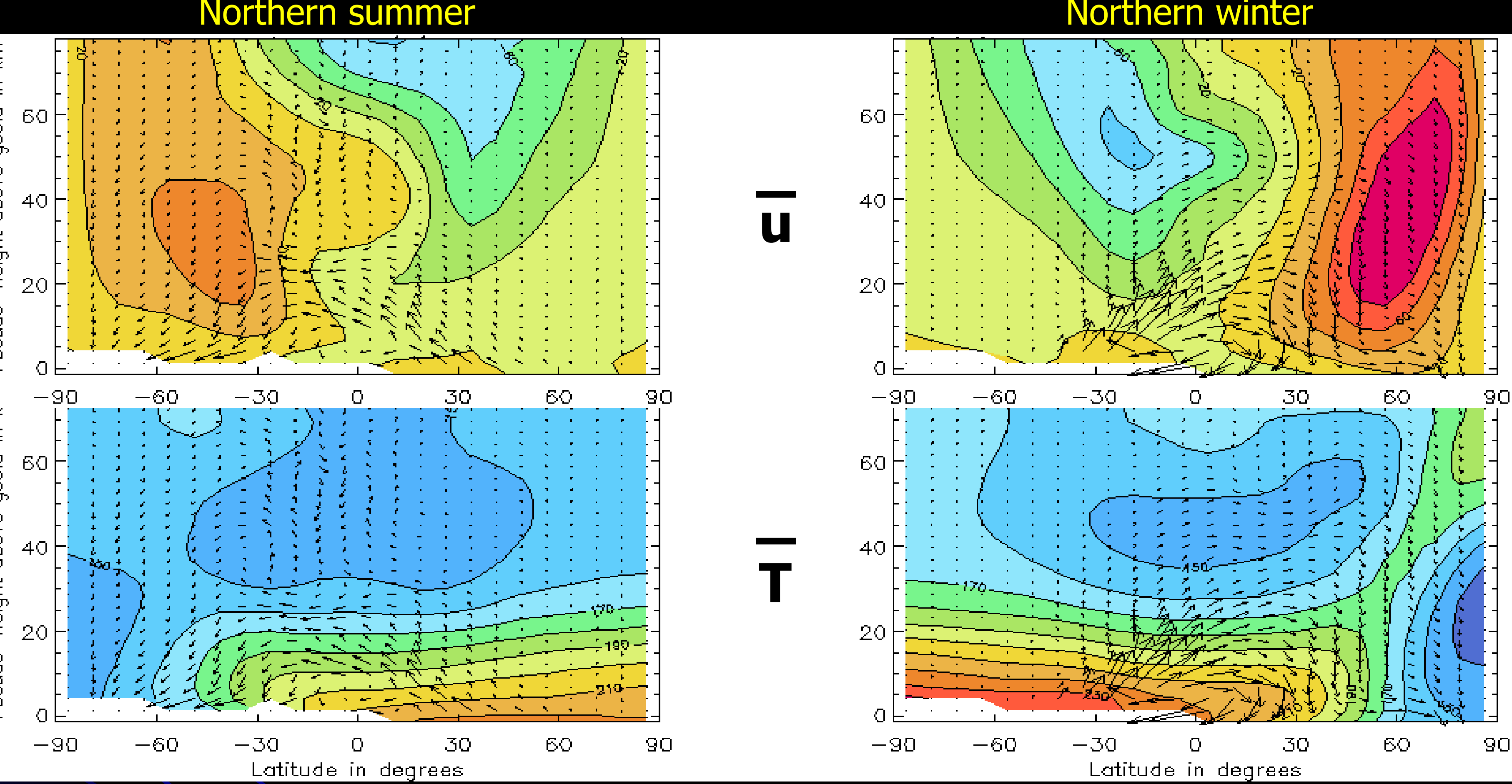

Northern Summer

← Solstices


Southern Summer

Equinoxes
↓




Northern summer

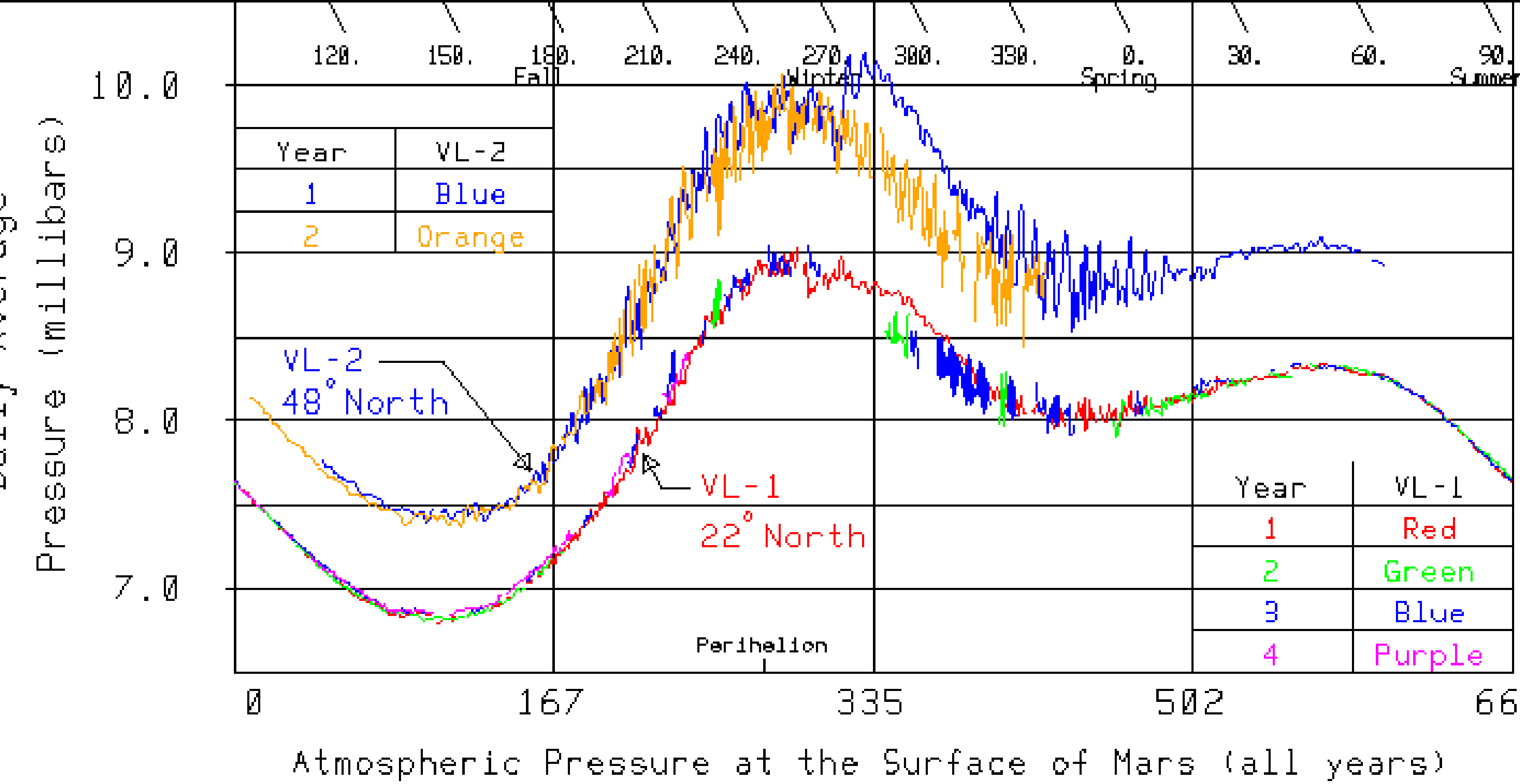
Northern winter

- Heating strongest near sub-solar latitude
- Single cross-equatorial Hadley cell
- Strong westerlies in summer mid-latitudes, equatorial easterlies
- Strong circumpolar winter jet: “Polar vortex”

Mars vs. Earth

Pressure

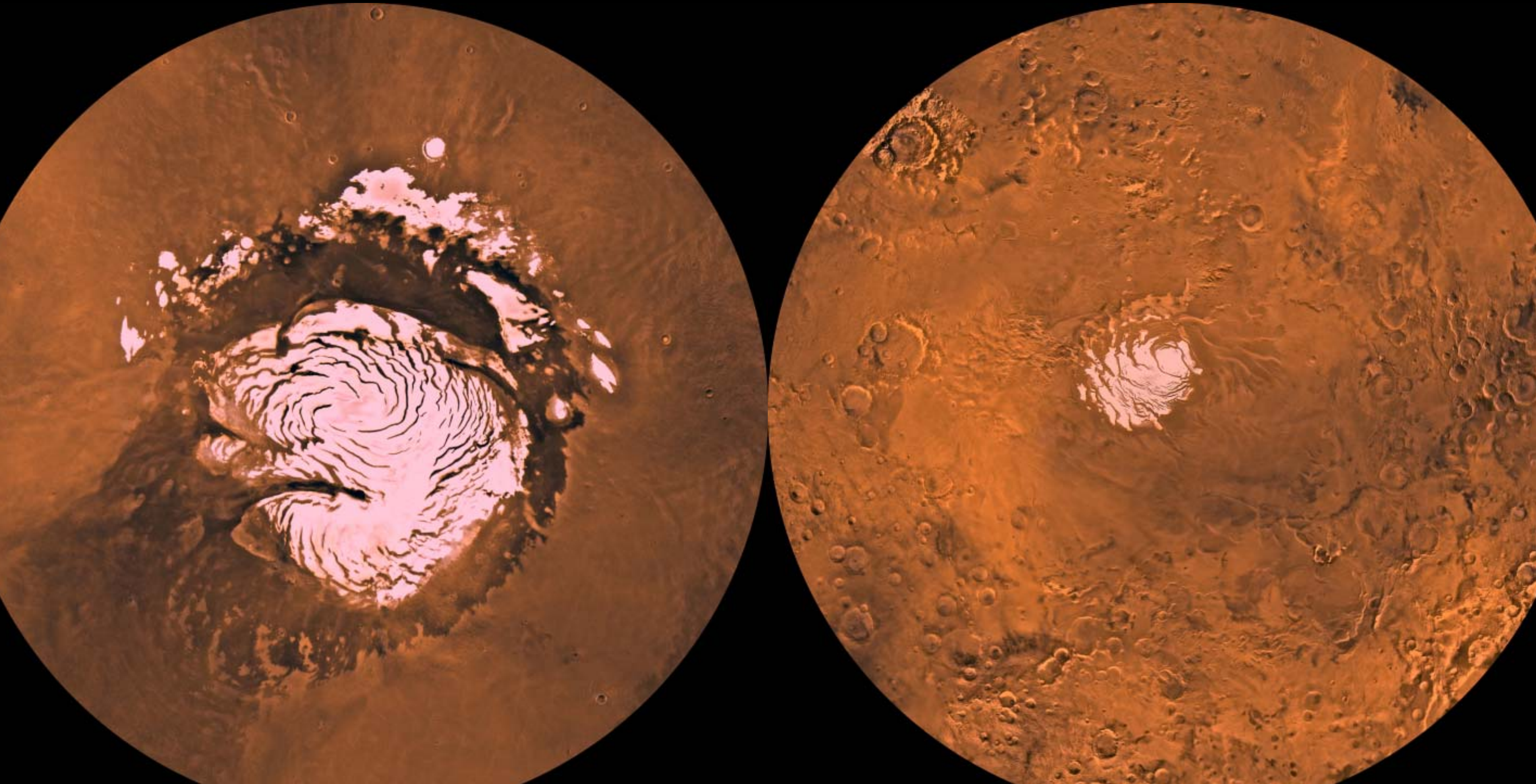
Martian Cycle of Surface Pressure



For Earth, curve would be nearly flat at 1000 mbar, with much smaller variations (< 5%) due to weather systems (storms, typhoons, etc.)

What causes the surface pressure change by over 25%?

The polar caps

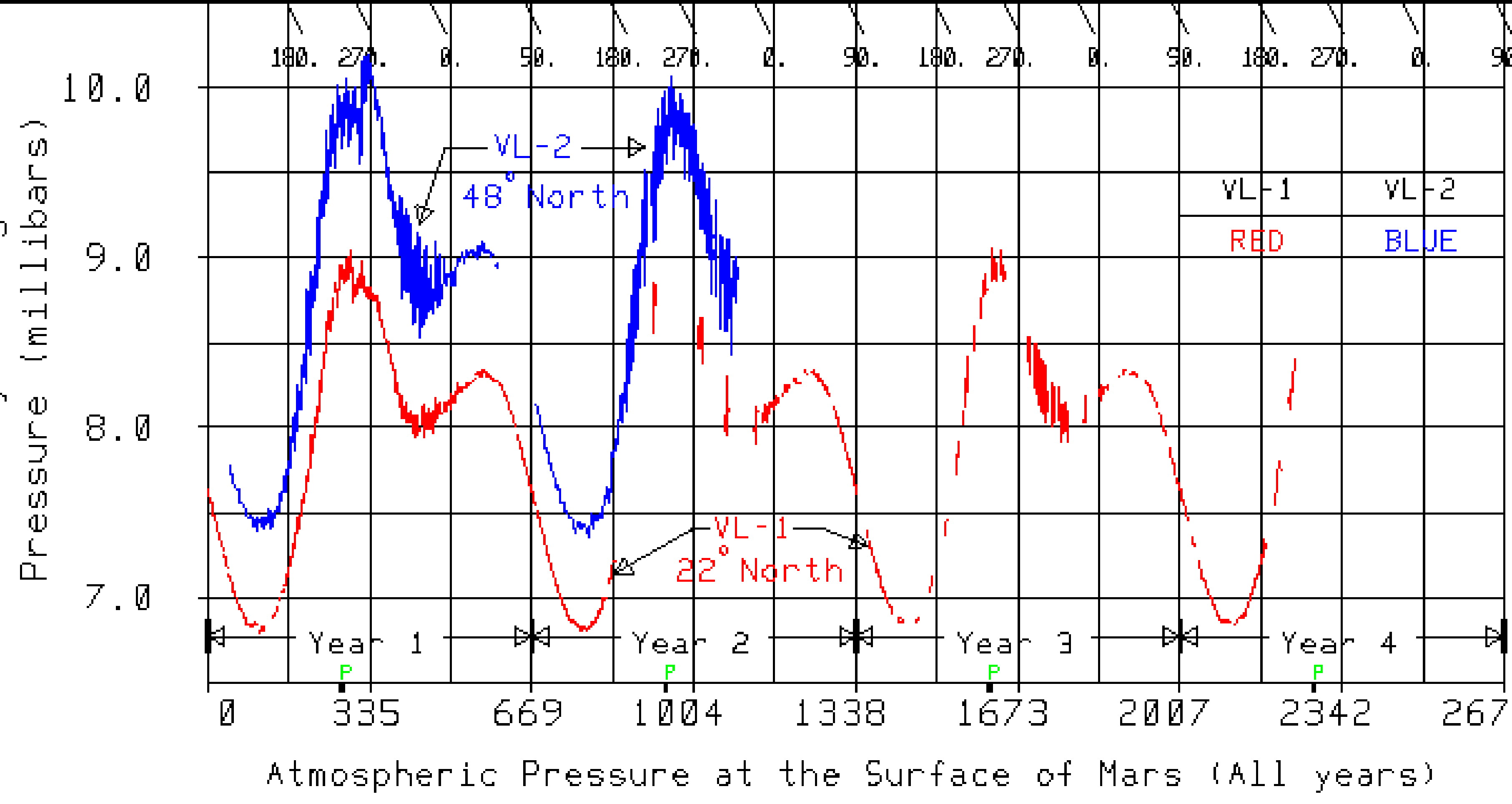


Seasonal Polar Cap

Cycle #1: CO_2

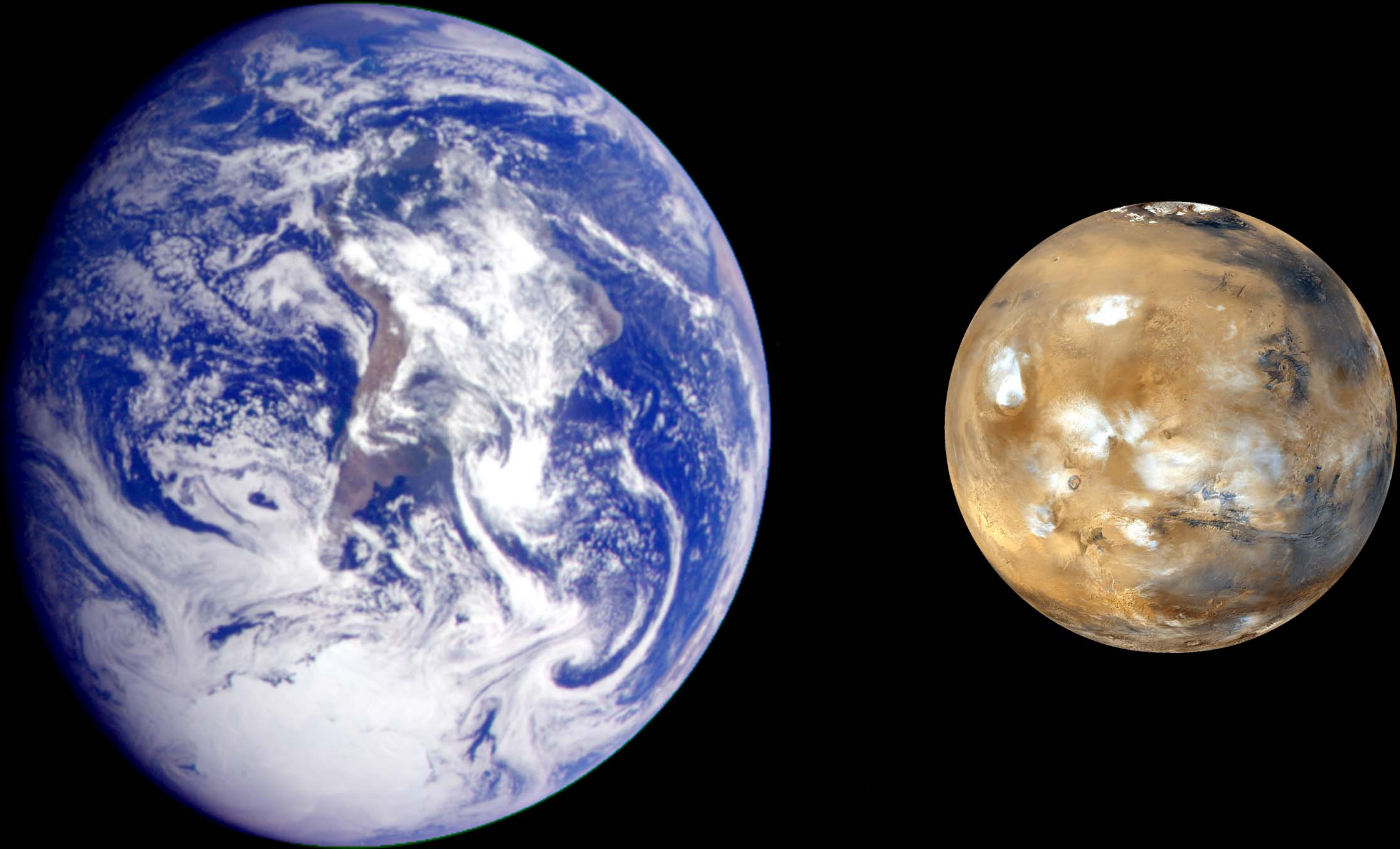
- Condensing and subliming at poles
- Surface pressure variation
- Polar clouds
  - in polar night
  - can’t be seen in visible images
  - detected by IR reflectance

Martian Interannual Variations (a preview)



Earth vs. Mars

Blue vs. Red

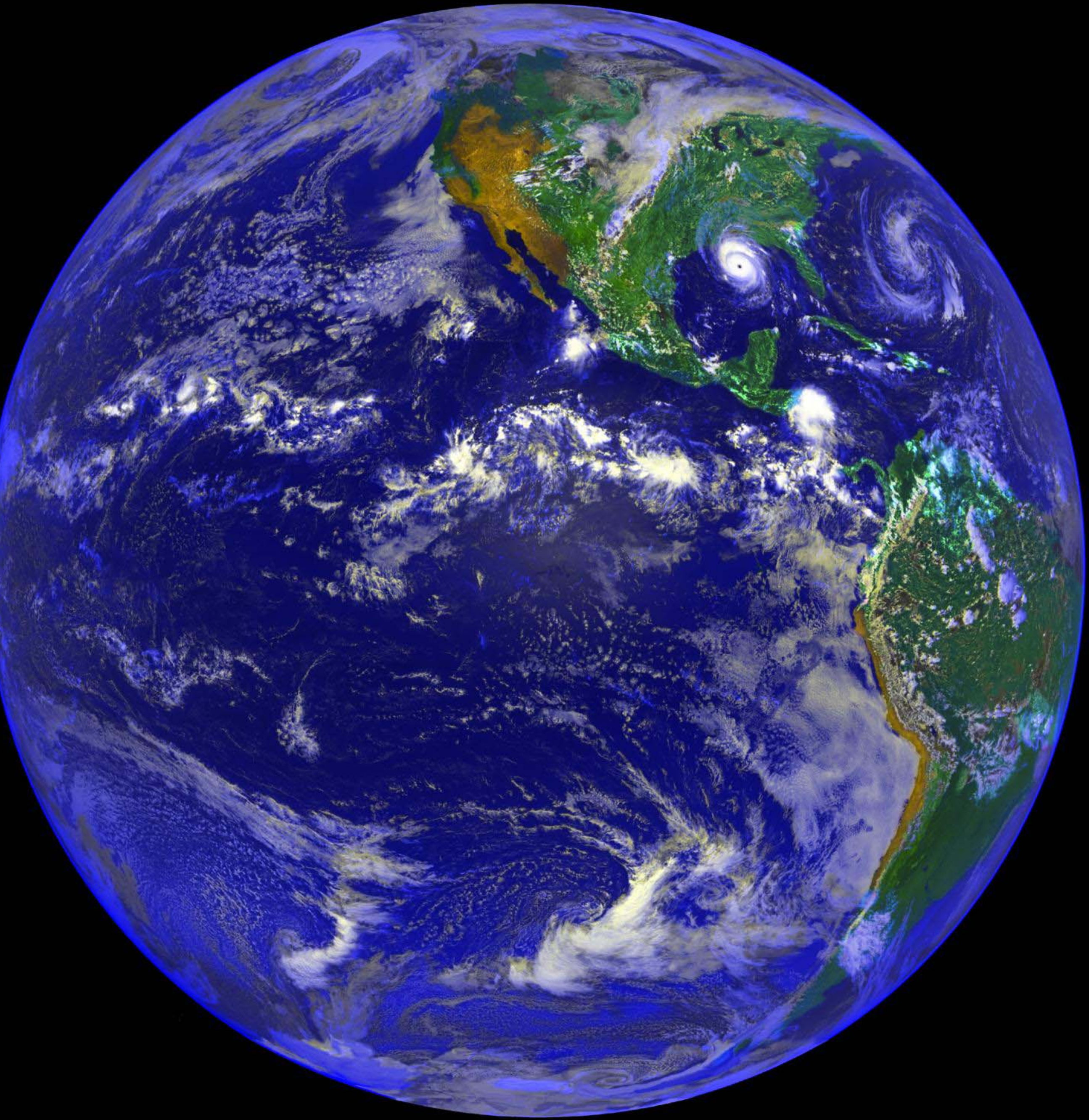


Mars vs. Earth

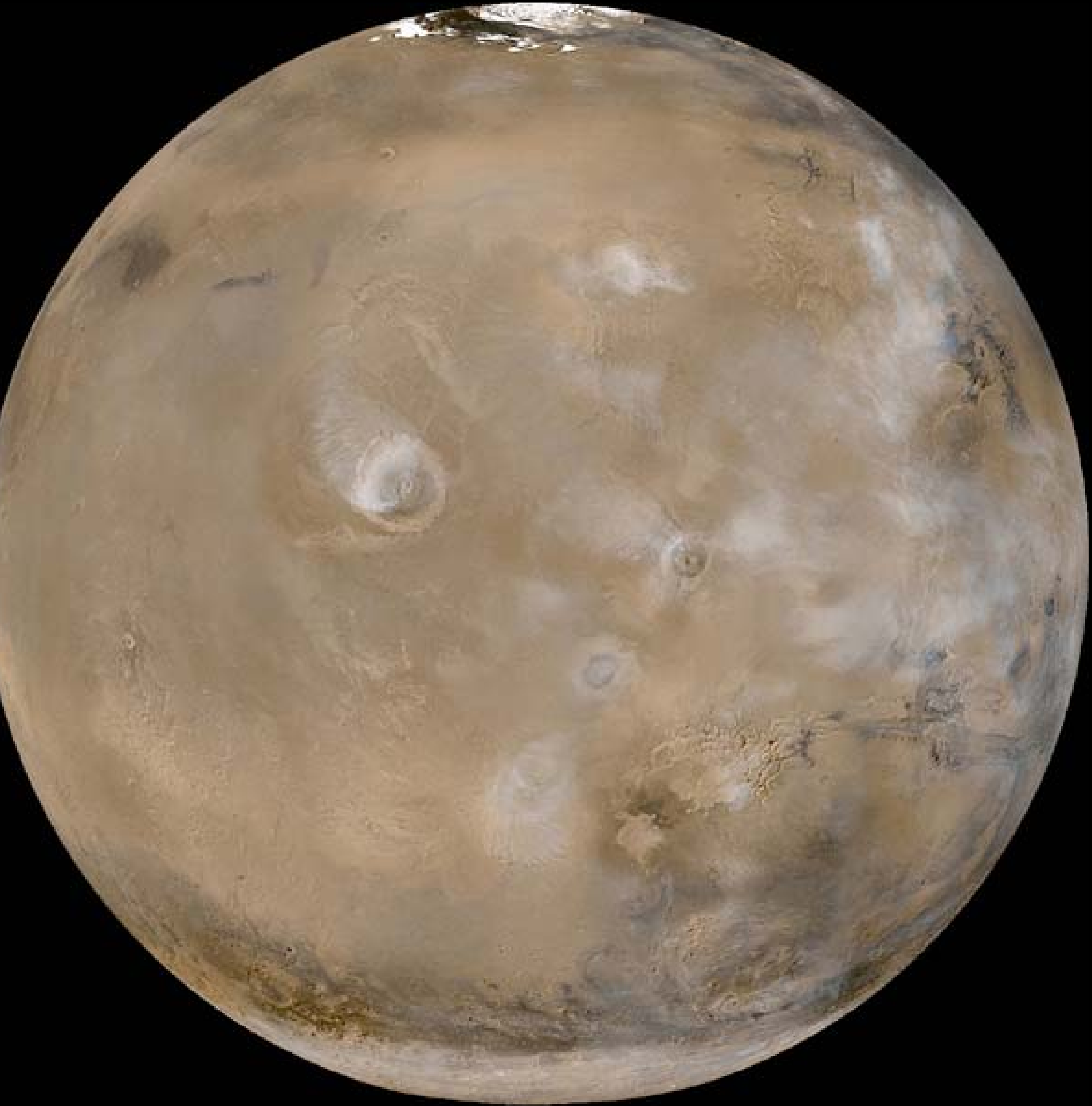
H_2O (Water)

Earth:

Water Vapor Clouds



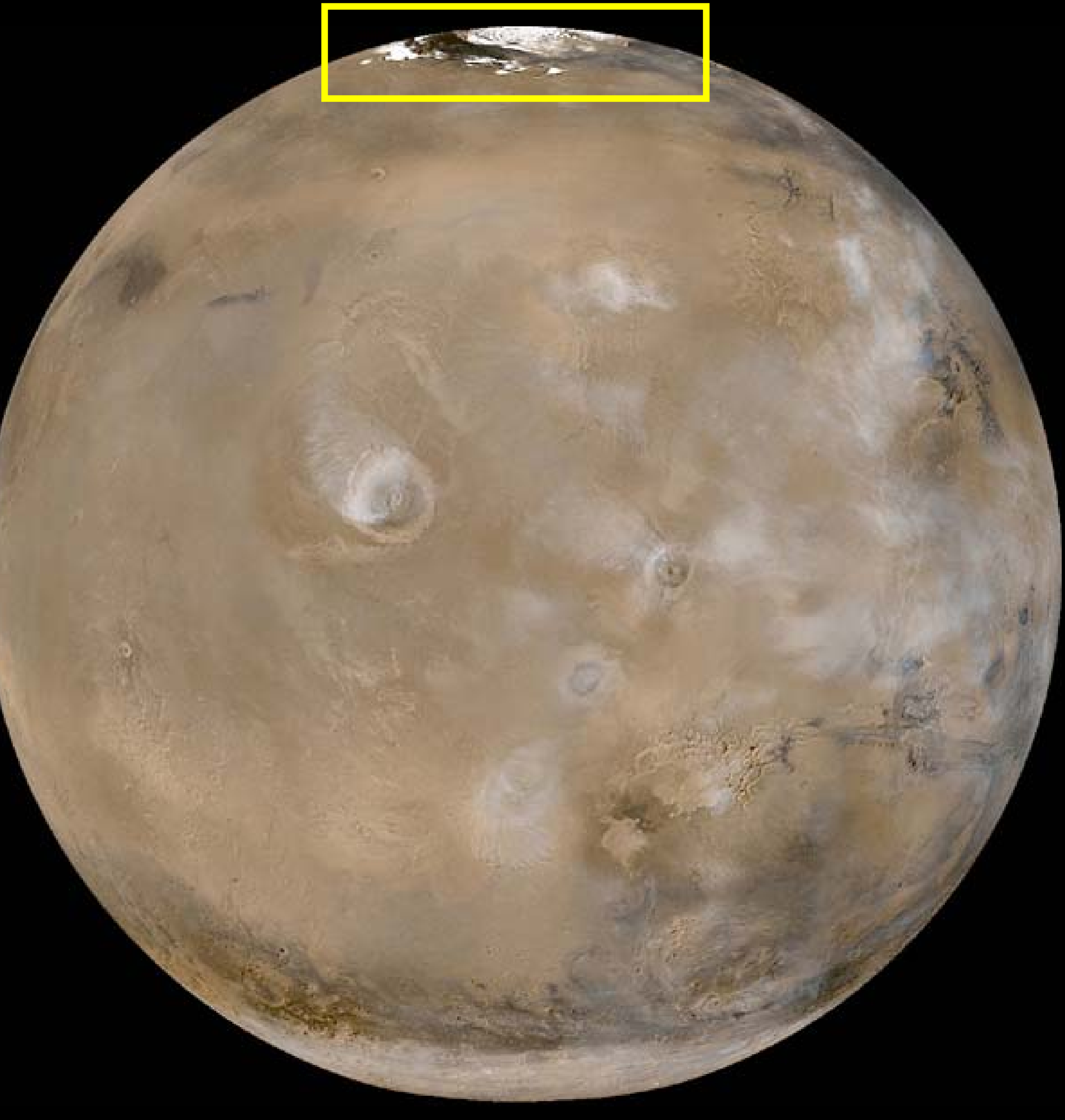
August 25, 1992: Americas and Hurricane Andrew



Mars:

Water
Ice
Clouds

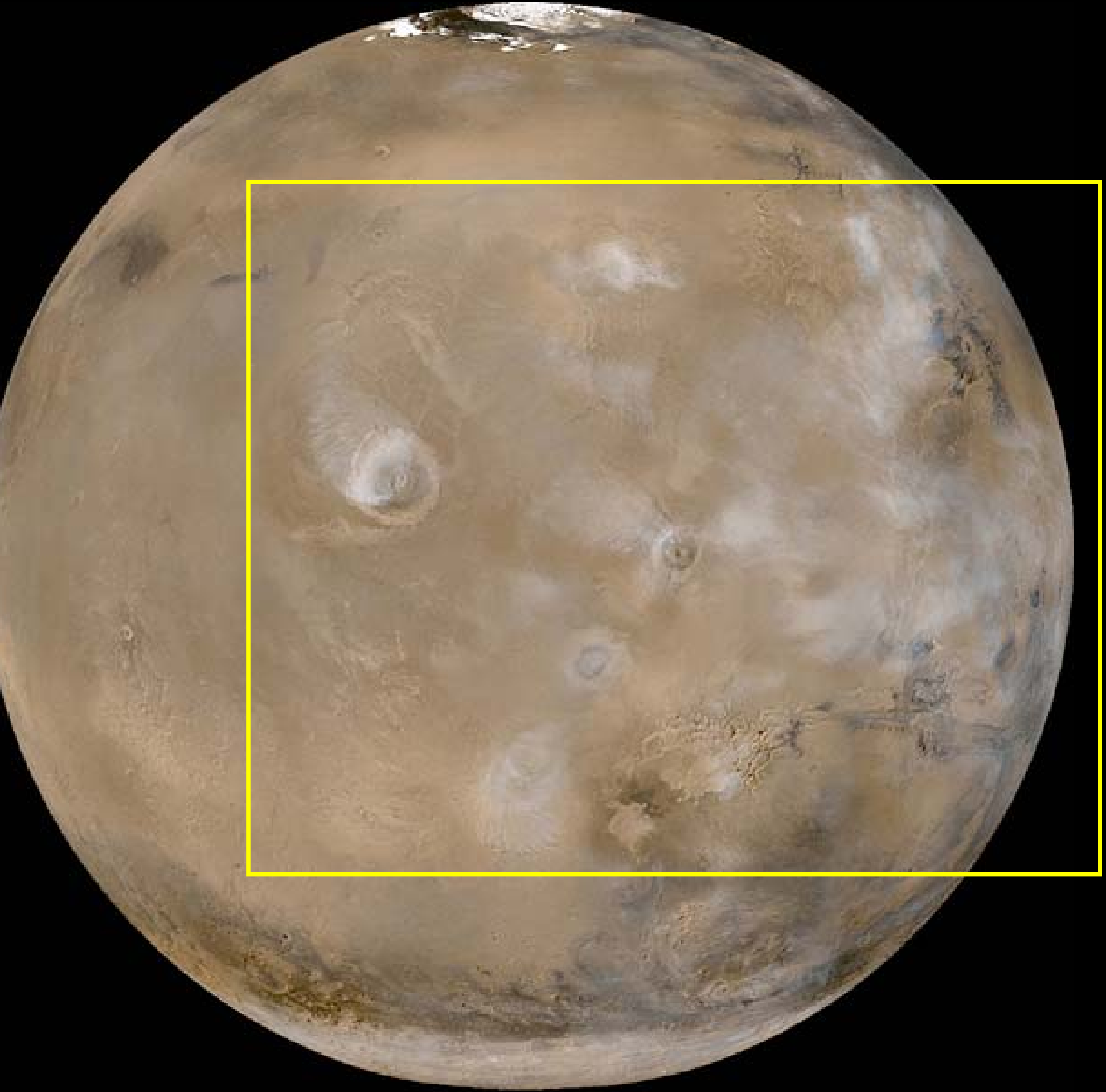
(and no
oceans)



Mars:

A Water Ice Polar Cap!

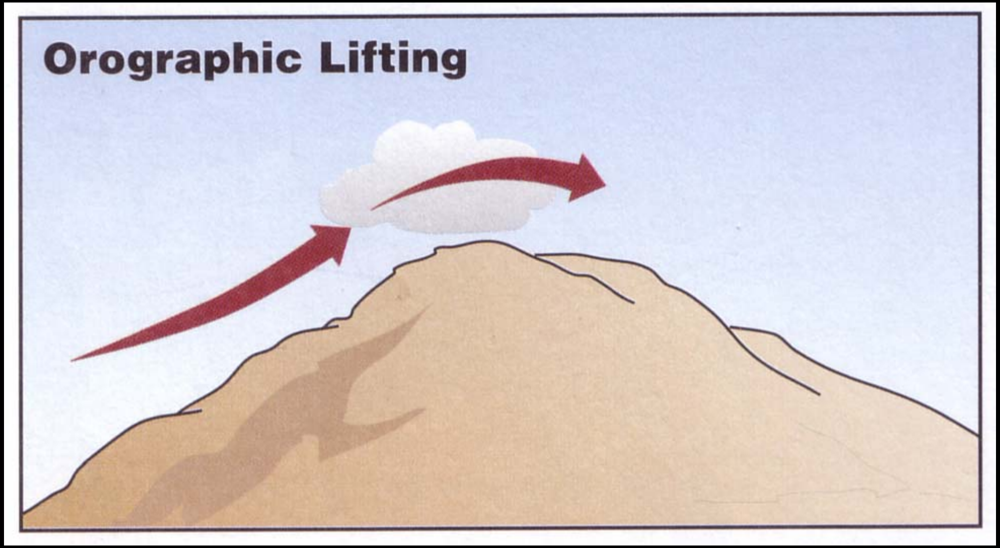
Mars:



Back to the clouds for a moment…

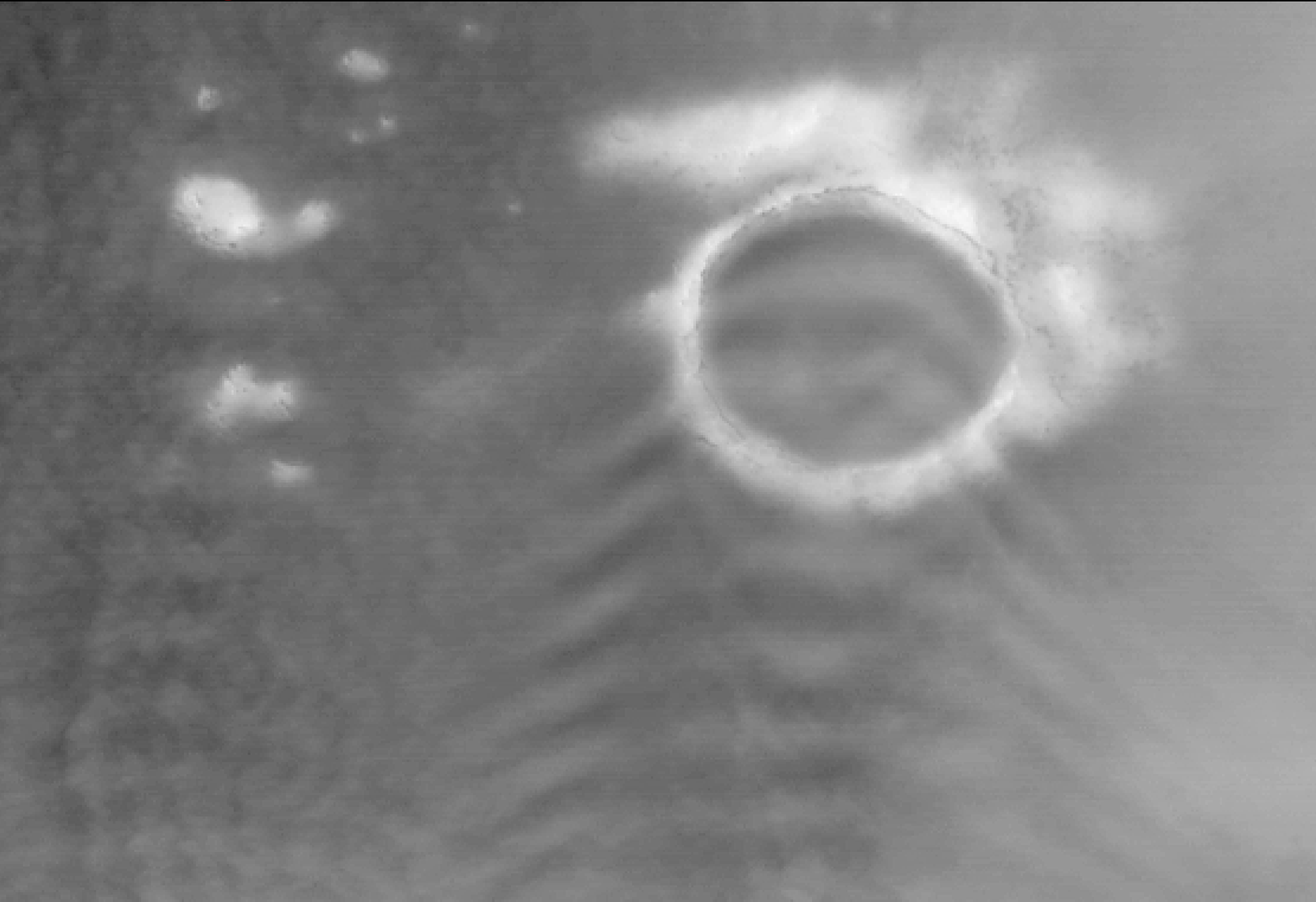
Topographically Forced Clouds: The Tharsis Volcanos

Topographically Forced Clouds

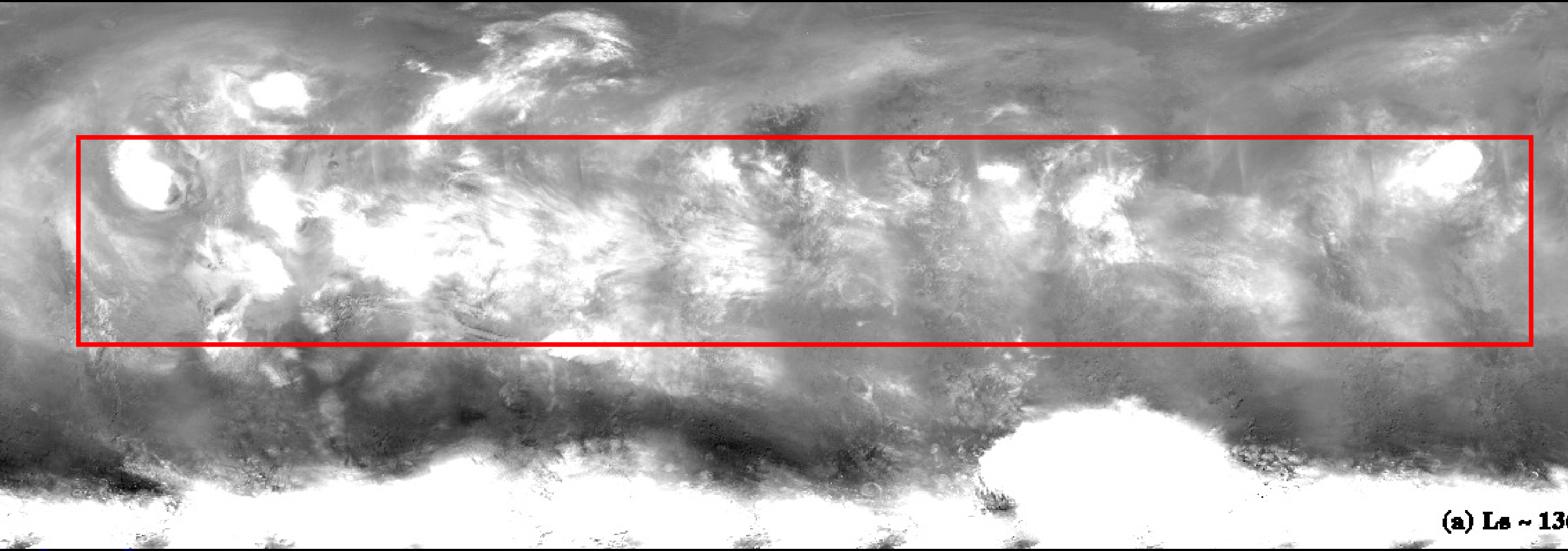


- “Moist” air rises over a mountain
- Cools as it rises
- Can’t hold as much water as it gets colder
- When the temperature gets cold enough, vapor condenses and forms a cloud

Topographic Clouds and Lee Waves

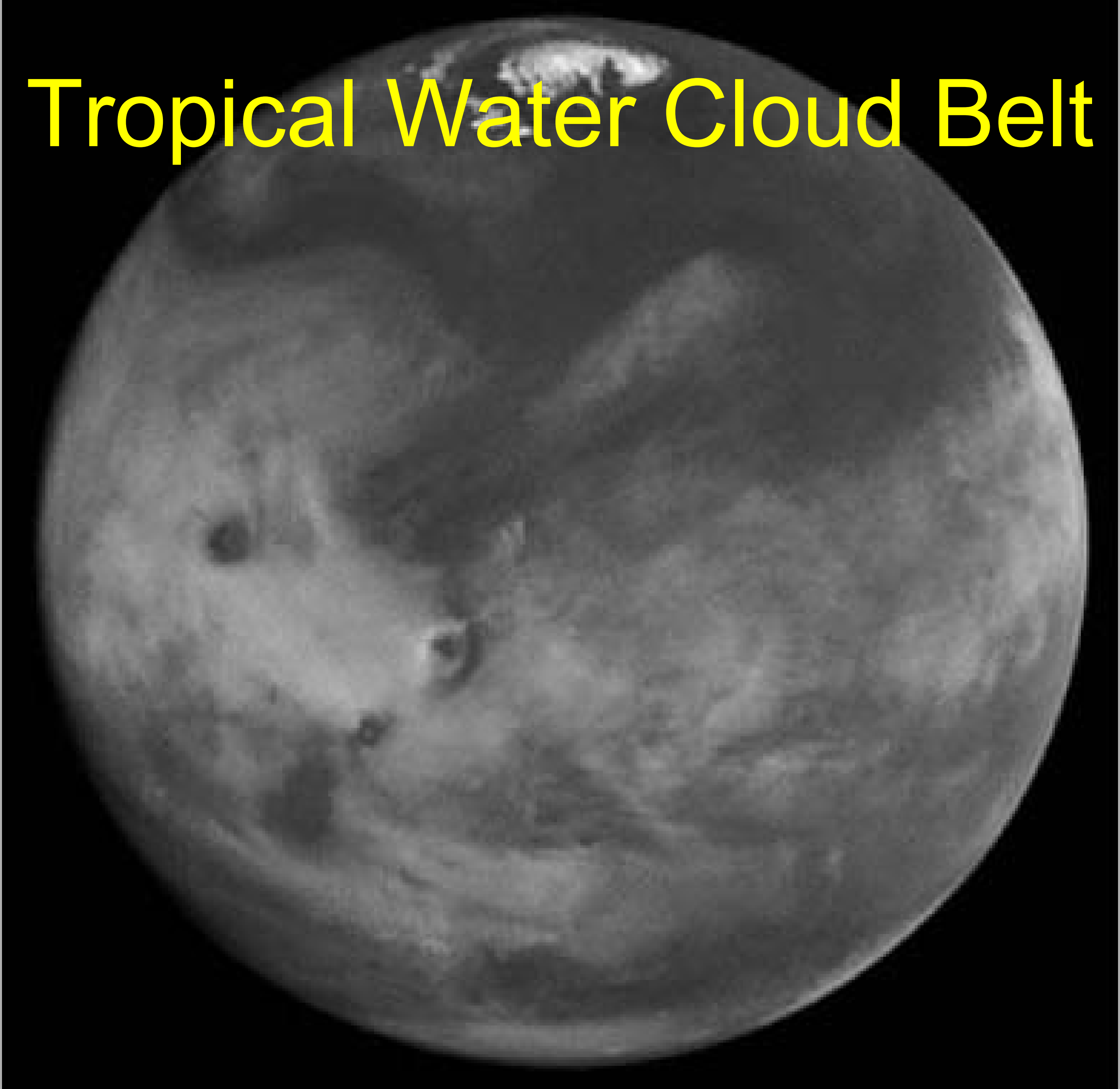


Tropical Water Cloud Belt

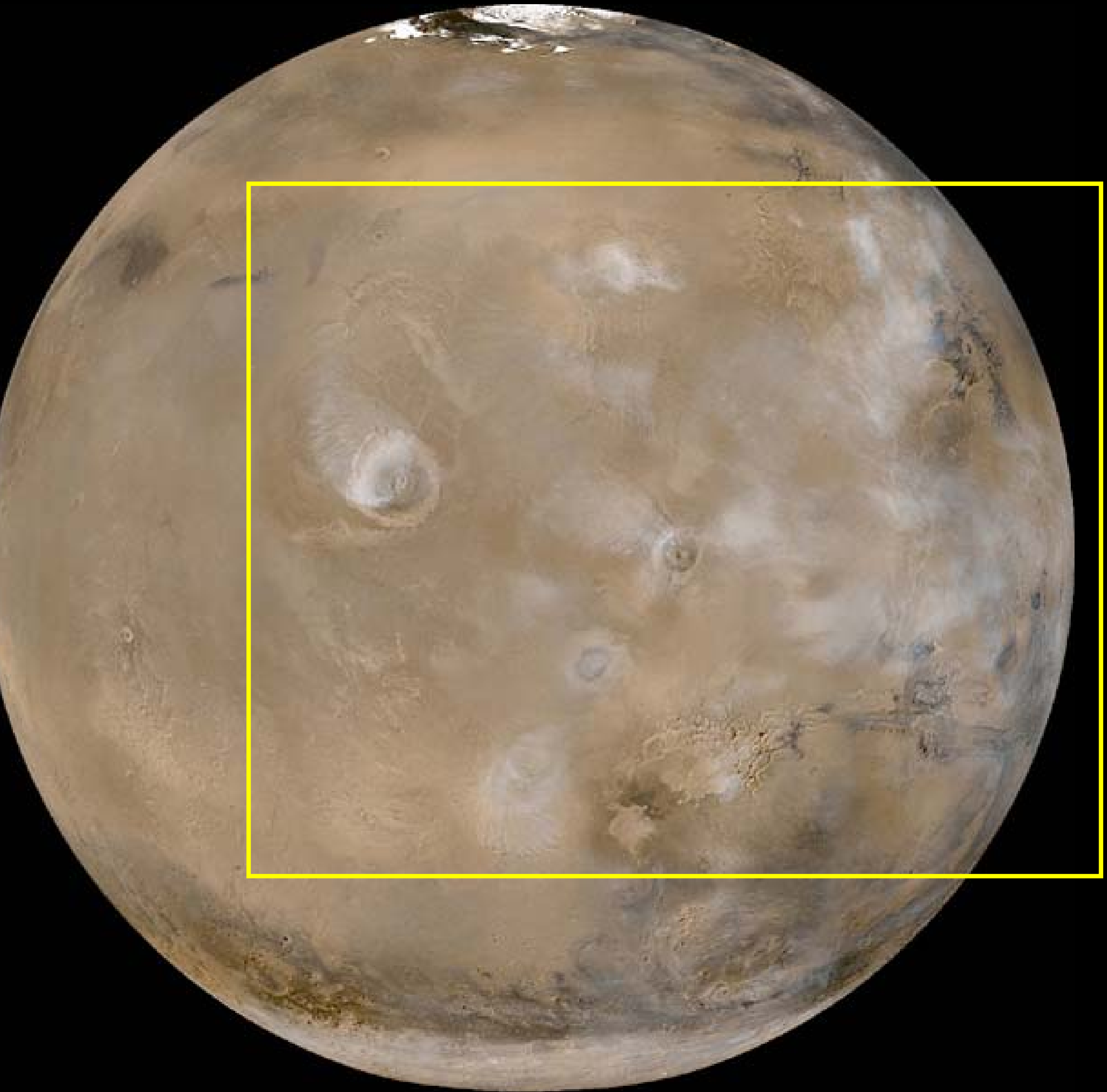


Develops during northern spring and summer (aphelion)

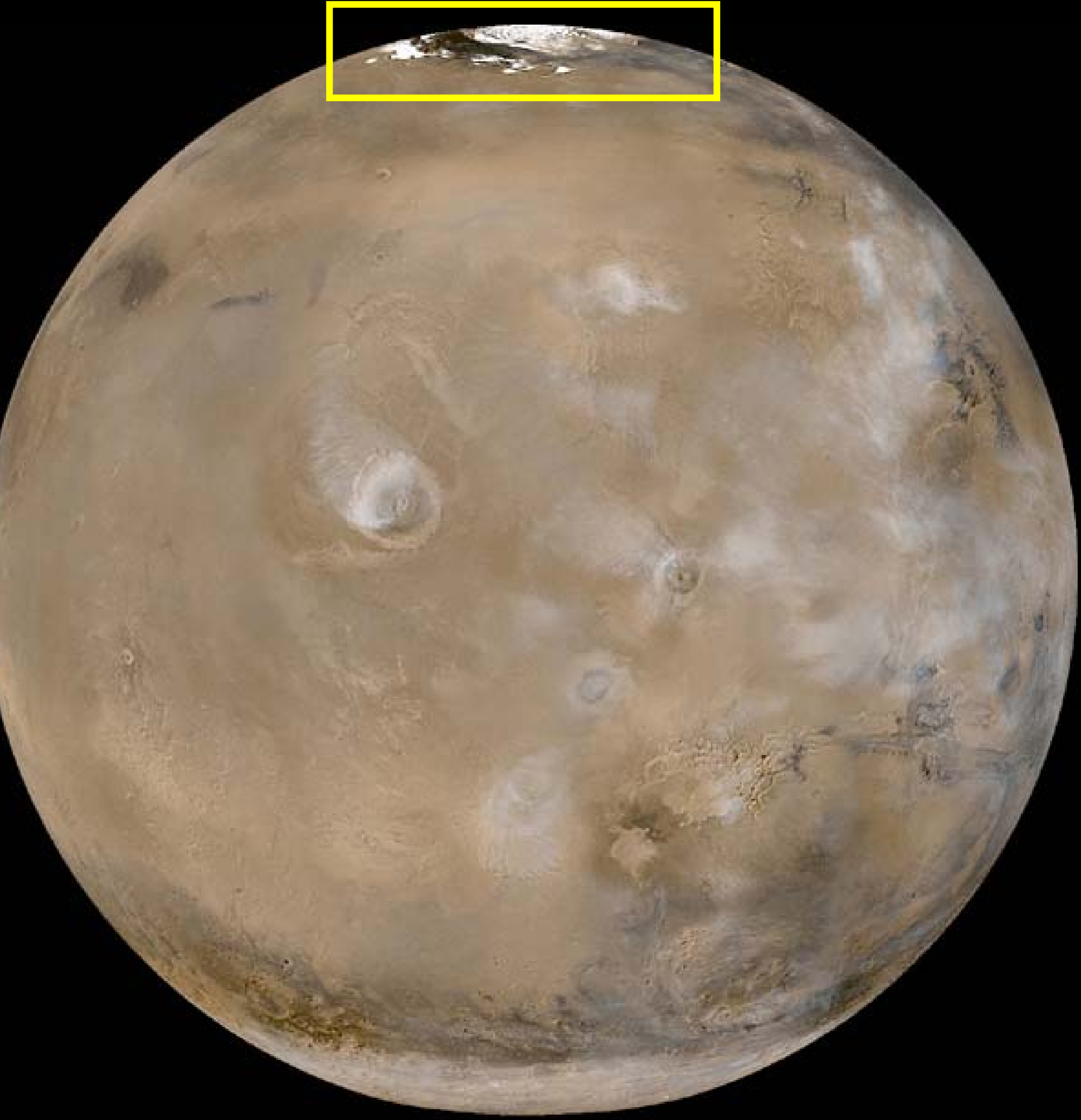
Tropical Water Cloud Belt



Mars:



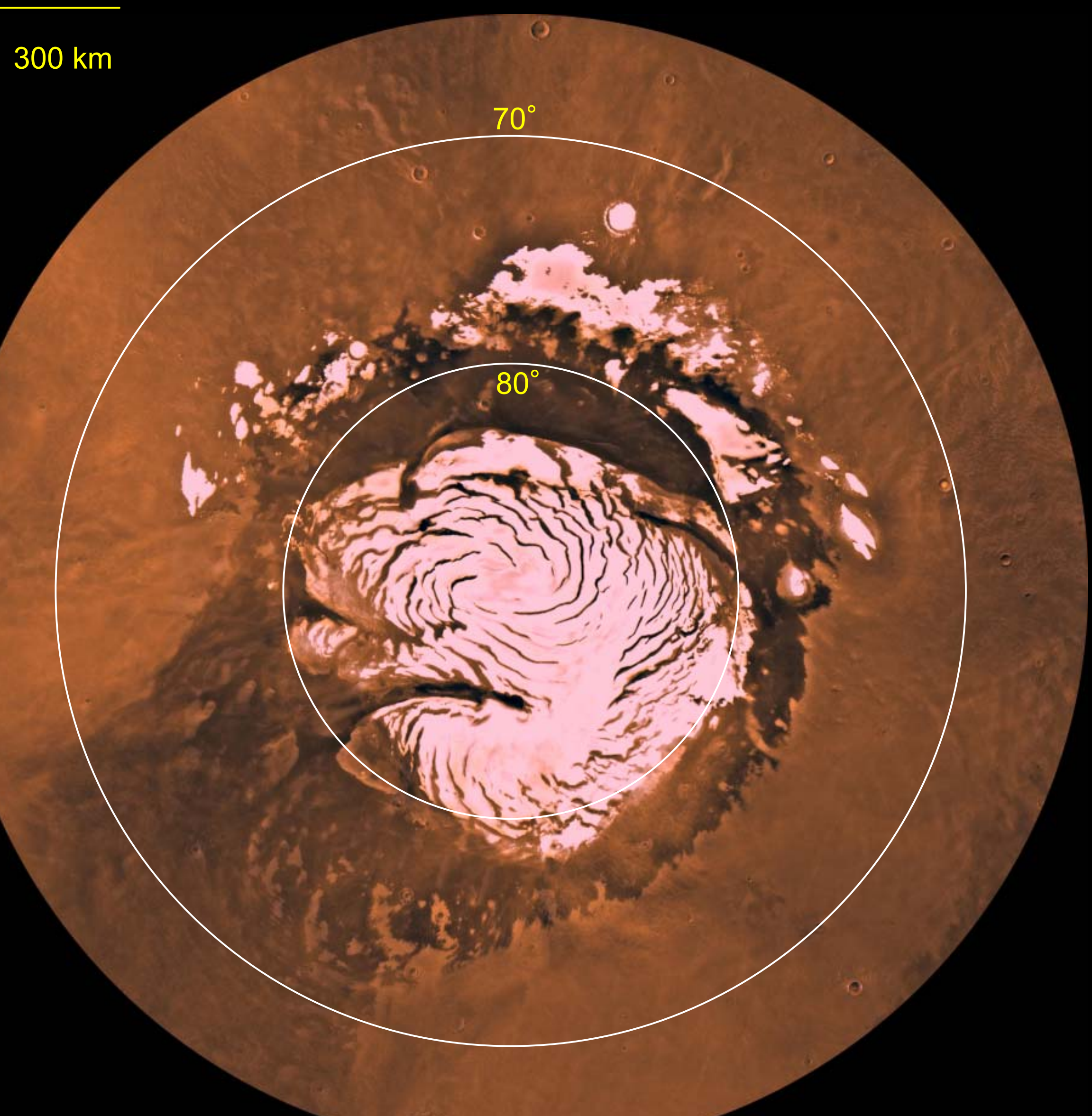
Back from the clouds…



Mars:

…to look at the polar cap again

North Polar Cap



Made almost entirely of water ice

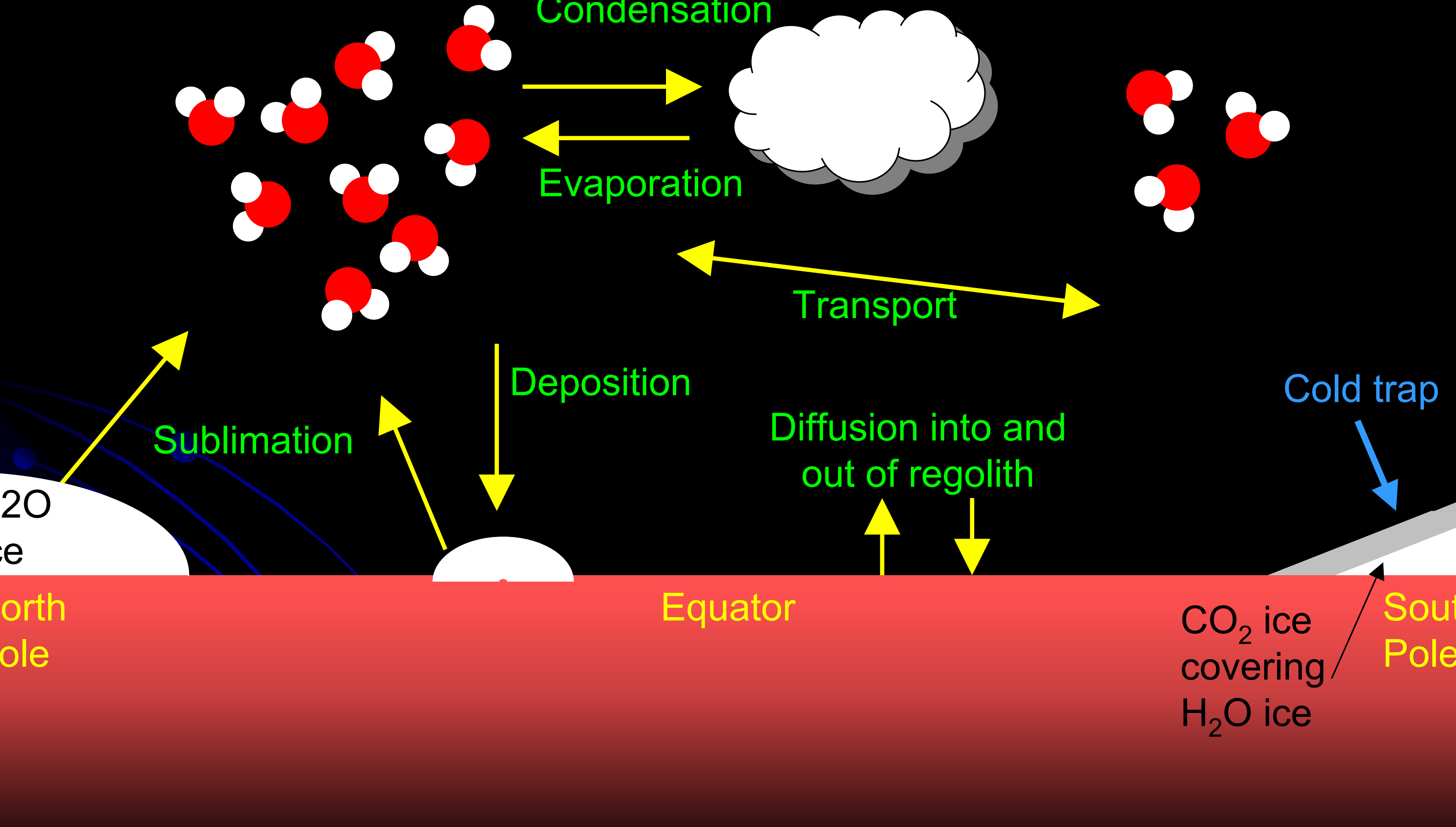
Sublimates water vapor during northern summer

Surface Frost Seen by Viking Lander 2

Cycle #2: H_2O

- North polar cap
- Atmospheric vapor
- Water Ice Clouds (topographic, aphelionic)
- Regolith (water in pore space in soil)
- Deeper regolith (long term cycling … yesterday’s talks and next talk)

Martian Water Cycle



Condensation

Evaporation

Transport

Deposition

Sublimation

Cold trap

Diffusion into and
out of regolith

2O
ce

orth
ole

Equator

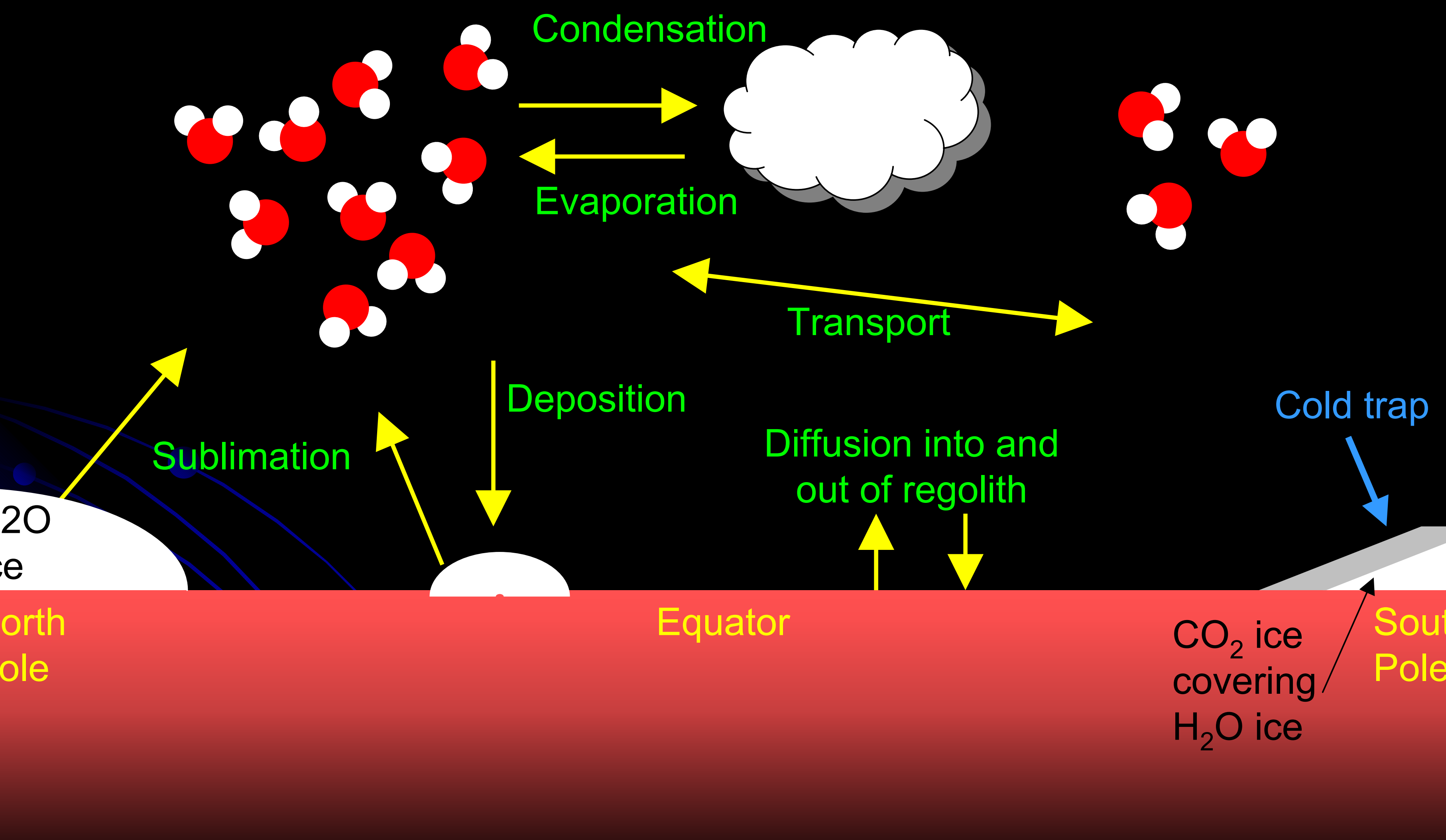
CO_2 ice
covering
H_2O ice

Sout
Pole

Martian Water Cycle

- North polar cap is (mostly) H_2O ice
  - Balance between the water in it and in the atmosphere largely controls the water cycle
- South polar cap is covered by CO_2 ice
  - Acts as a cold trap for water vapor reaching south polar regions
  - Some of this water sublimates off during southern summer
- Exchange of water between the atmosphere and regolith is not as important as once thought
  - Cycle is mostly net transport (by the atmospheric circulation) of vapor released by the north polar cap in summer into the southern hemisphere

Martian Water Cycle



Condensation

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Diffusion into and
out of regolith

Cold trap

2O
ce

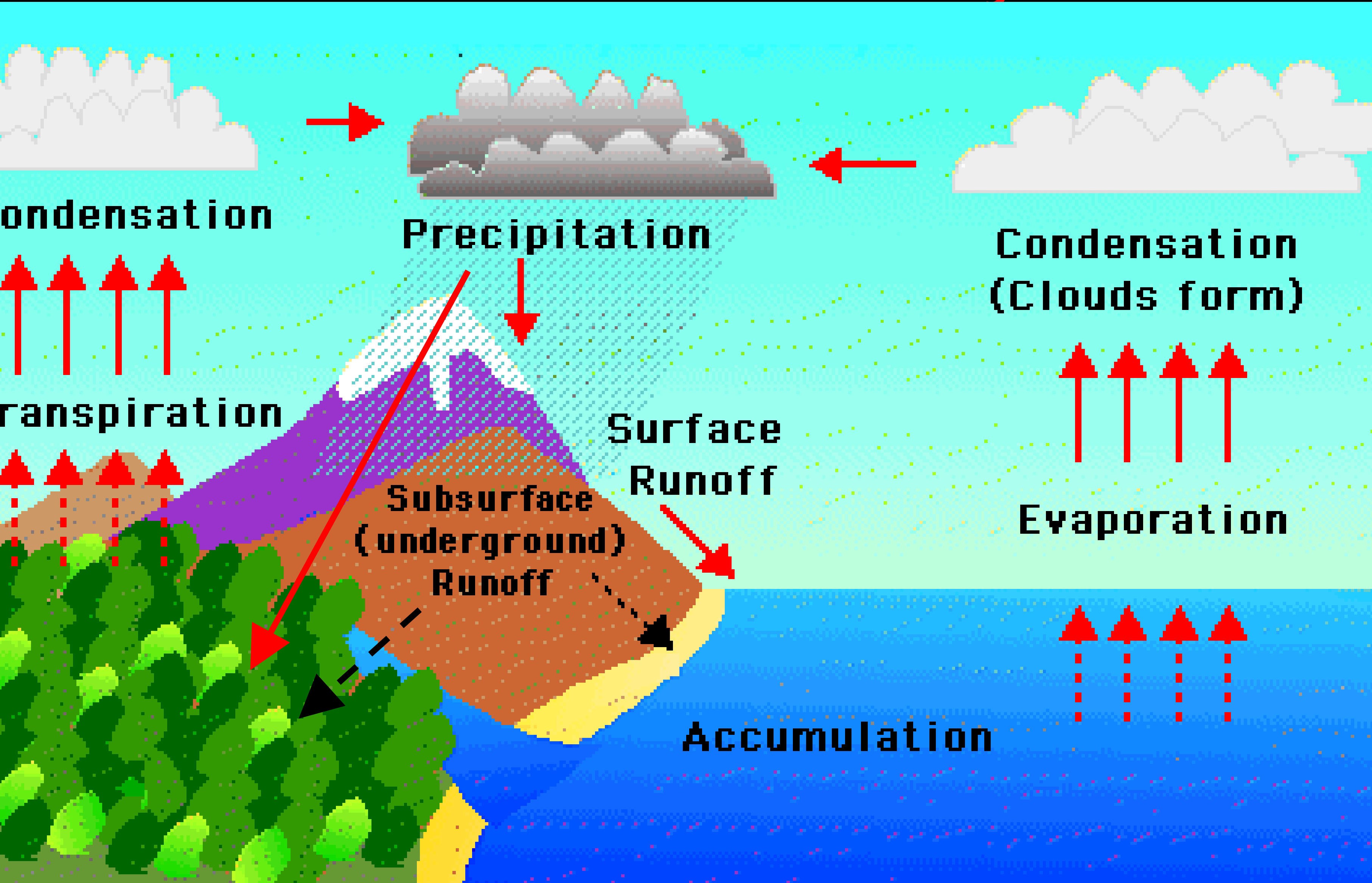
orth
ole

Equator

CO_2 ice
covering
H_2O ice

Sout
Pole

Terrestrial Water Cycle



Terrestrial Water Cycle

- Water is the dominant control on terrestrial weather
  - Water has a heat capacity (per kg) 4 times that of air, and a density 1000 times that of air, so, per volume, water can hold 4000 times as much heat
- Latent heat of condensation: 2.5×10^6 J/kg
  - an enormous source and sink of atmospheric energy

Terrestrial Water Cycle

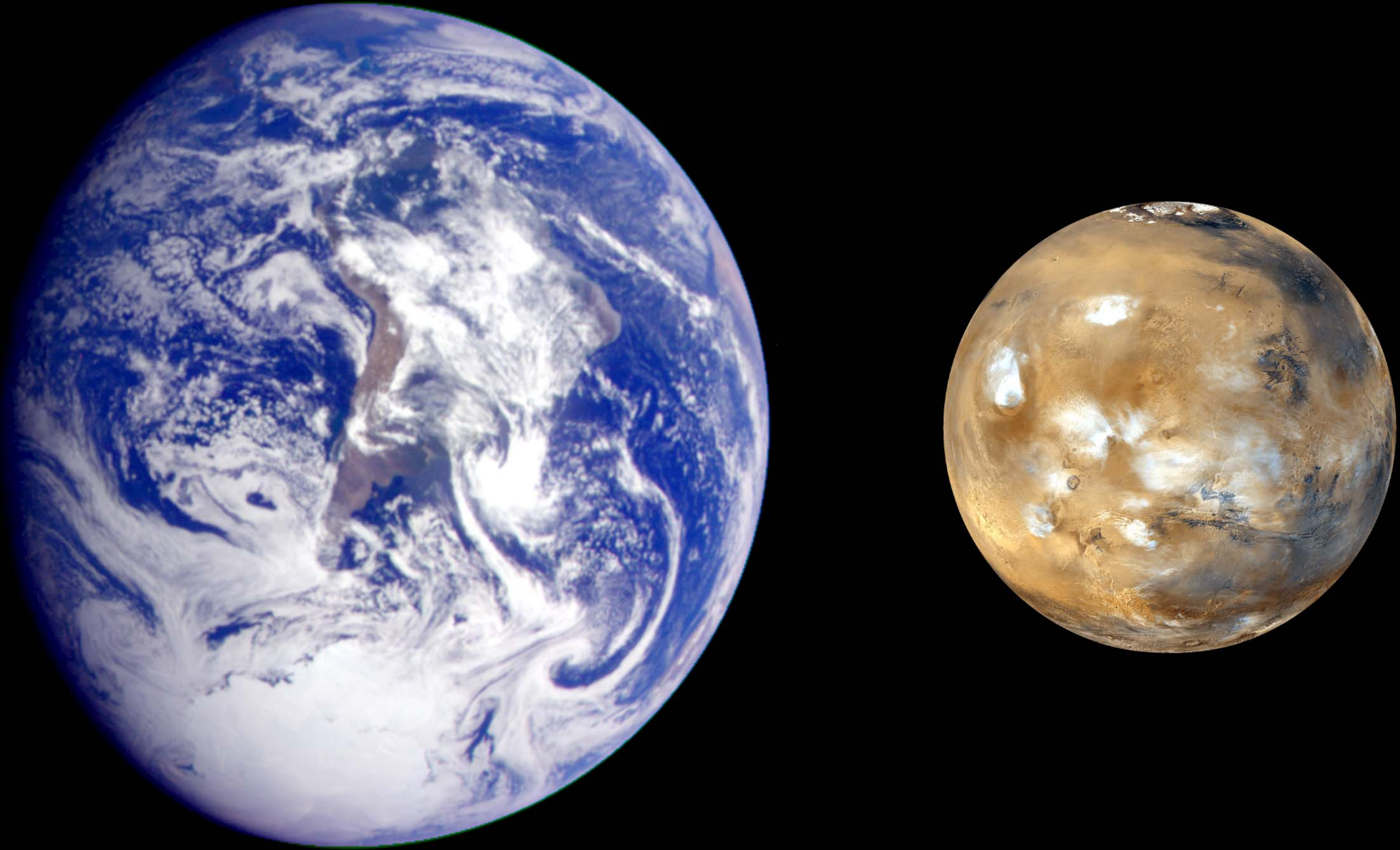
- Ocean water also transports heat, and buffers atmospheric temperatures
- Water vapor transport also transports a lot of heat energy

- What can Mars do without oceans and a lot of water?

Mars vs. Earth

Dust (aerosol)

Earth vs. Mars



Control of Meteorology and Climate

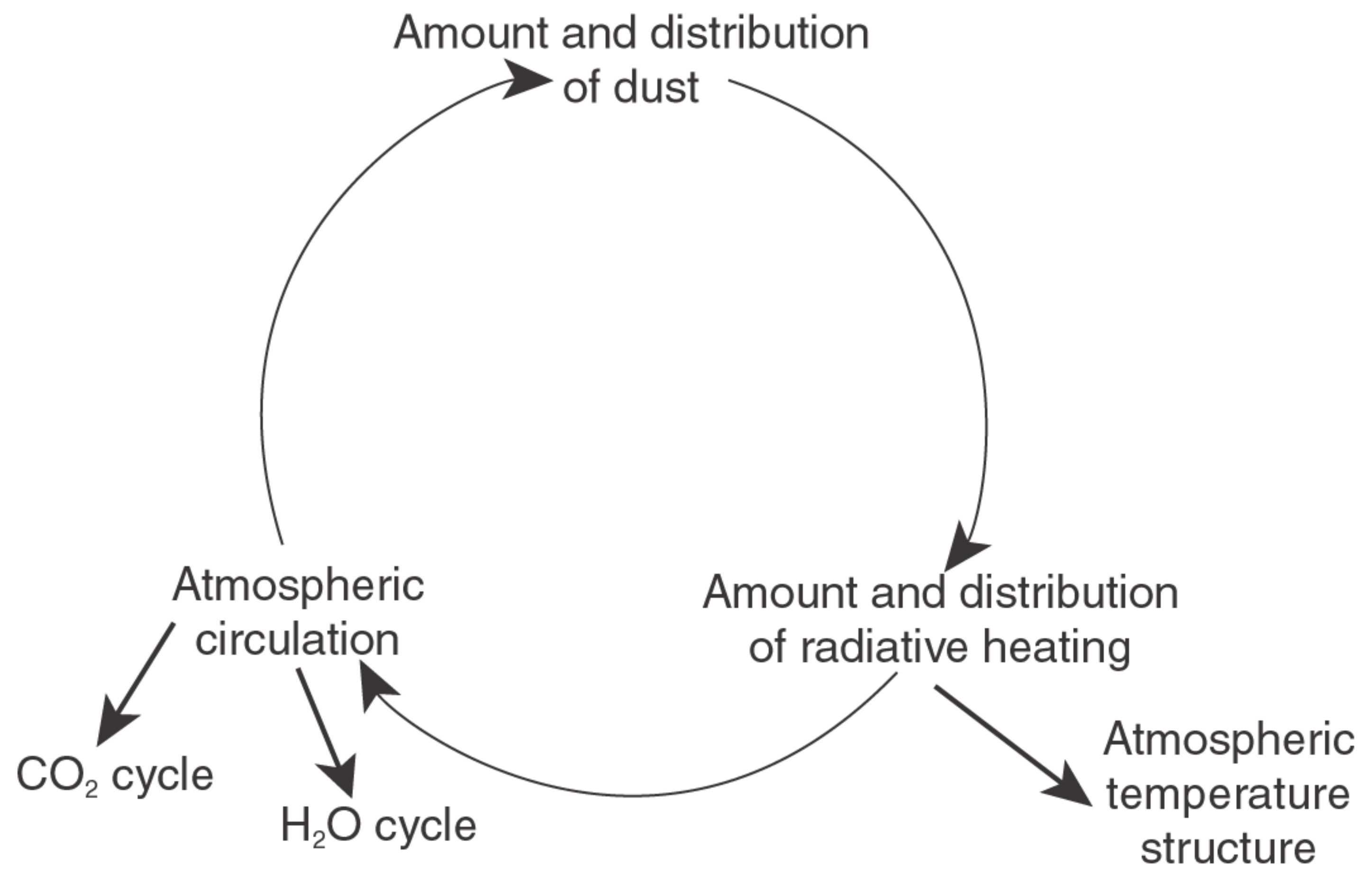
Earth: <u>water</u>

- *Latent heat exchange (evaporation and condensation)*

Mars: <u>dust</u>

- *Absorption and re-radiation of solar energy*

Control of Climate by Dust



Amount and distribution of dust

Amount and distribution of radiative heating

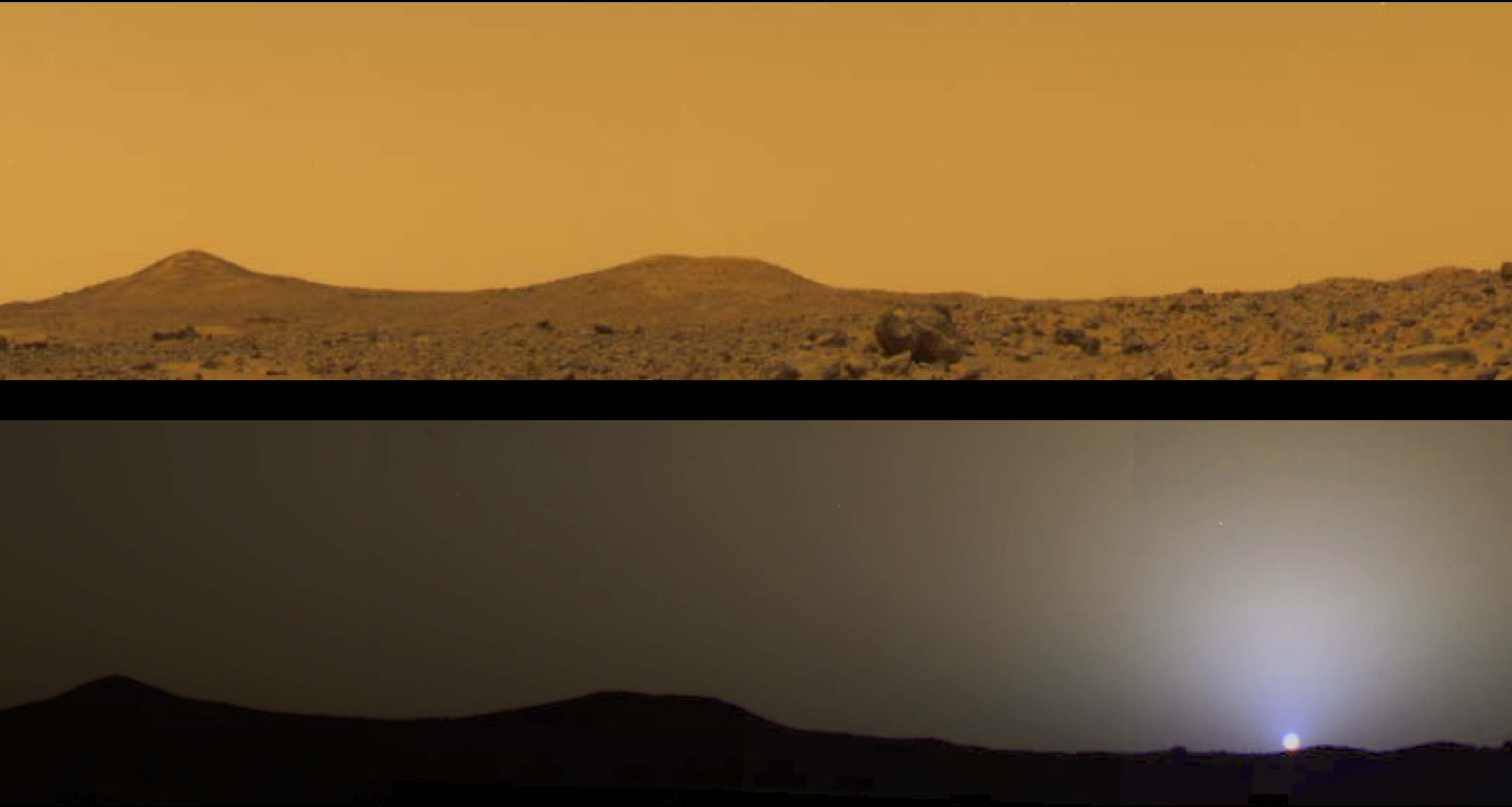
Atmospheric temperature structure

Atmospheric circulation

CO_2 cycle

H_2O cycle

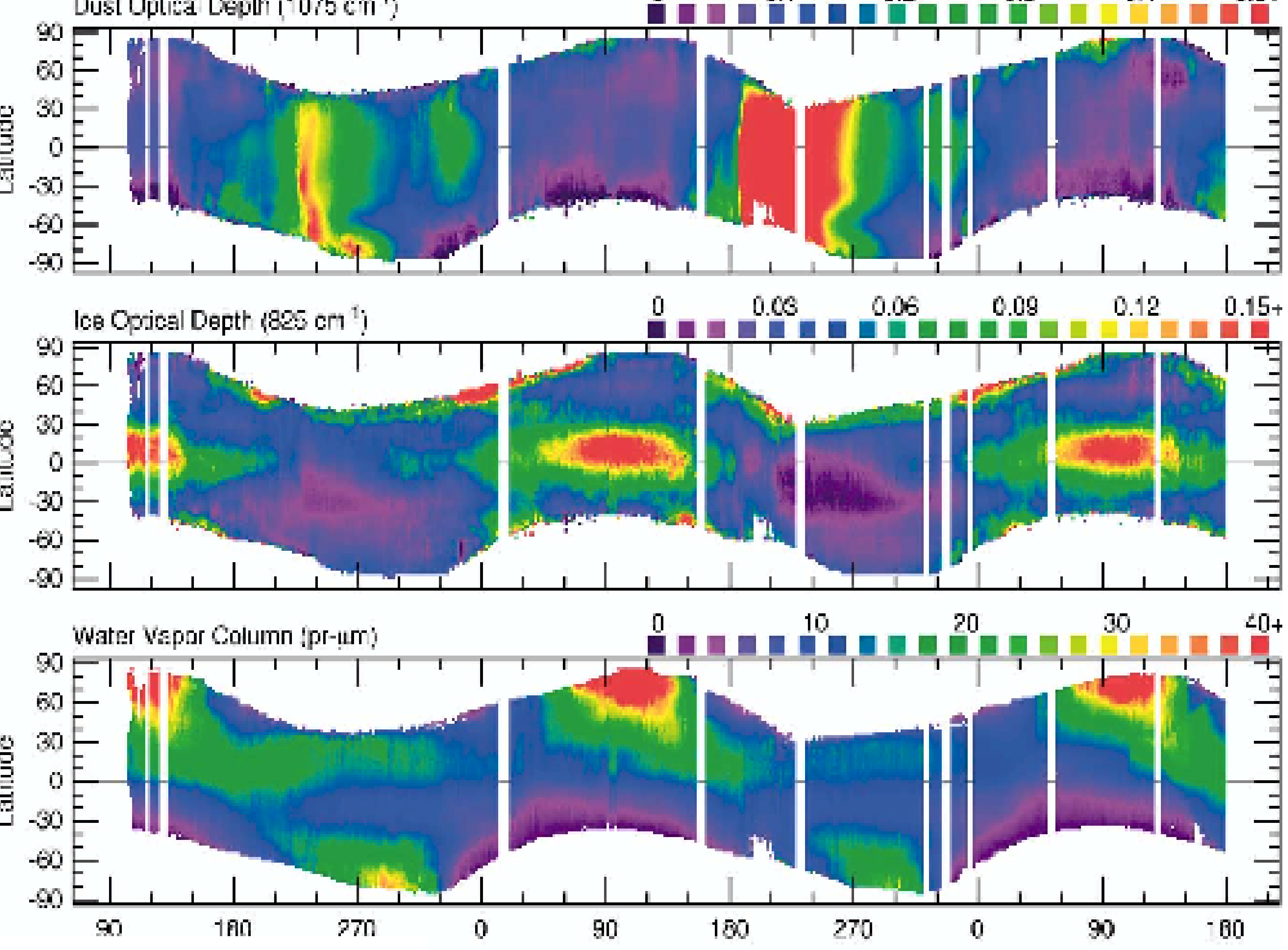
Dust on Mars



Dust in the Martian Atmosphere

Cycle #3: Dust

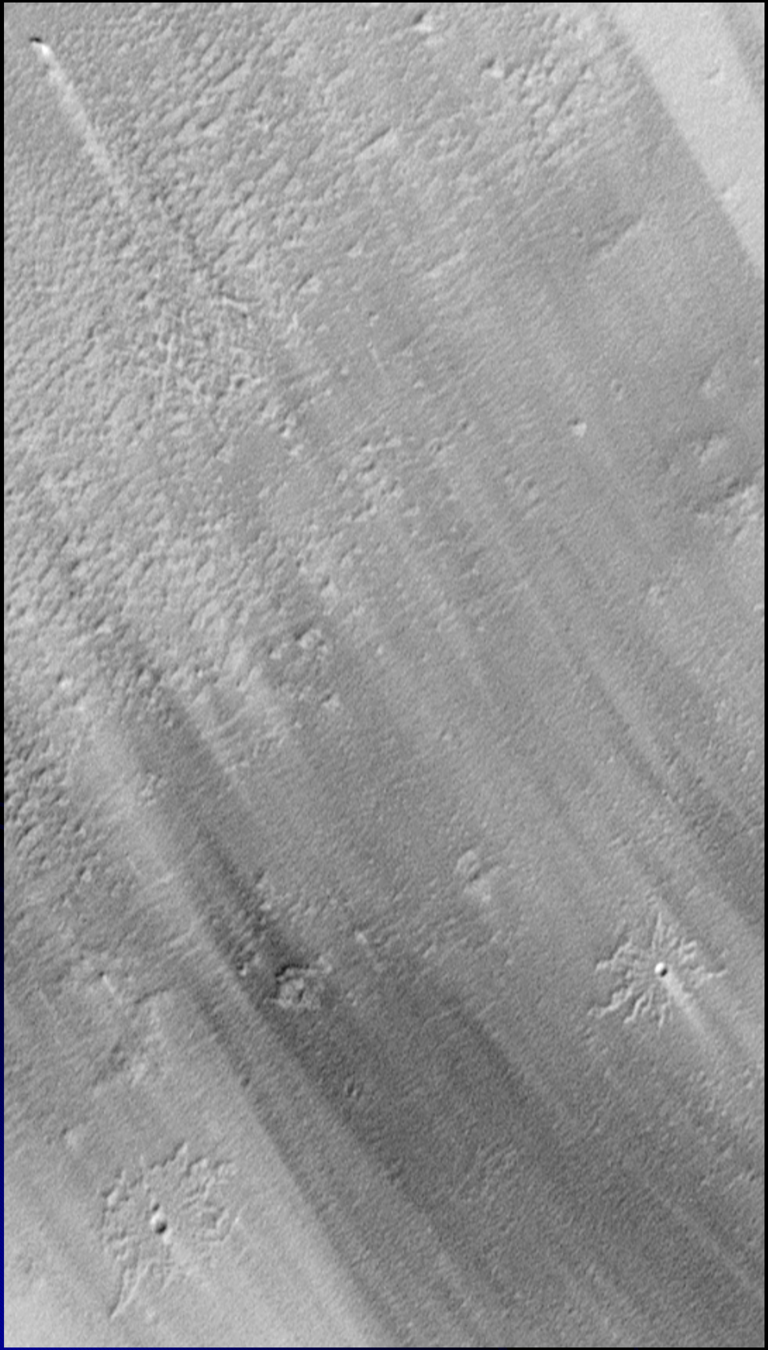
- Much more important for Mars than the Earth
- Source of “weather”
- Interaction of atmosphere with surface
- Largest present source of erosion
  - Water acts faster, but too little of it presently to be of much effect
- Dust in the atmosphere affects absorption of radiation
  - changes lapse rate
  - makes it warmer and more stable



of the 3 Martian cycles

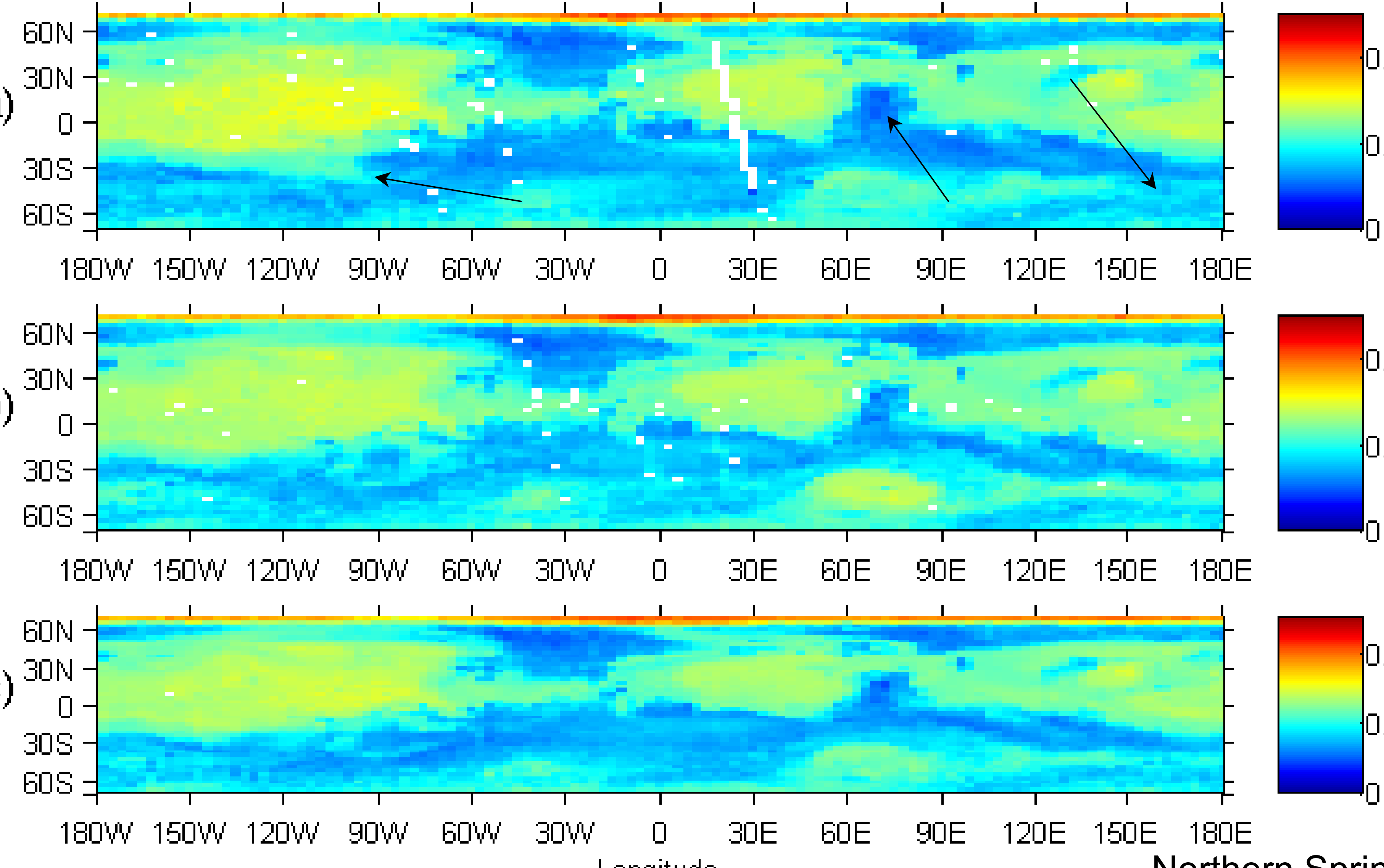
Dust Cycle

- Dust lifting processes
  - Saltation
  - Dust devils
- Dust Storms and Types
  - Local: cap edge, slope induced
  - Regional
  - Global
- Modification of global circulation by dust storms → leads back to lifting



Movement of dust on the surface

Albedo: 3 consecutive years

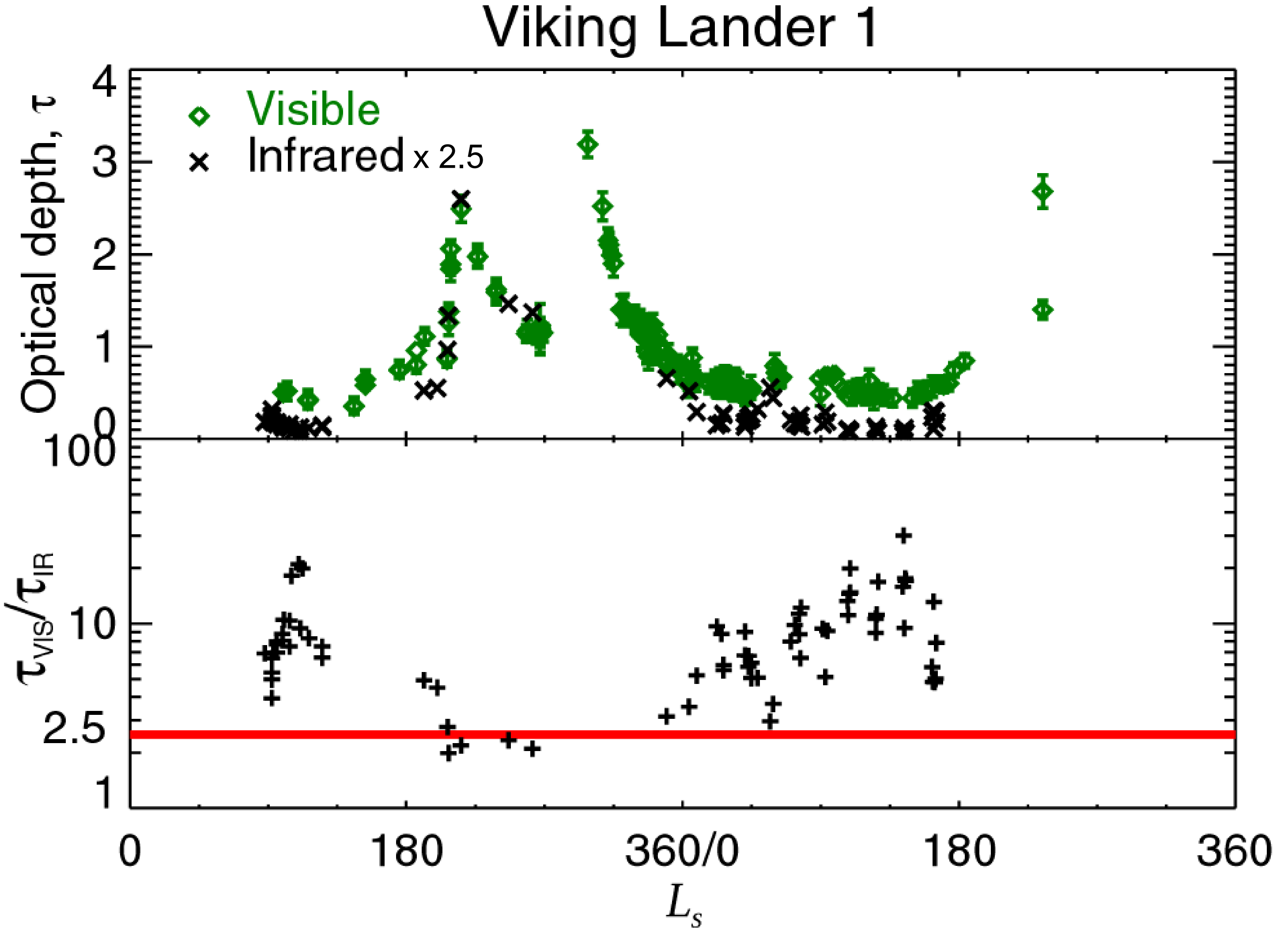


Northern Sprin

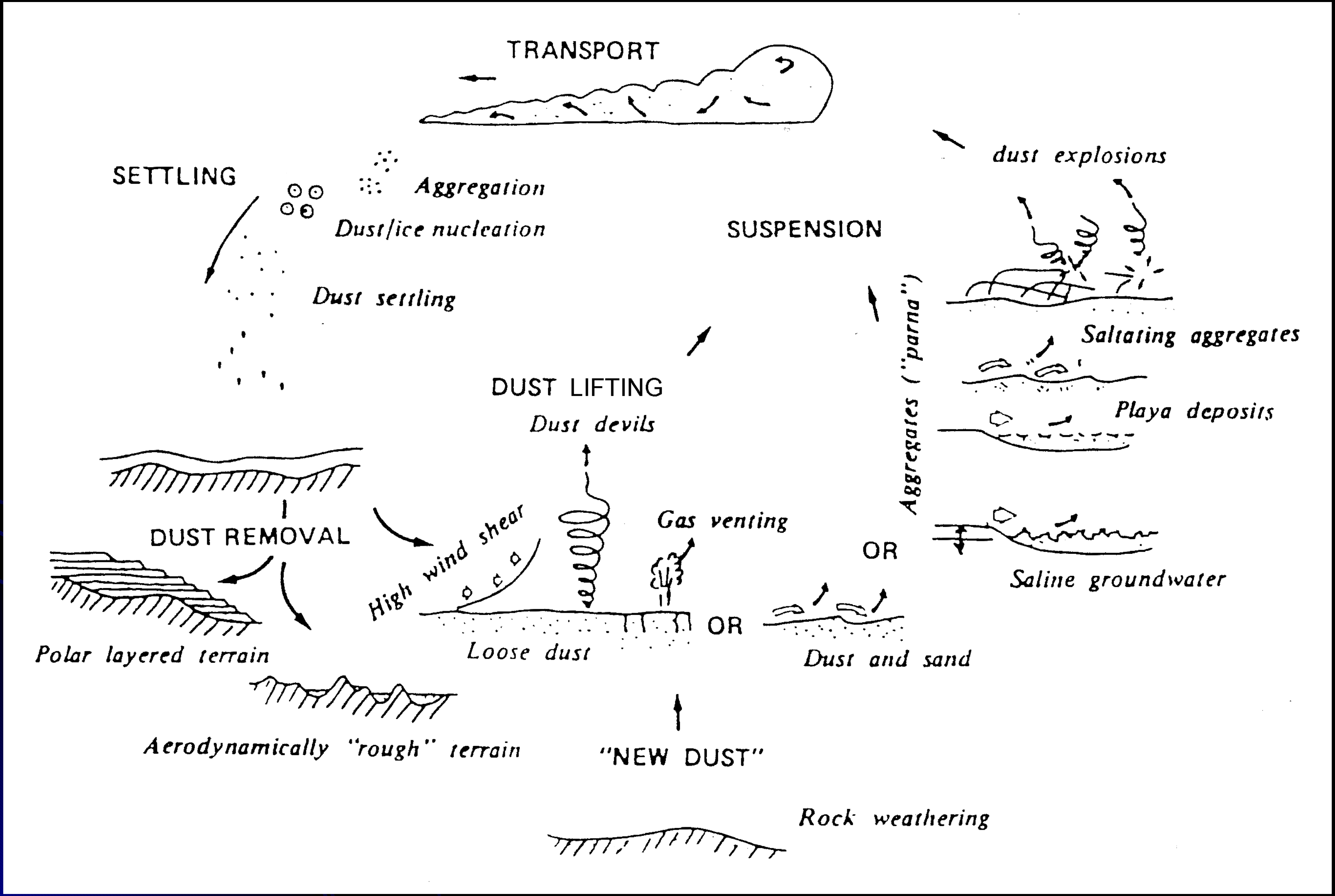
Measurements

- Viking Landers
  - Measured extinction of sunlight (visible)
  - Measured amount every day at one place
  - Assumed to represent annual cycle of dust
    - Climate models tuned to these values
- Viking Orbiters
  - Measured 9 μm silicate absorption band depth (infrared)
  - Specific to dust
  - Didn't see the same place every season

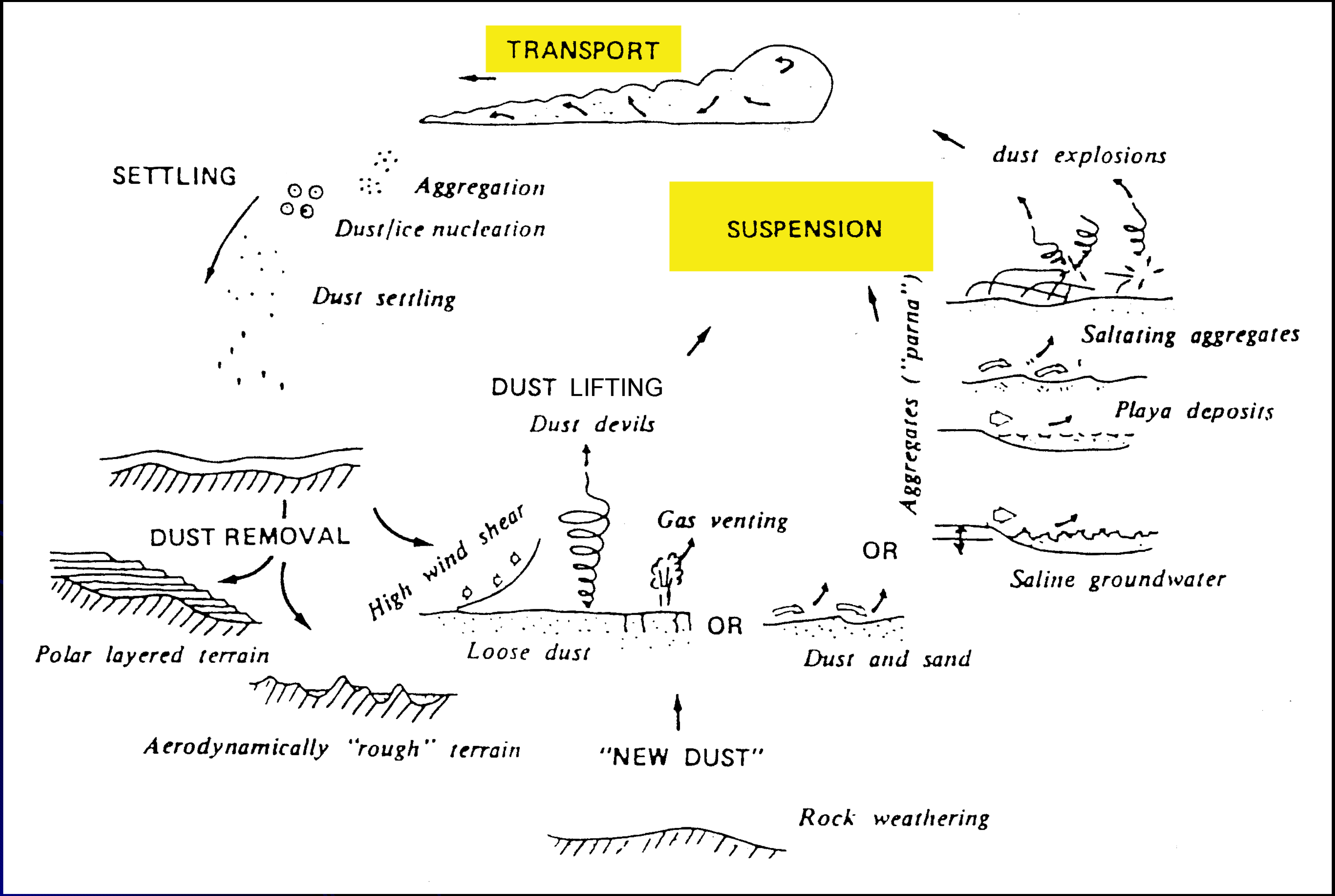
Optical depth at VL1



The Dust Cycle



The Dust Cycle



Dust Storms are Martian Weather

(in the absence of water)

How do dust storms form?

- Dust must get lifted off of the ground
- Typically, high winds create forces to lift dust in a local region
- Lofted dust modifies the local circulation to either impede (local dust storm) or enhance (regional dust storm) further lifting of dust
- If modification of circulation in one region causes dust lifting to begin in another region, or two different local dust storms combine constructively rather than destructively, a global dust storm can form.
- Dust storms redistribute heat and dust around the planet

Local Dust Storms

Local Dust Storms

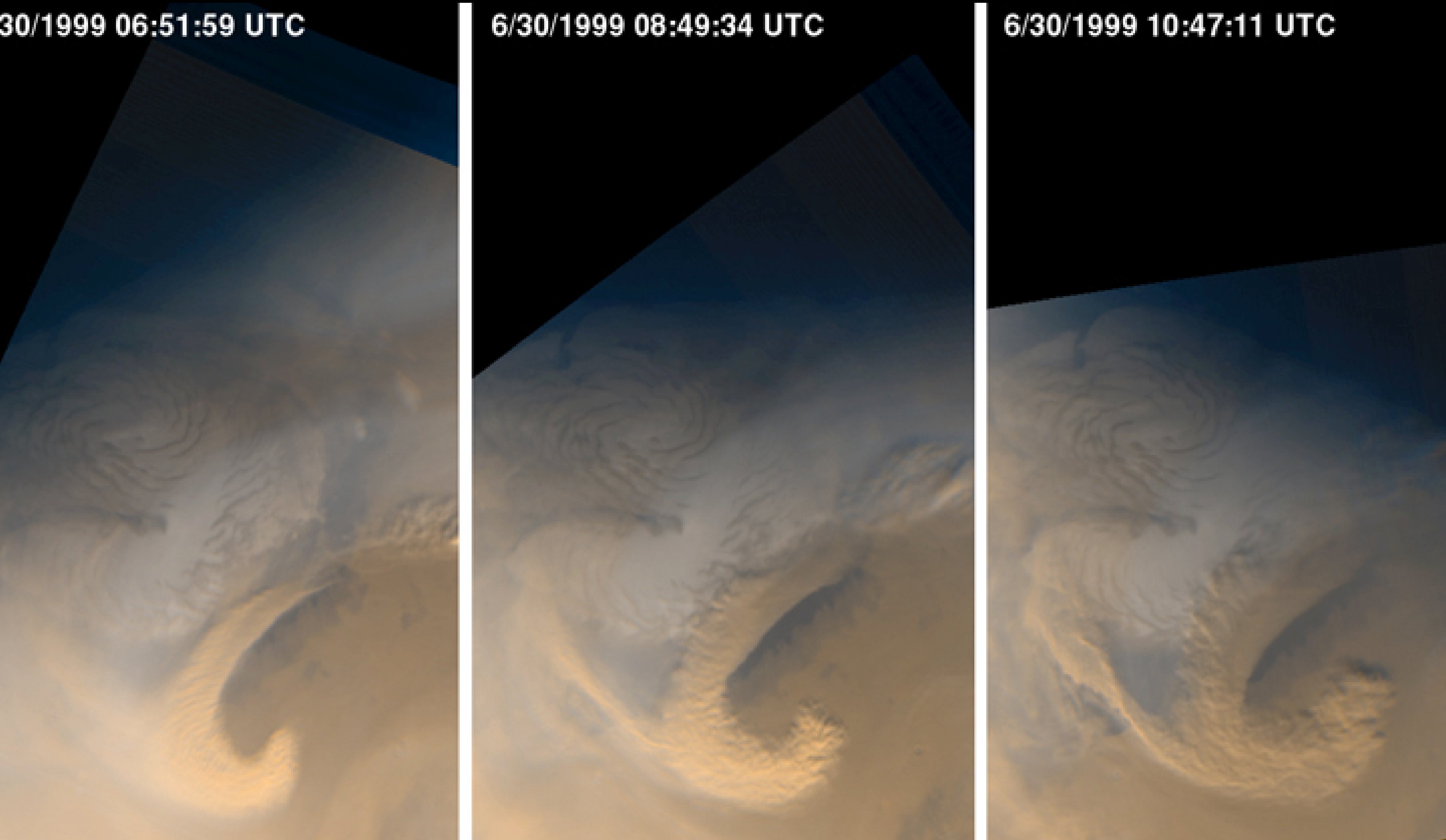
$L_s \sim 300^\circ$
(southern
summer)

Local Dust Storms

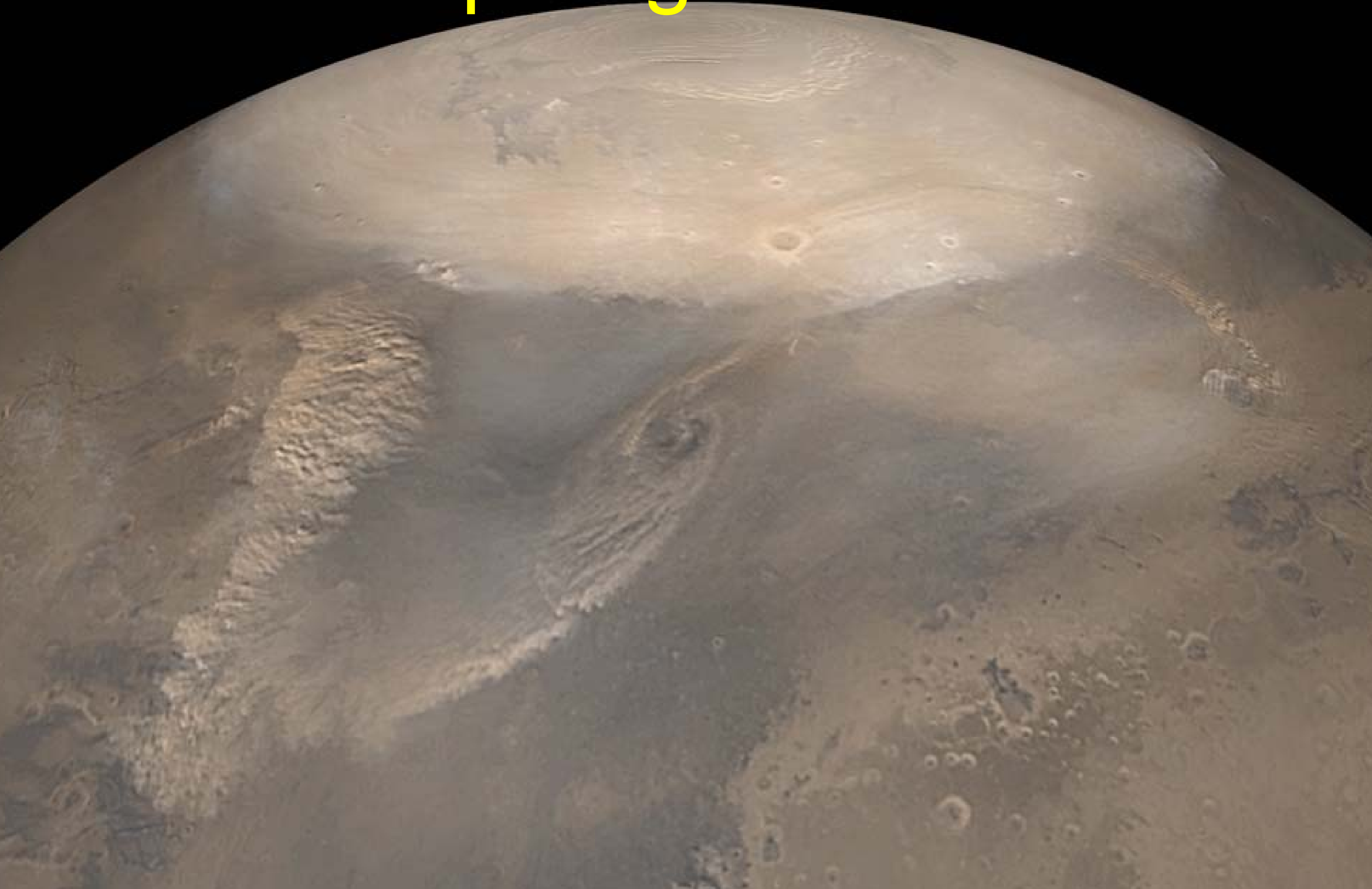
- High-resolution image of a dust lifting front
- Big local dust storm in southern polar layered deposits
- Dust lifted in small plumes

Polar Cap Edge Dust Storms

Polar Cap Edge Dust Storms

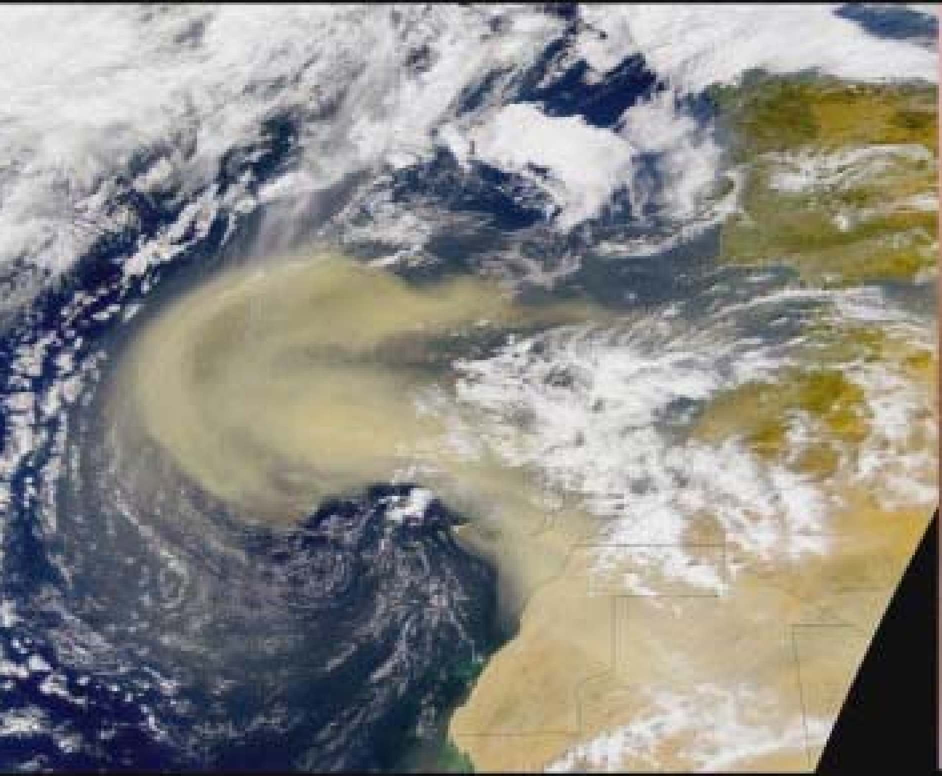


Polar Cap Edge Dust Storms

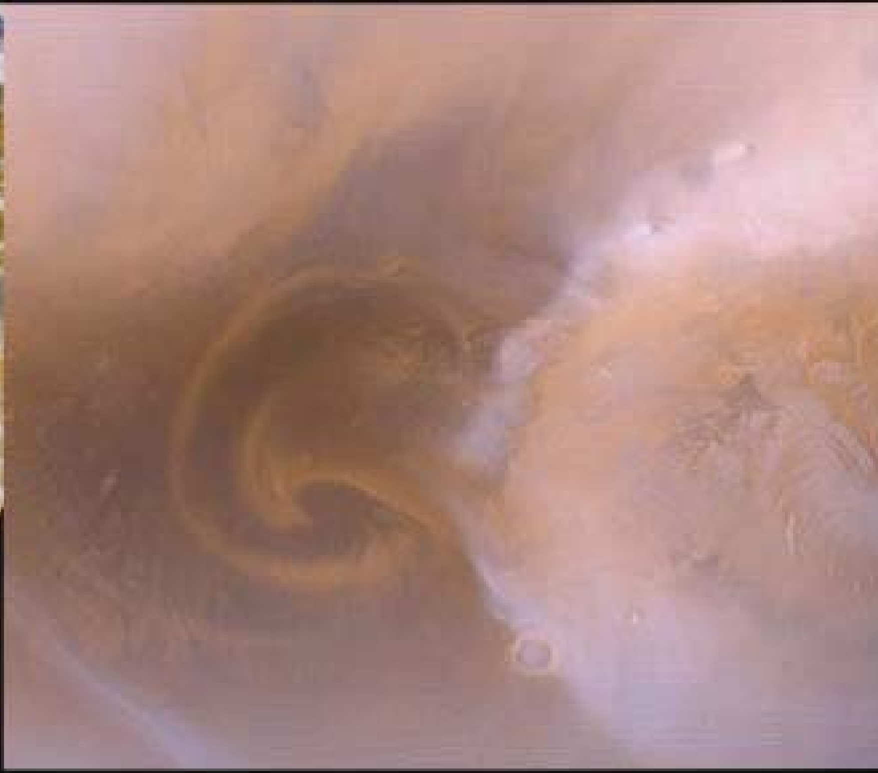


Similar Dust Storms

Terrestrial dust storm (26 February 2000)
Storm extends about 1800 km off NW Africa
near the equator



North Polar Cap

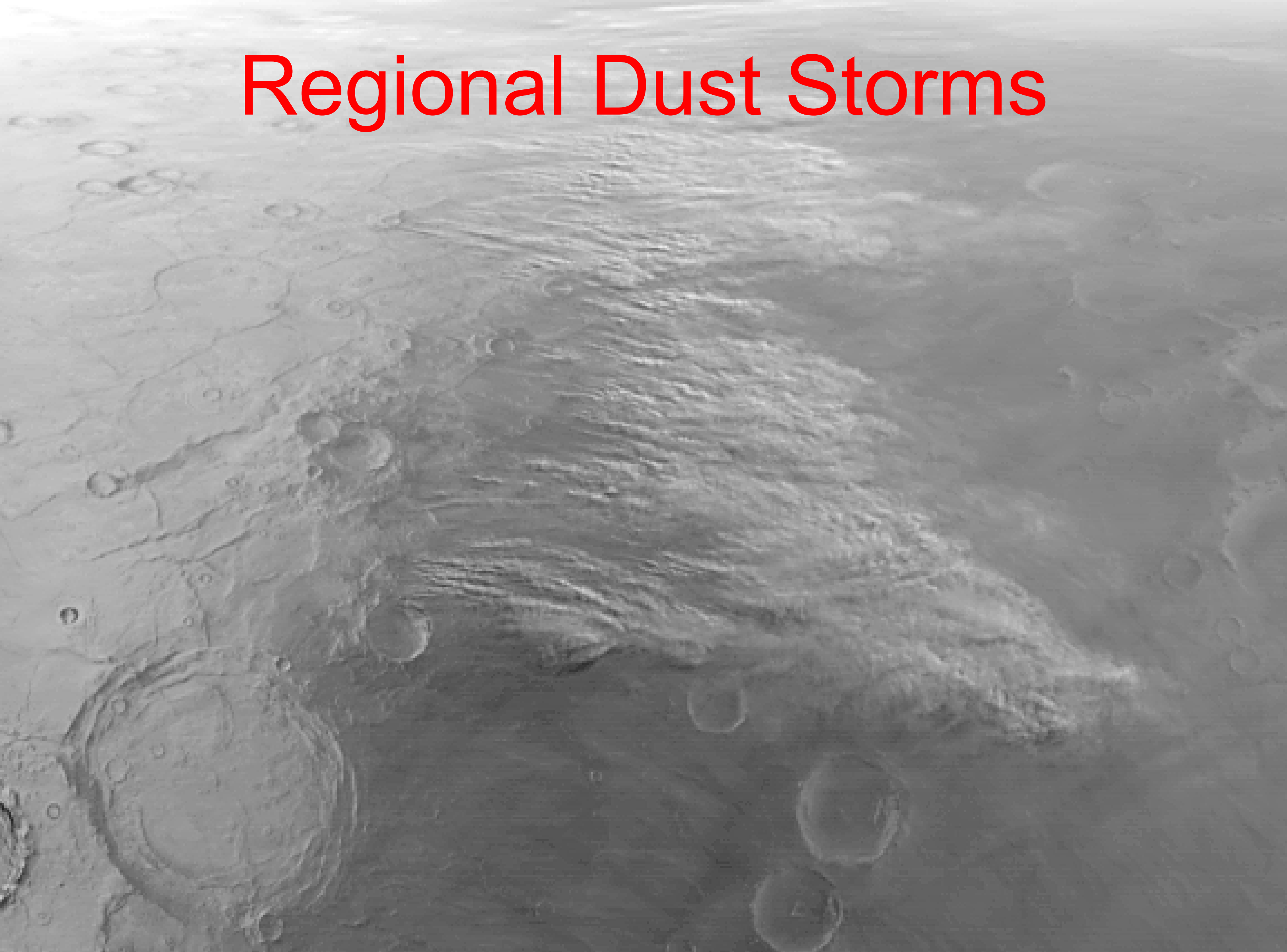


How do dust storms form?

- Polar Cap Edge Storms
  - Temperature contrasts between the cold CO_2 seasonal frost cap and the warm ground adjacent to it--combined with a flow of cool polar air evaporating off the cap--sweeps up dust and funnels it into swirling dust storms along the cap edge.

Regional Dust Storm:

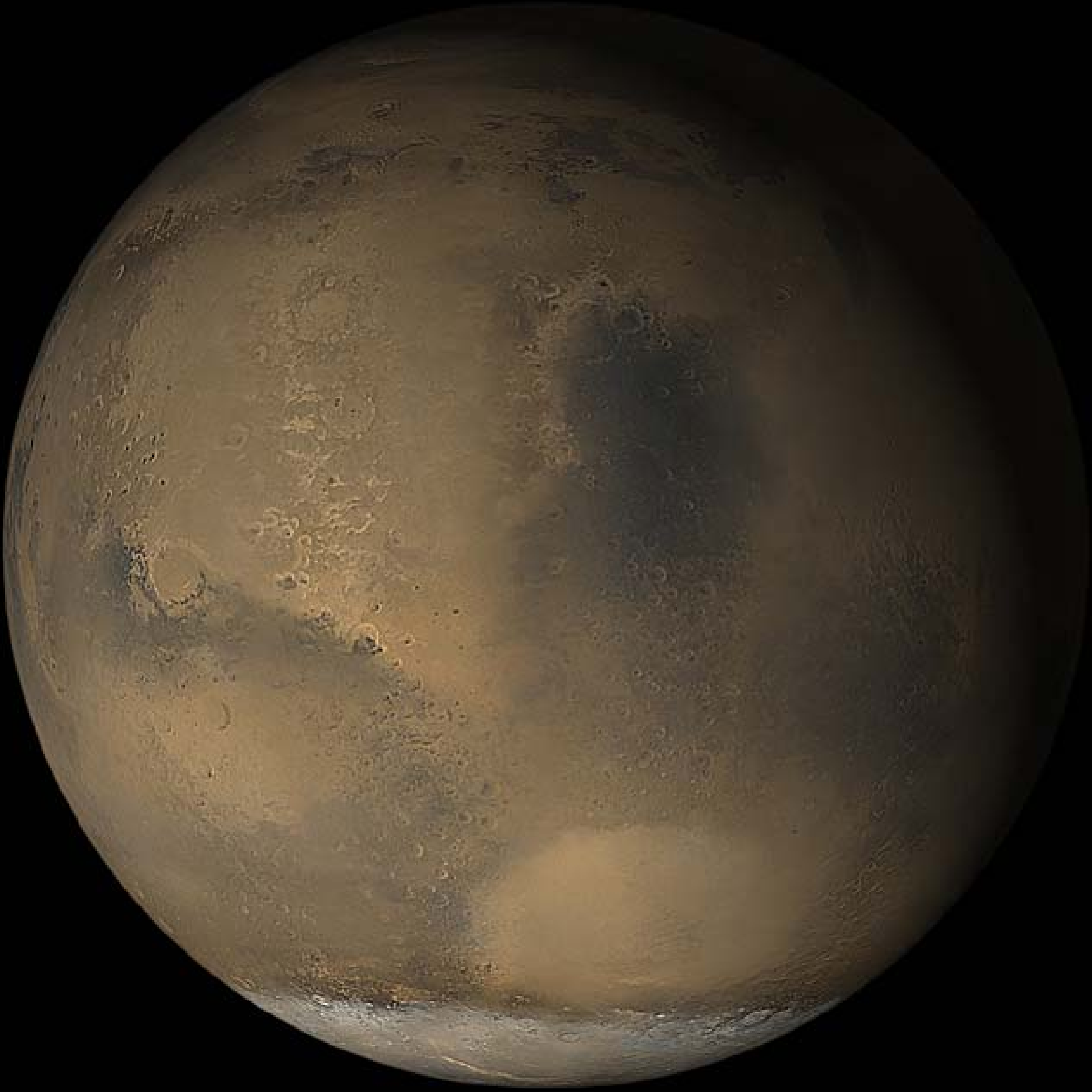
Dust front coming down Chryse Planitia



Regional Dust Storms

Global Dust Storms

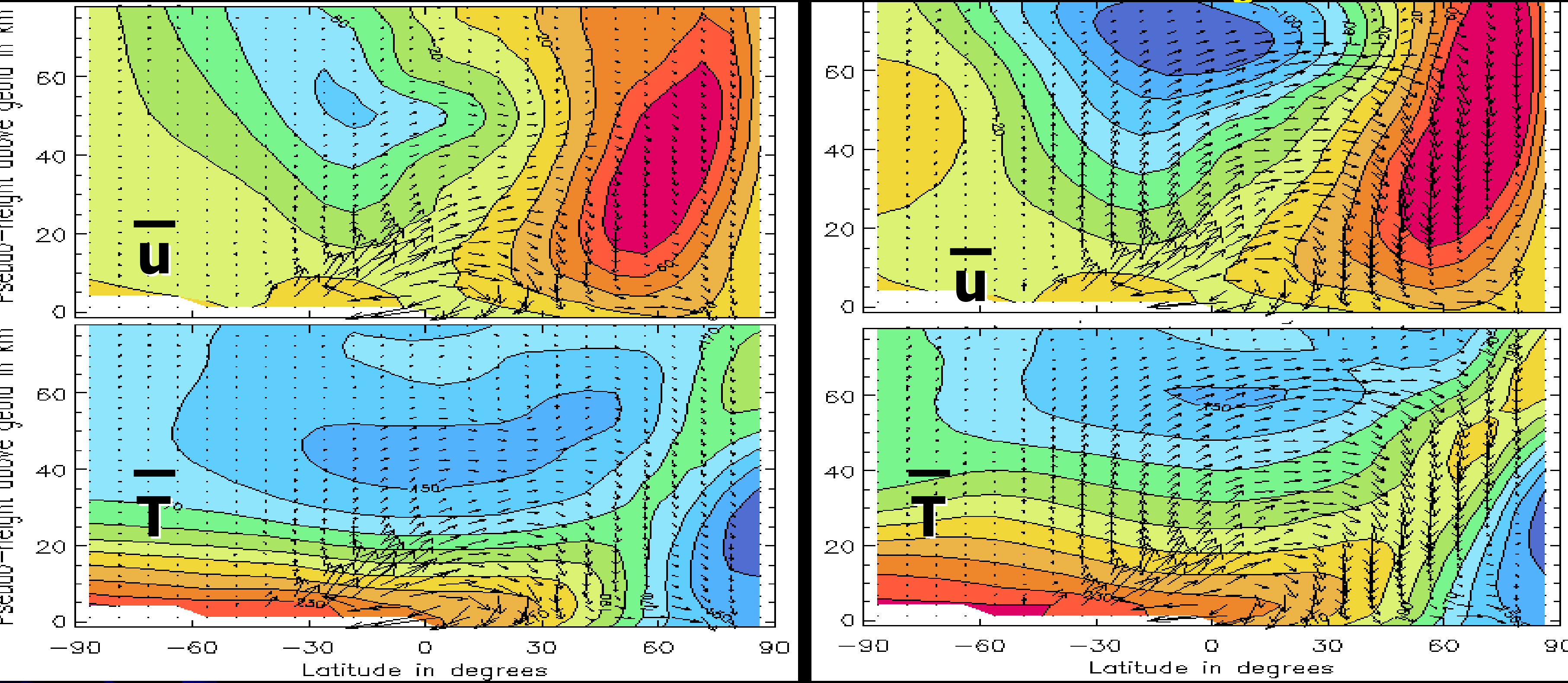
Global dust storm seen by
Mariner 9 upon arrival in 1971



Summer 2001 Global Dust Storm

- Images from late in June 2001 (southern Martian winter transitioning to spring)
- By early July, dust storms had popped up all over the planet, particularly throughout the southern hemisphere and in the Elysium/Amazonis regions of the northern hemisphere.
- Soon, the entire planet (except the south polar cap) was enshrouded in dust.
- There was never a time when the entire planet was in the midst of a single storm. Several large storms would occur at the same time, and dust was kicked high into the atmosphere to cause much of the rest of the planet to be obscured.
- The dust storms largely subsided by late September 2001, but the atmosphere remained hazy into November of that year.
- First image was from June and shows the Tharsis volcanic region (left), Valles Marineris chasms (right) and the late winter south polar cap (bottom).
- Second image was from July and shows the same regions

The effect of more dust on the circulation…

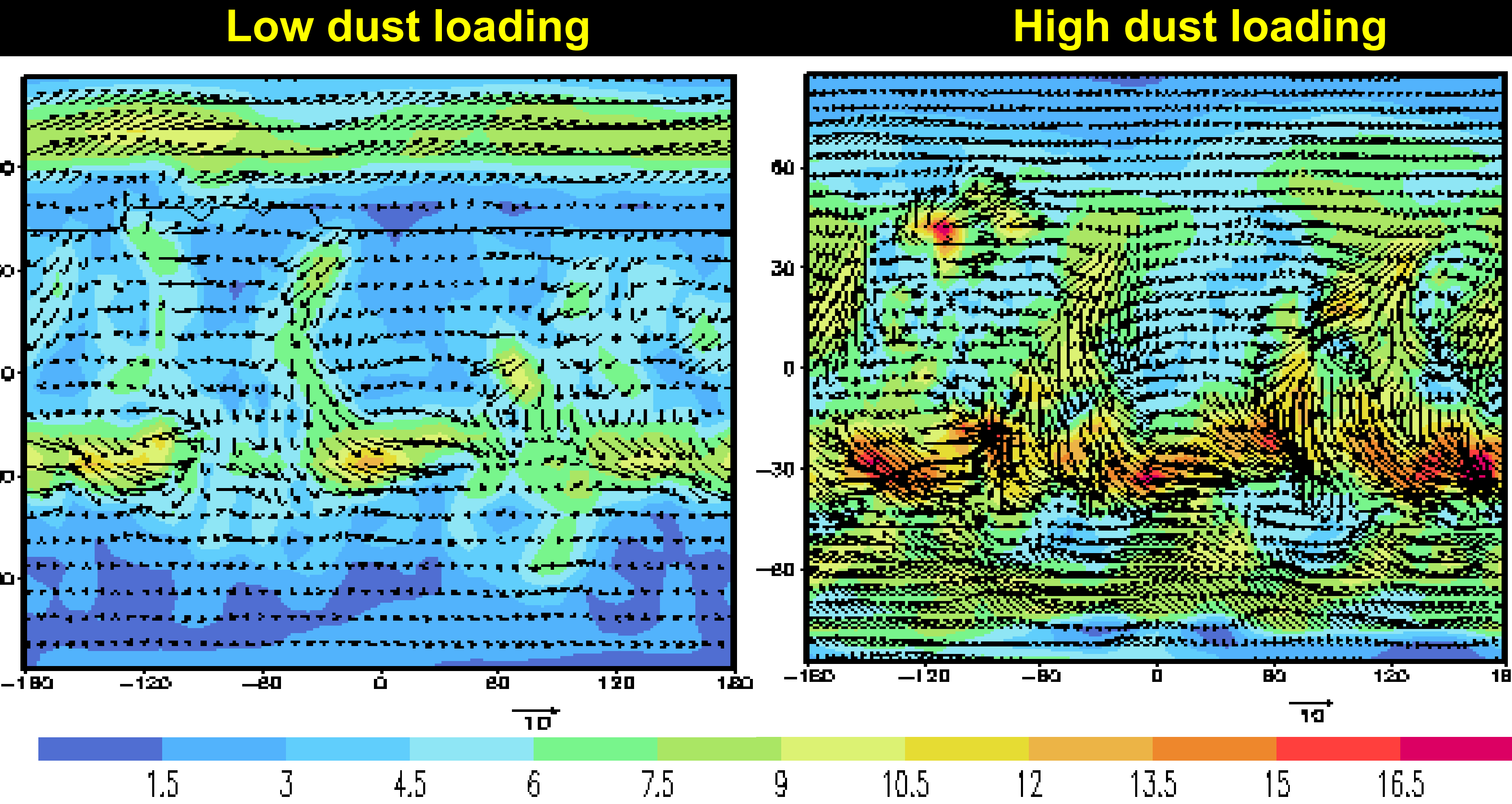


Southern summer: *low* dust levels

Southern summer: *higher* dust levels

- Increased dust levels lead to increased absorption of incoming solar radiation
- Increased heating leads to a strengthening of the Hadley cell
- Stronger Hadley circulation yields increased downwelling over the winter pole, which induces stronger polar warming

...and on surface winds (southern summer)



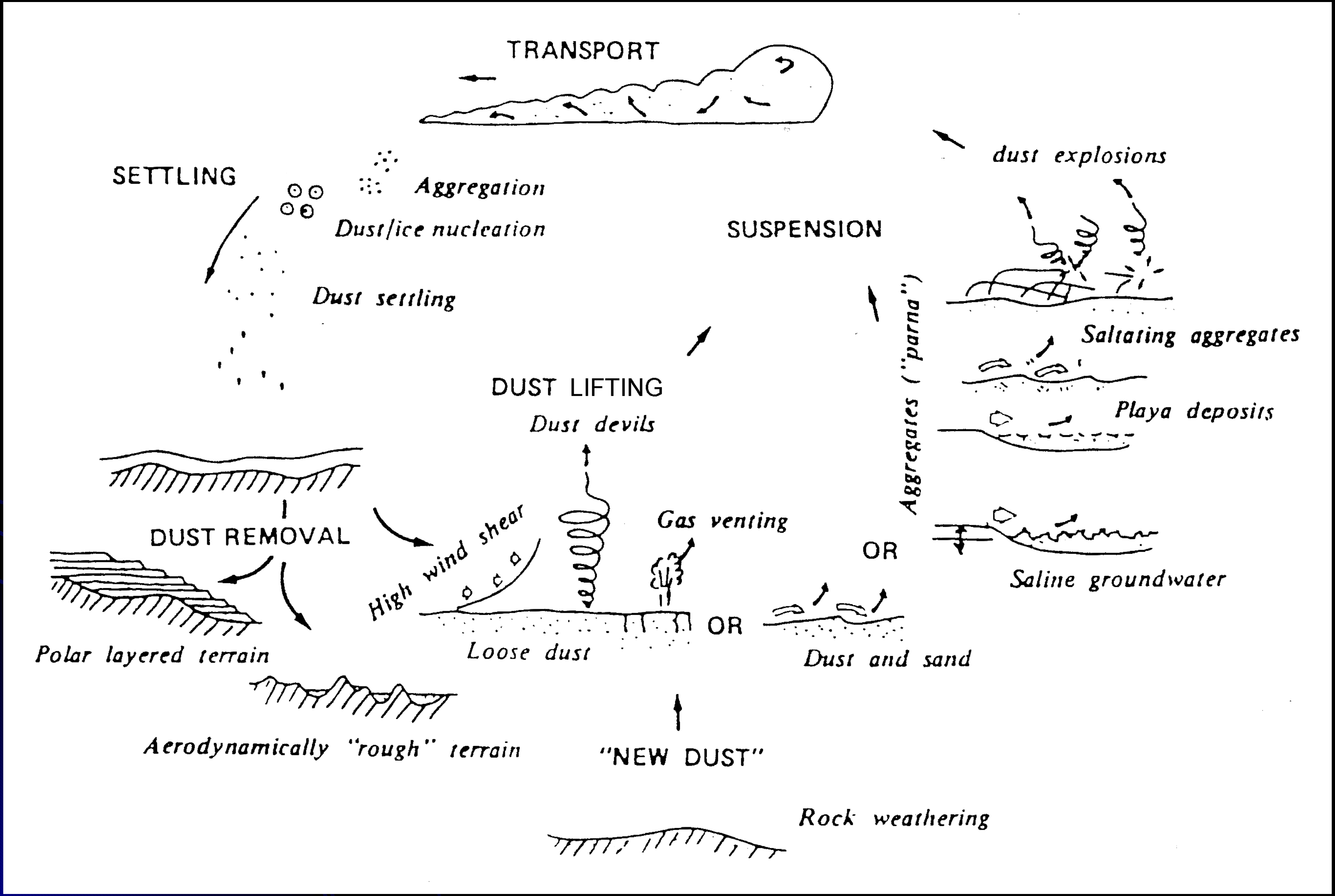
Low dust loading

High dust loading

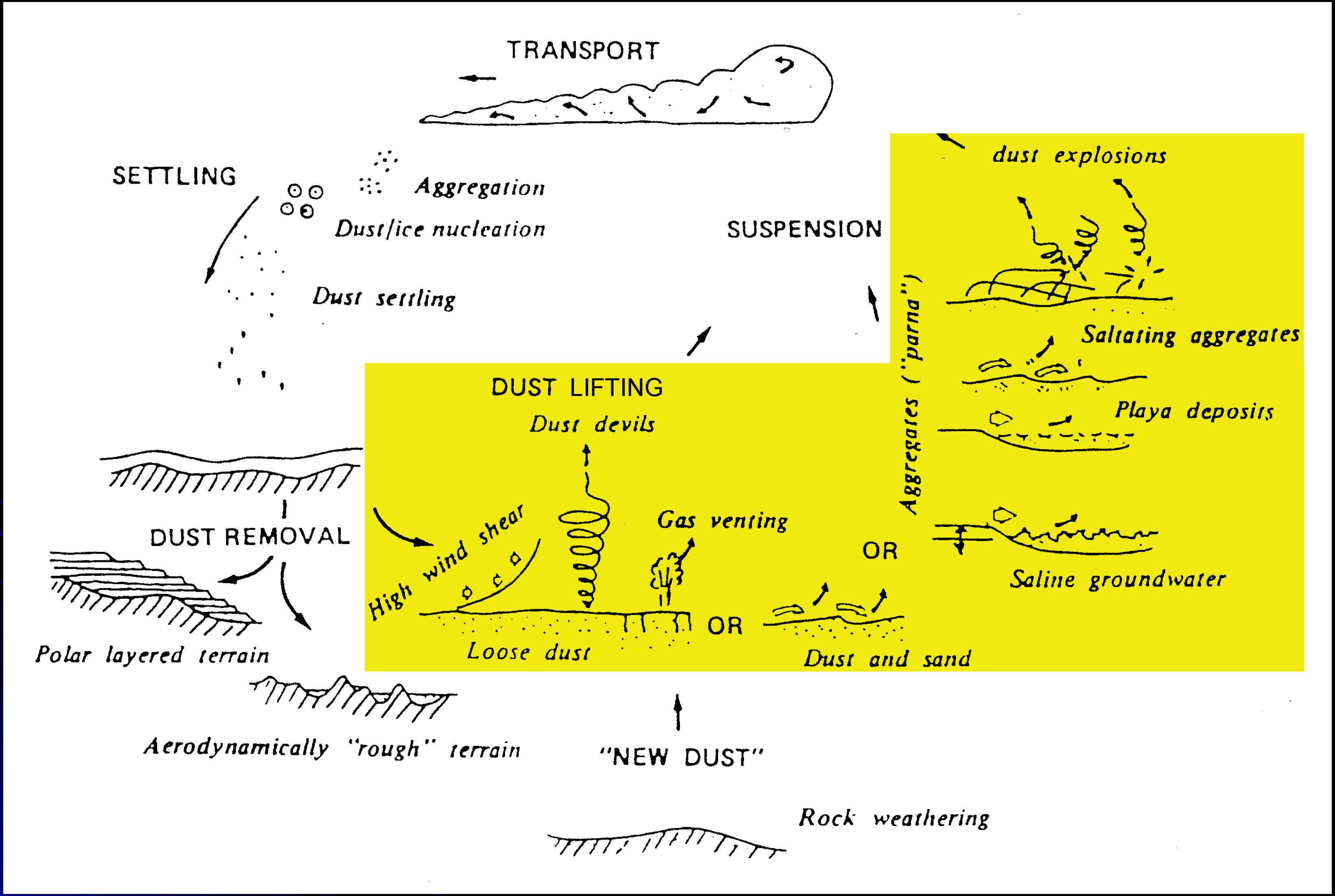
As dust loading increases, so does the strength of flows linked to the main meridional circulation

How does the dust that forms these storms get in the air?

The Dust Cycle



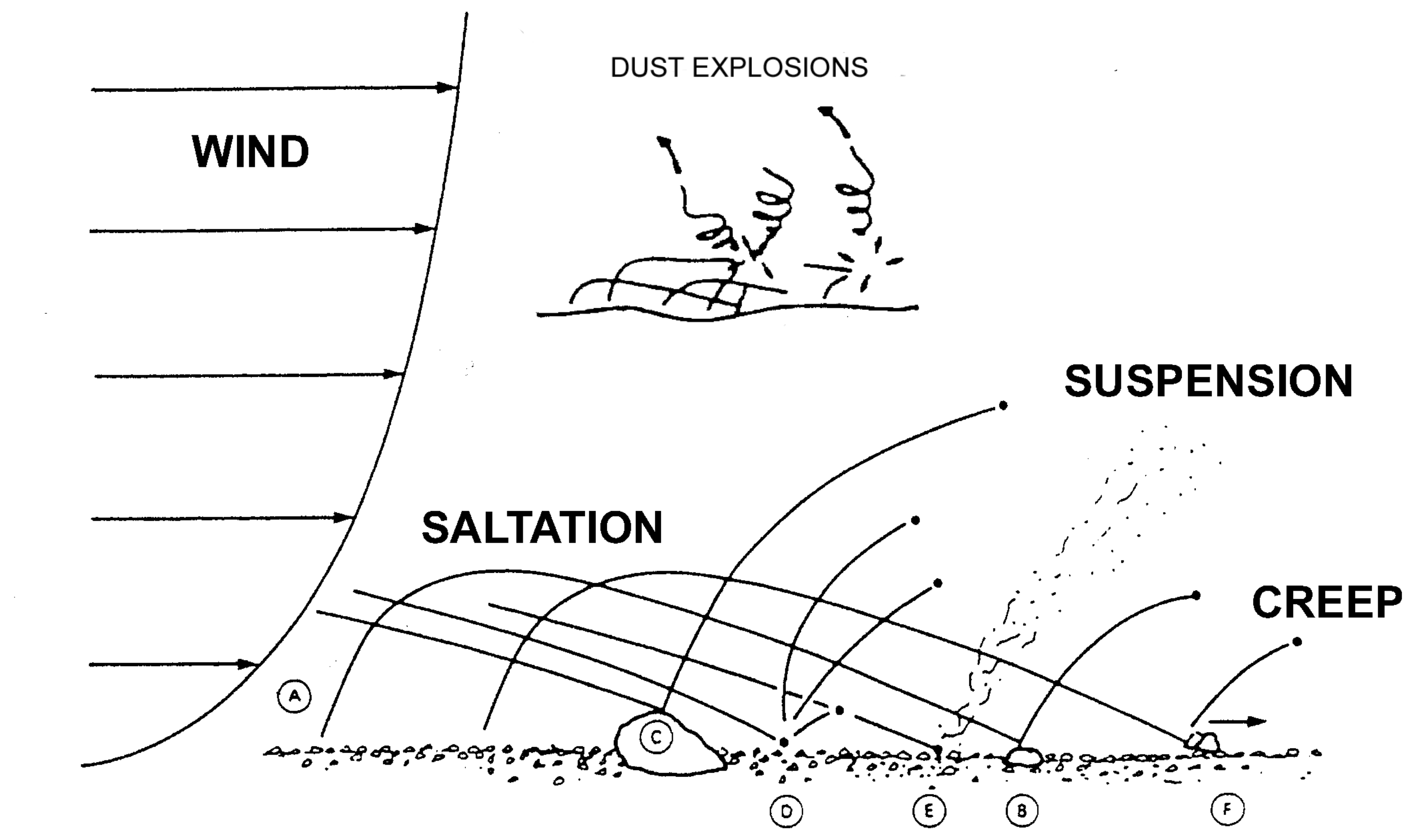
The Dust Cycle



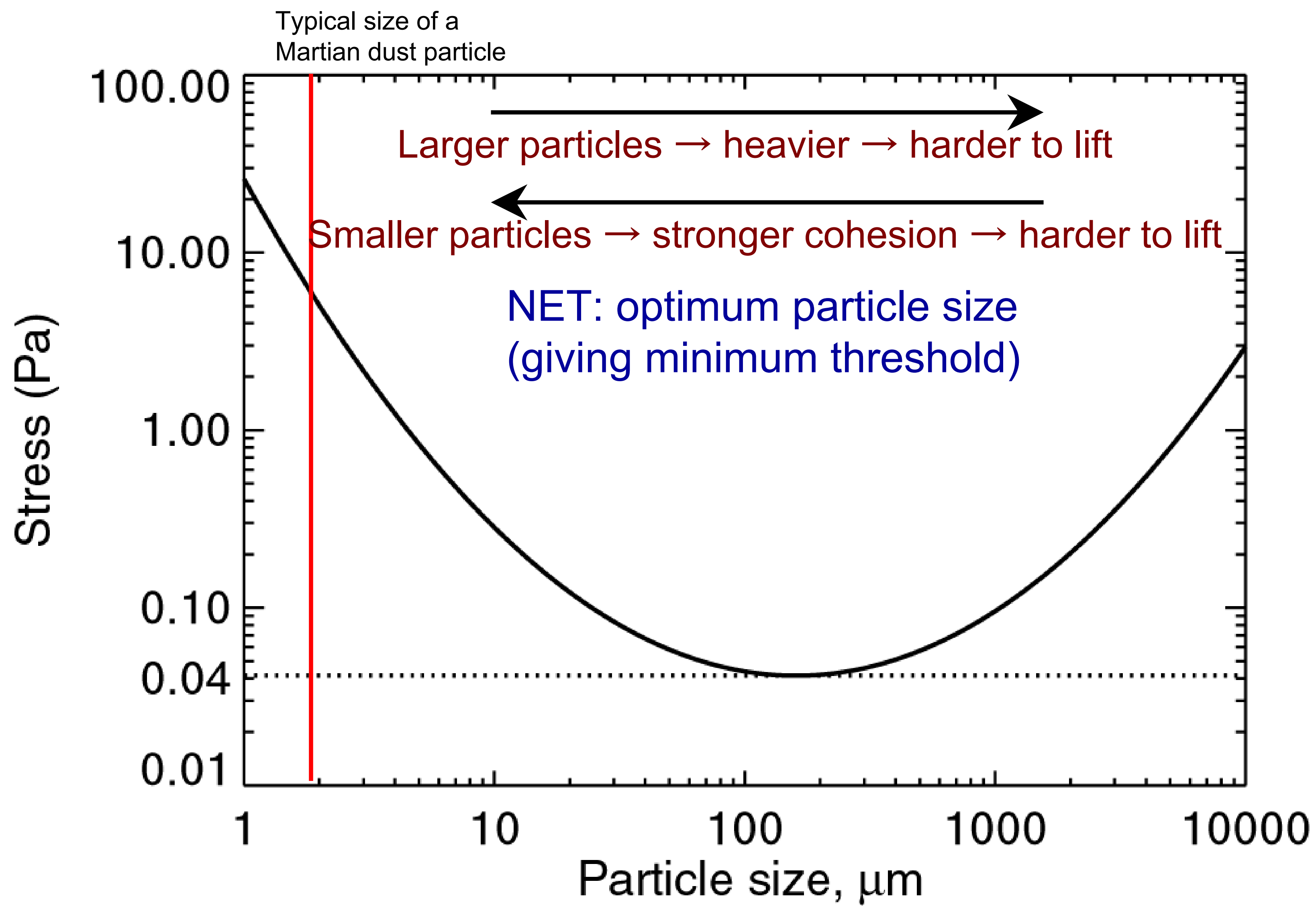
How does dust get in the air?

- Dust fountaining from explosive release of volatiles
- Mobilization by
  - Triggering by sand particles (saltation)
  - Clumping of dust into more easily mobilized particles, which then saltate and break apart in the air by collisional impacts
- Convective vortices (“dust devils”)

Saltation



Threshold Wind Stresses



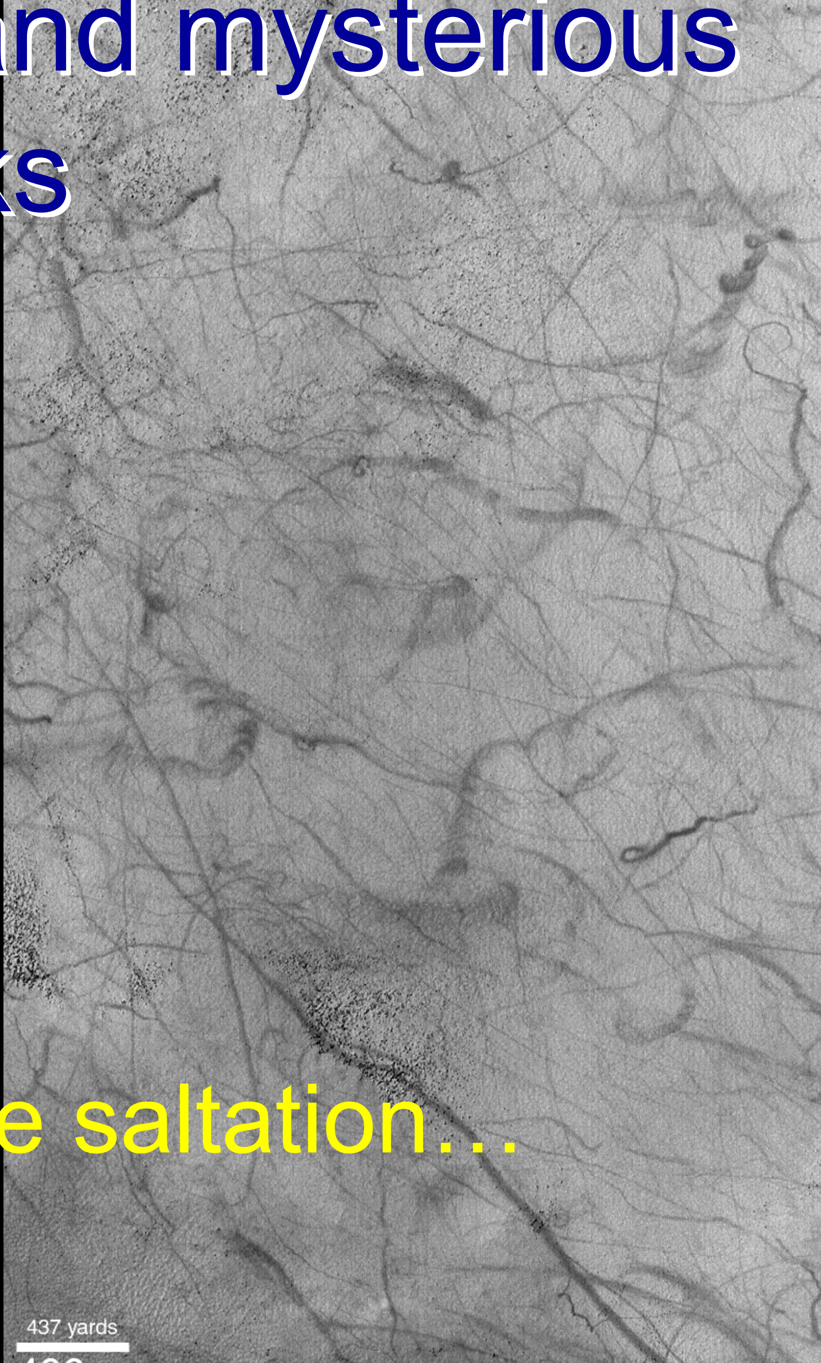
Typical size of a Martian dust particle

Larger particles → heavier → harder to lift

Smaller particles → stronger cohesion → harder to lift

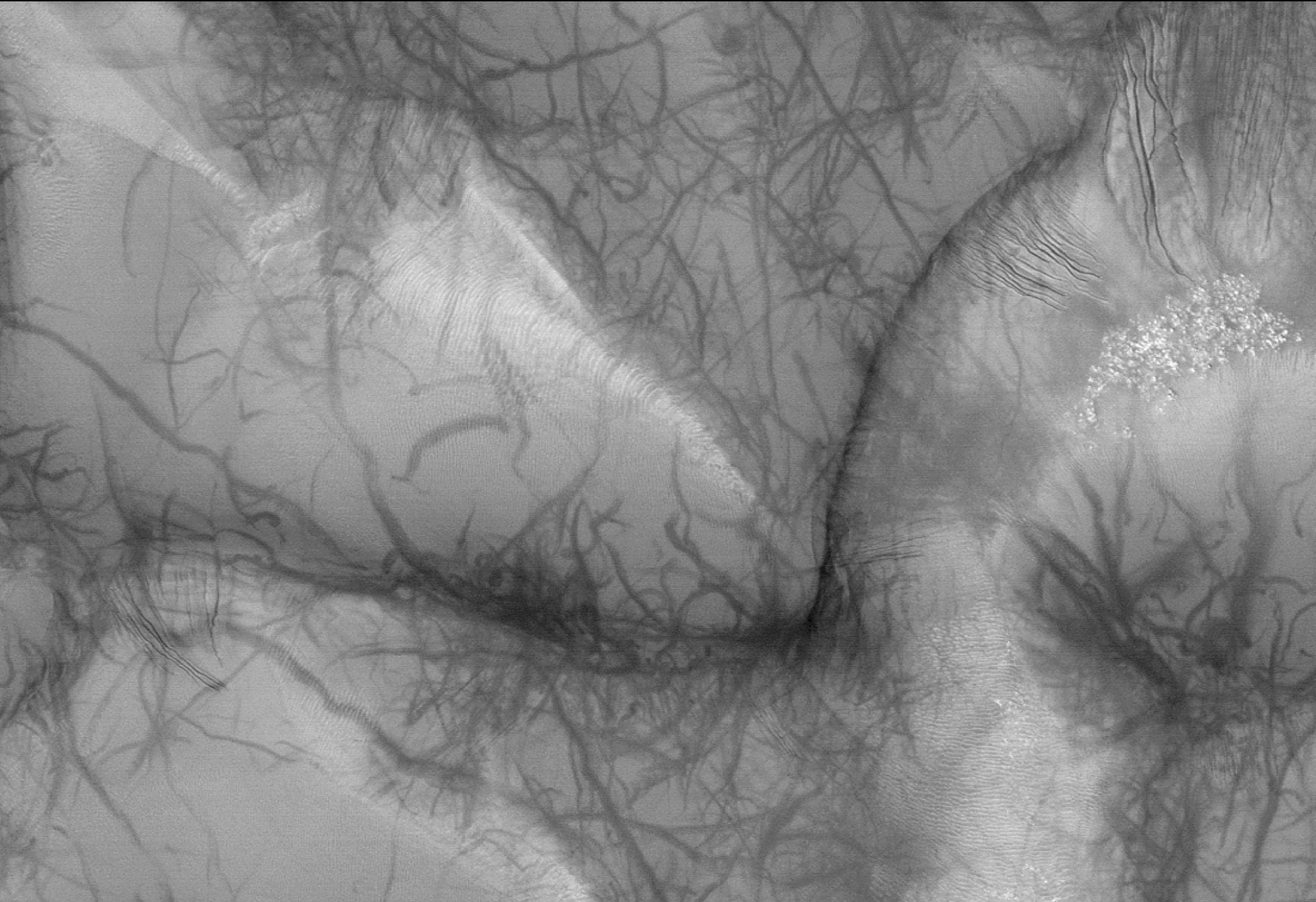
NET: optimum particle size (giving minimum threshold)

Aeolian Erosion and mysterious tracks



Unlikely to be saltation…

Dust Devils!

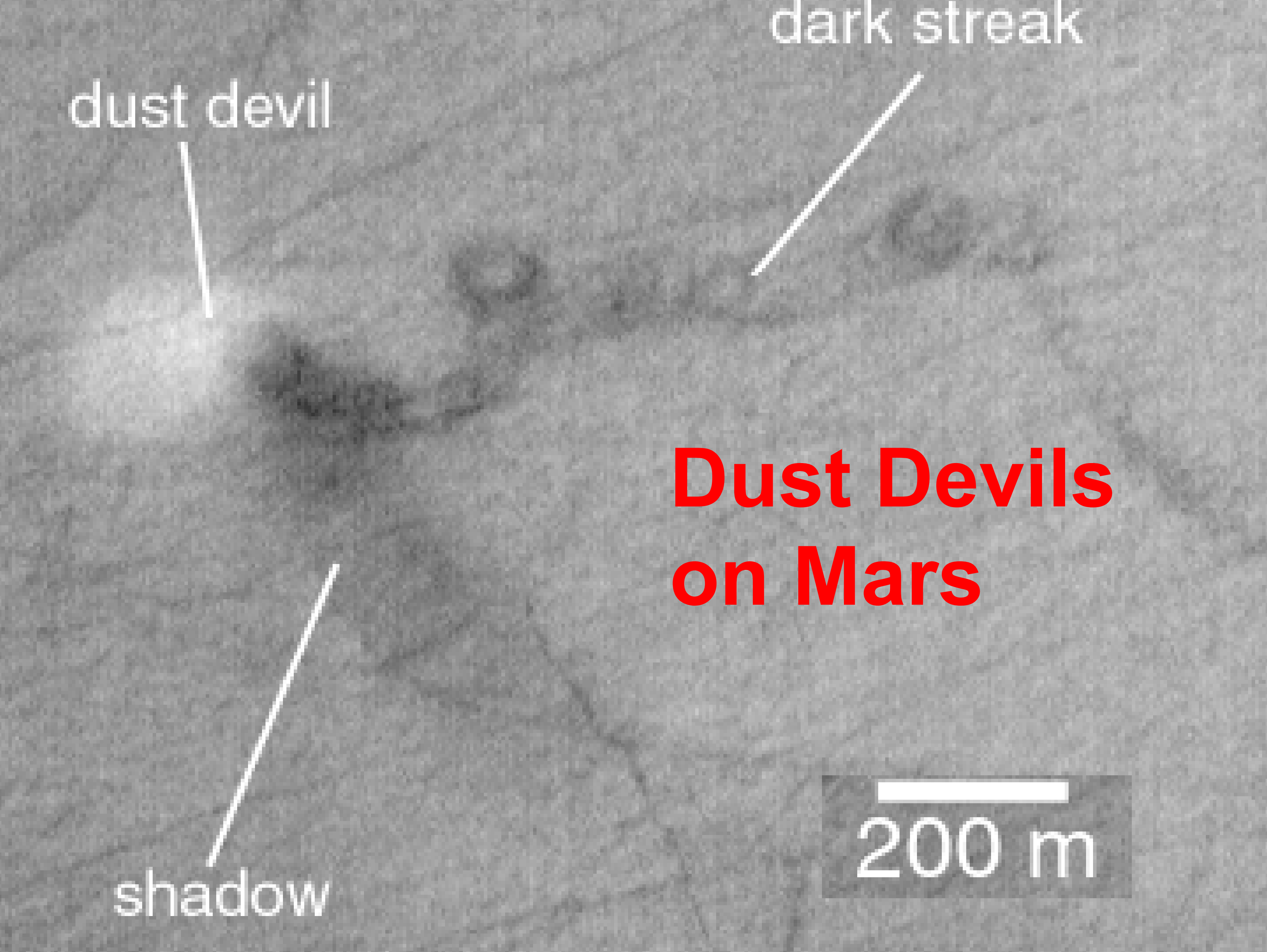


Dust Devils Caught in the Act

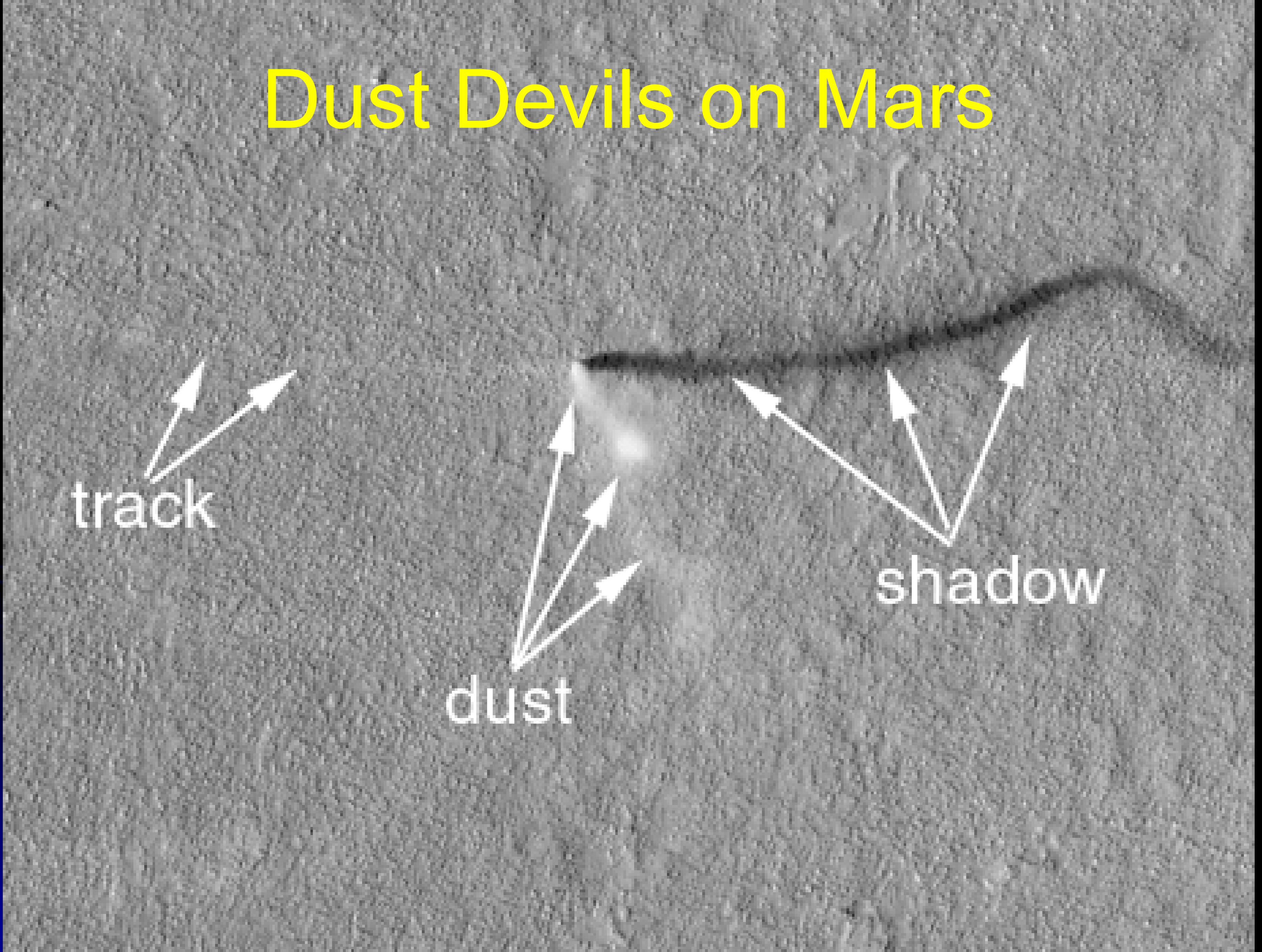
Dust Devils on Earth

Dust Devils on Earth

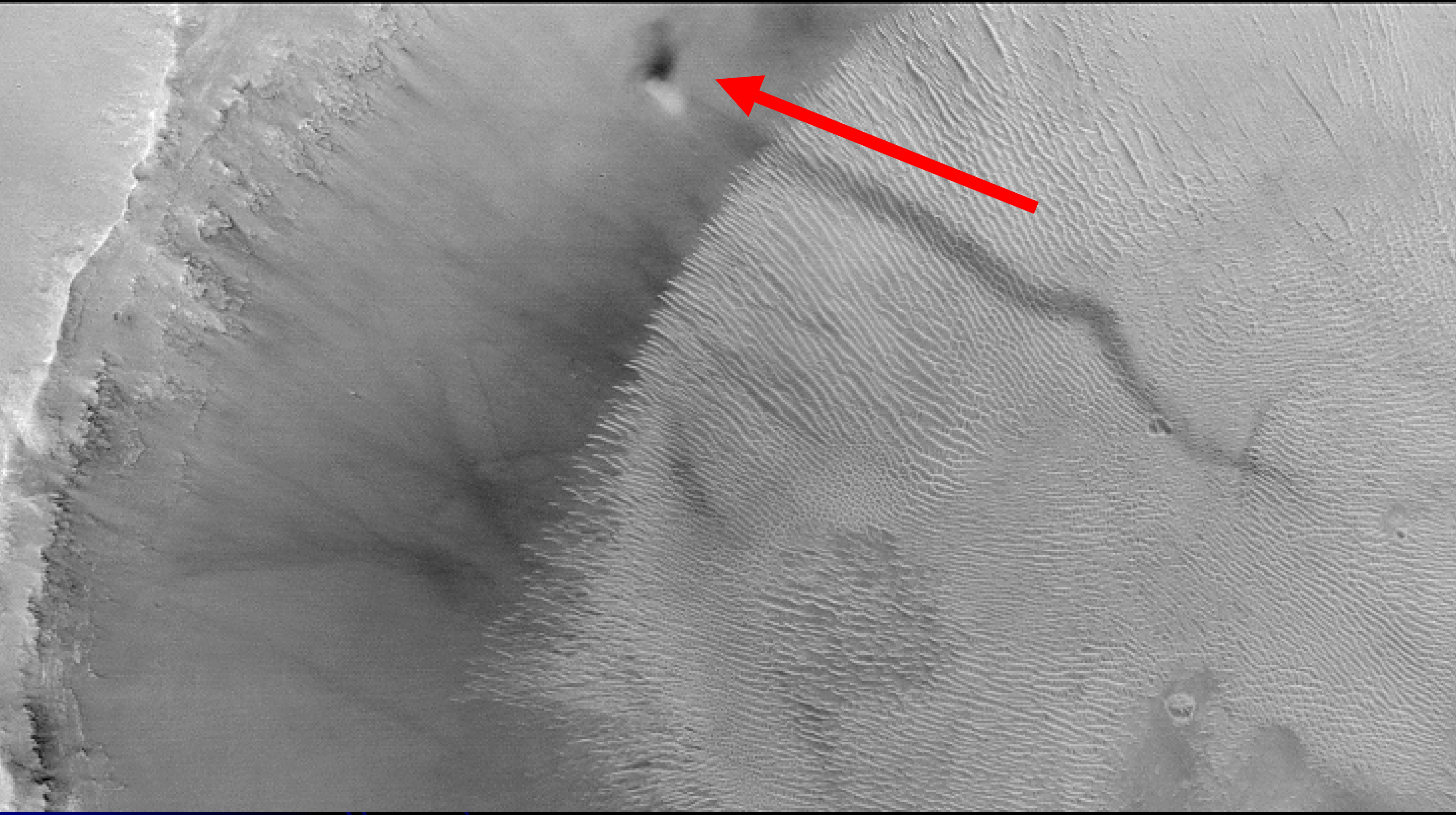
Dust Devils on Mars



Dust Devils on Mars



Dust Devils on Mars



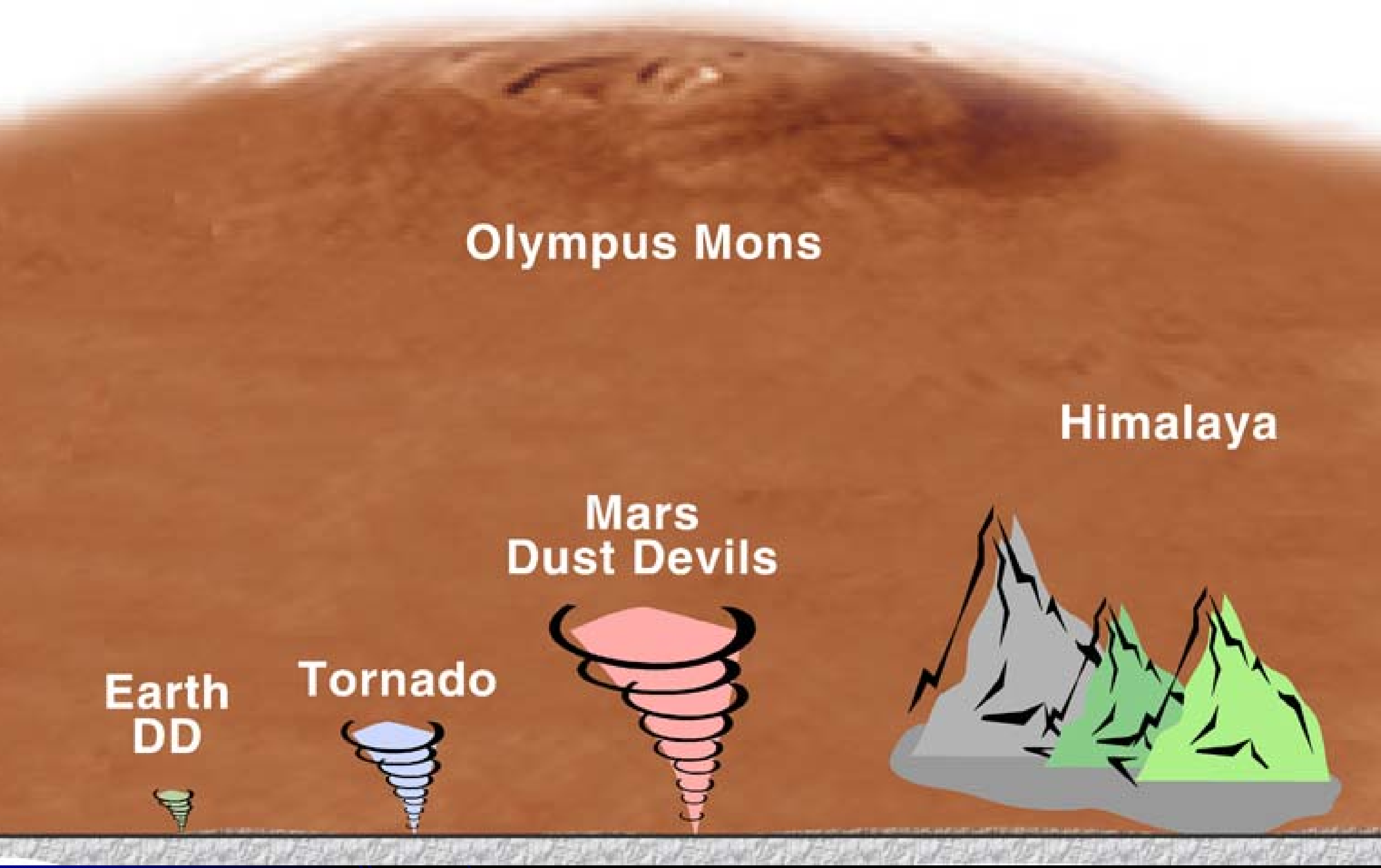
What is a Dust Devil?

- A tornado-like swirling “vortex” or cyclone
- The visible apparition of a vertical wind vortex. Swirling vortices can still arise even when there is no dust to make them visible.

Terrestrial Dust Devil Characteristics

- Wind speeds: 7 – 20 m/s (40 m/s)
- Diameter: 2.5 cm – 300 m
- Height: ≤ 300 m (1.5 km)
- Lifetime: 1 – 30 minutes (≥ 60 minutes)
- Can suck up anything loose it passes over: there are *trash devils*, *snow devils*, *water devils*, and, around fires, even *flame devils*.
- Size of dust devil is directly proportional to the near-surface temperature gradient

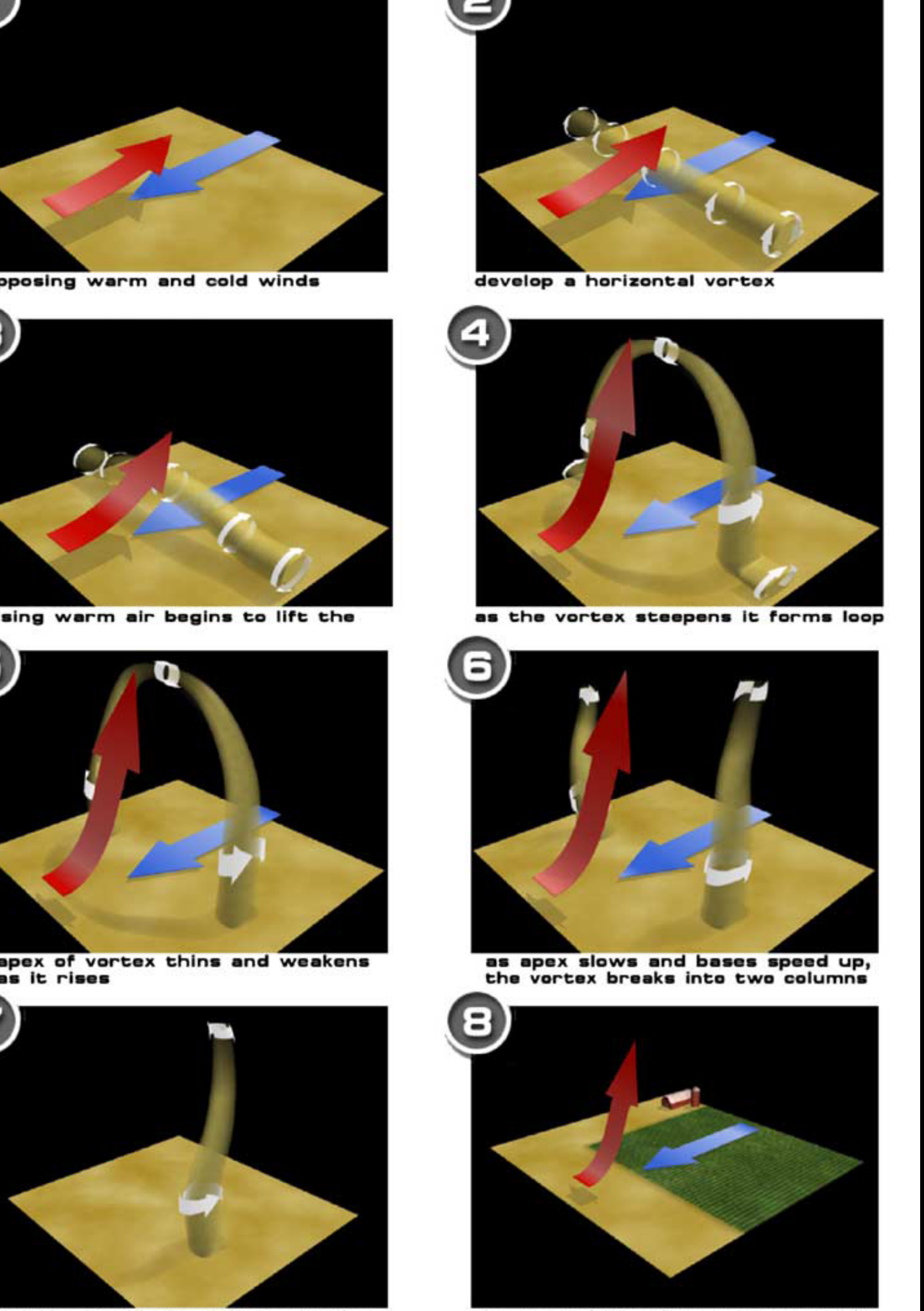
Size Comparison



How do they live and die?

- Air above a particular patch of ground is heated more than the surroundings and rises, pulling in cooler air to replace it.
- If the warm unstable air at the surface that feeds the dust devil becomes depleted, or the air circulation is broken up in some other way (e.g., physical obstacles), the dust devil will break down and dissipate.

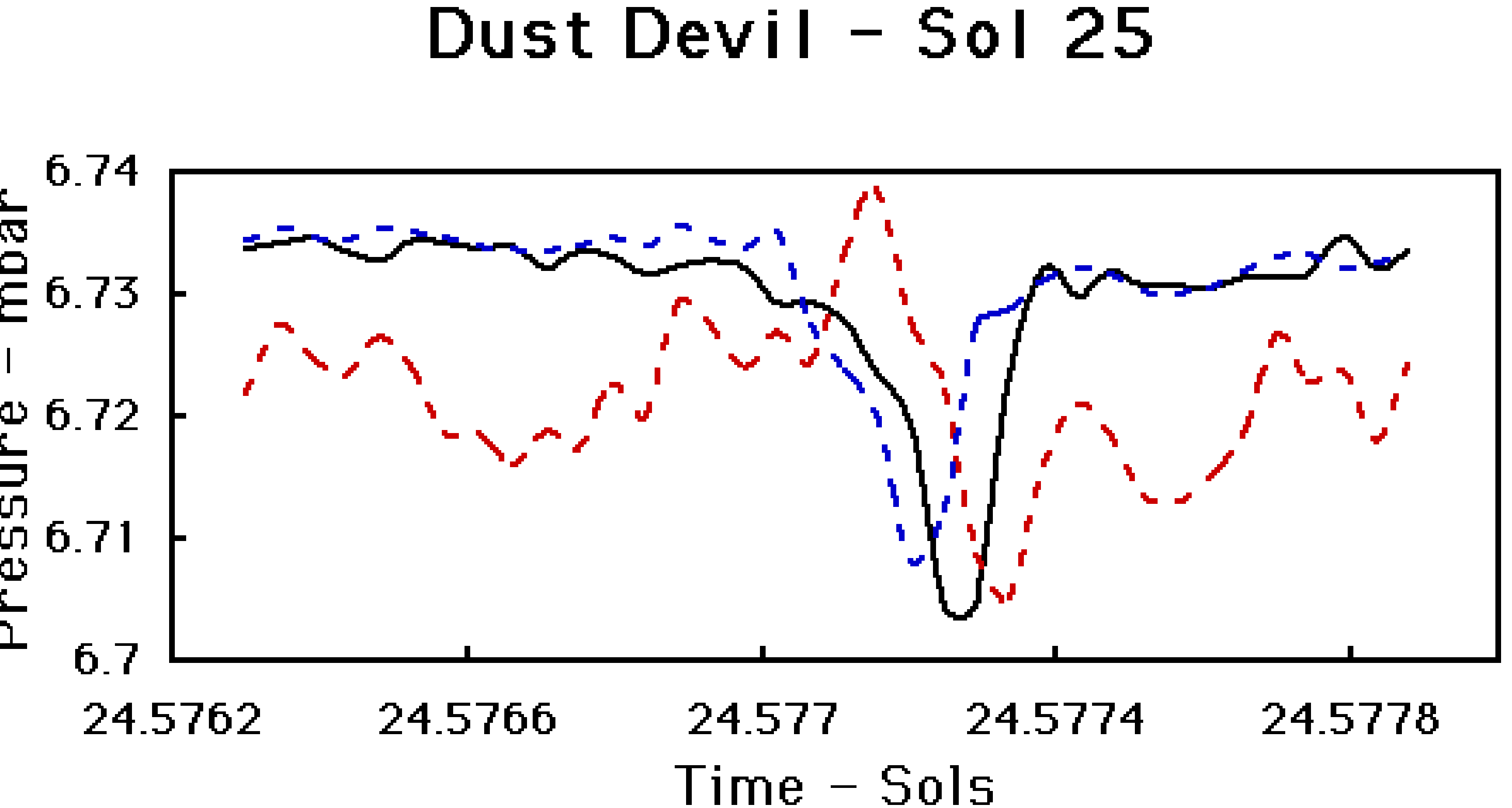
How a dust devil forms



Ability to lift dust

- High tangential speeds
  - Balme et. al (GRL, 2003) measure surface stresses from terrestrial dust devils at 1-7 Pa
  - Compare with earlier graph
- Low pressure core
  - Means there is a vertical pressure gradient from air right at surface (same as ambient air pressure) and lower pressure in devil core; provides a vertically upward force to lift dust
  - Difficult to quantify due to interparticle cohesive forces (opposes lift)

Low Pressure Core of Dust Devil



Terrestrial Pollution

In arid to semiarid regions of the U.S., in particular the Great Basin, the Desert Southwest, and western Texas, dust devils are now considered to be a large reason that some communities exceed EPA limits on 2.5 and 10 μm particulates. A single dust devil may be responsible for lifting and transporting several hundred kilograms of sand, dust, and debris. A particular local region may have several tens, or hundreds, of dust devils develop in a day.

Electromagnetic Fields

- Swirling particles rubbing against each other exchange electrons. Dust particles gain electrons, while heavier particles such as sand lose electrons. Since the sand is flung out, the dust devil ends up with a negative charge overall – roughly 10 kV/m, but with almost no current.
- On Earth, it takes an electric field of 3000 kV/m to generate lightning.
- On Mars, the thin atmosphere requires only 20 kV/m to generate lightning.

Summary: Mars & Earth

- Similarities
  - rotation rate
  - obliquity
  - convection and boundary layer behavior
  - water clouds
  - Hadley circulation and jets
- Differences
  - dust vs. water as prime weather source
  - Moderate vs. extreme diurnal temperature cycles
  - Condensation of main atmospheric constituent leading to annual pressure cycle
  - eccentricity of orbit

THE END