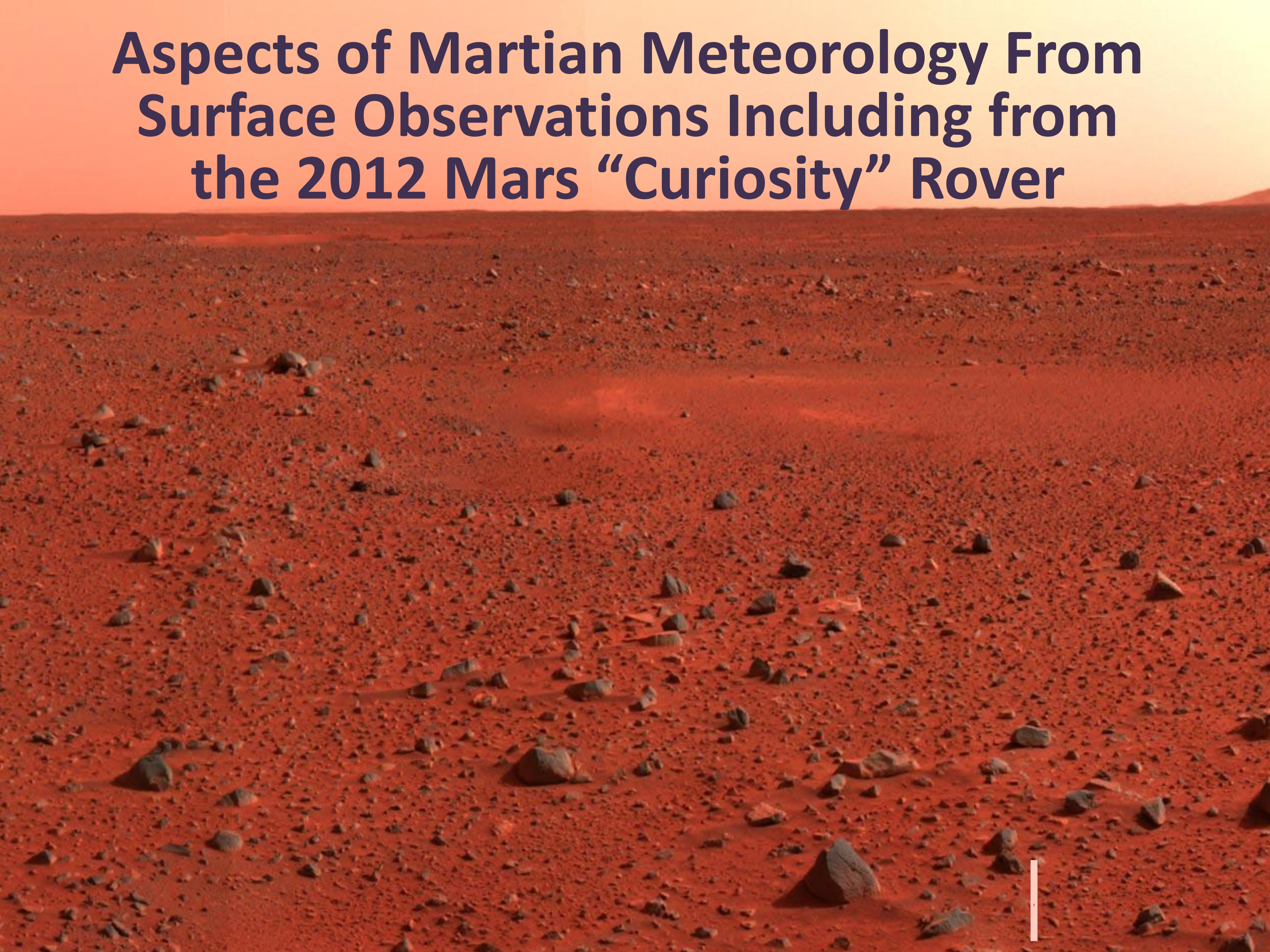
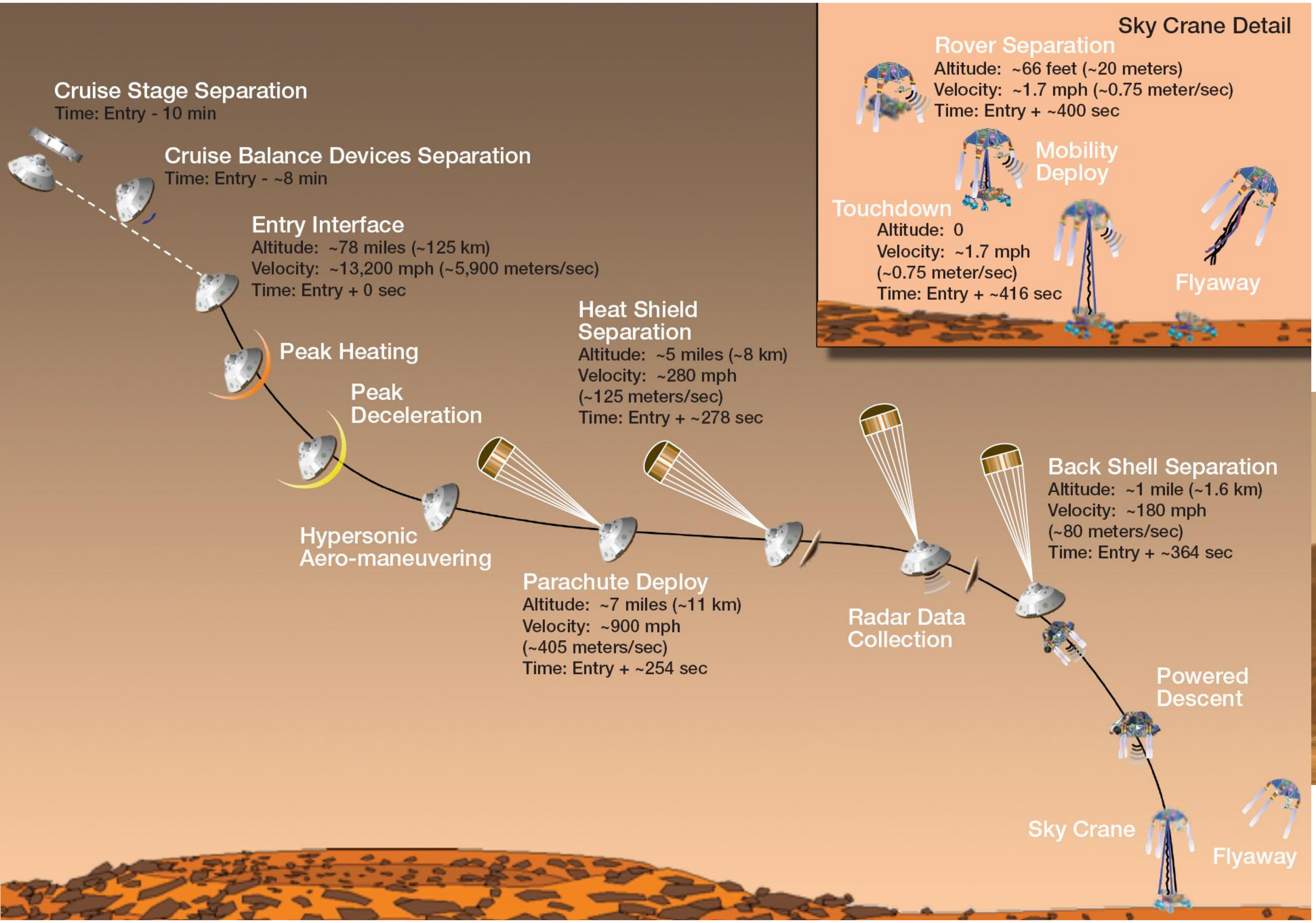
Aspects of Martian Meteorology From Surface Observations Including from the 2012 Mars “Curiosity” Rover

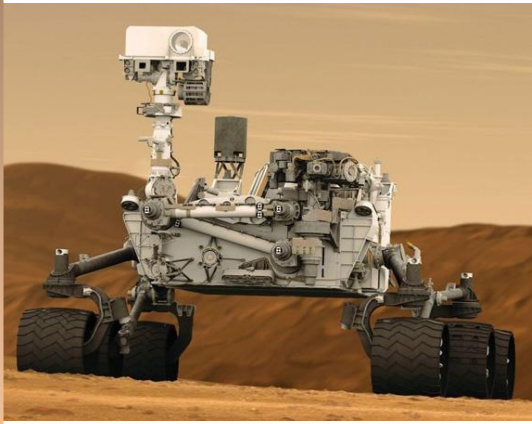


Mars Science Laboratory *Curiosity*

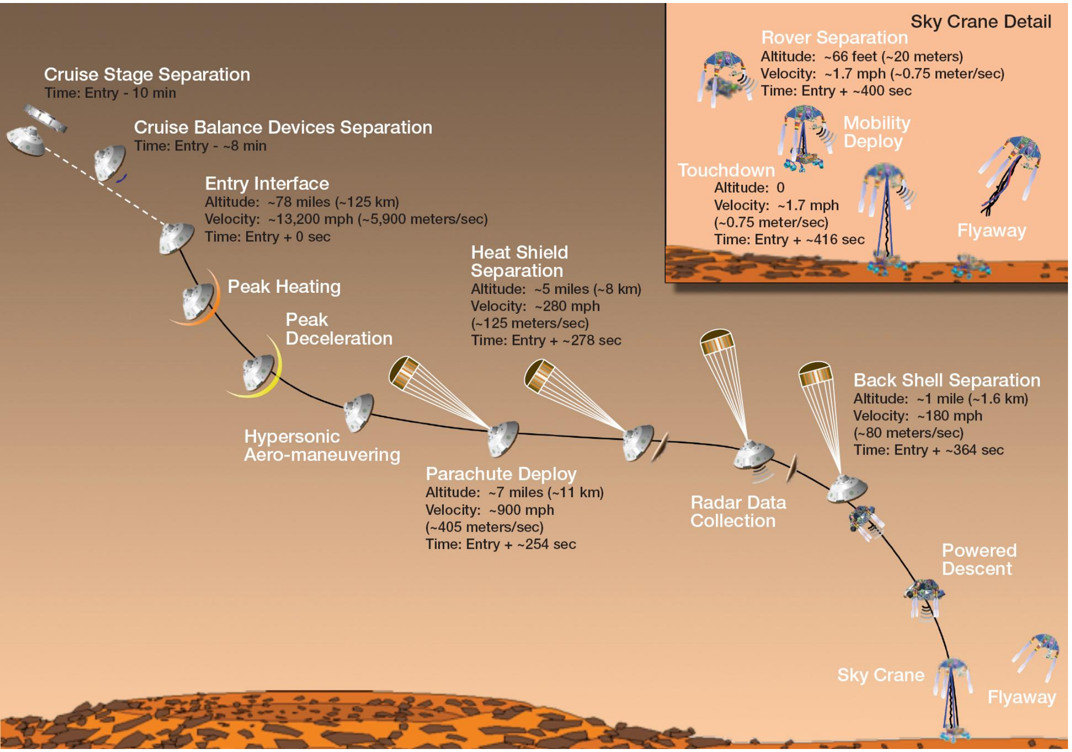
The *"Curiosity"* rover in clean room at JPL

Mars Science Laboratory *Curiosity*





Mars Science Laboratory *Curiosity*

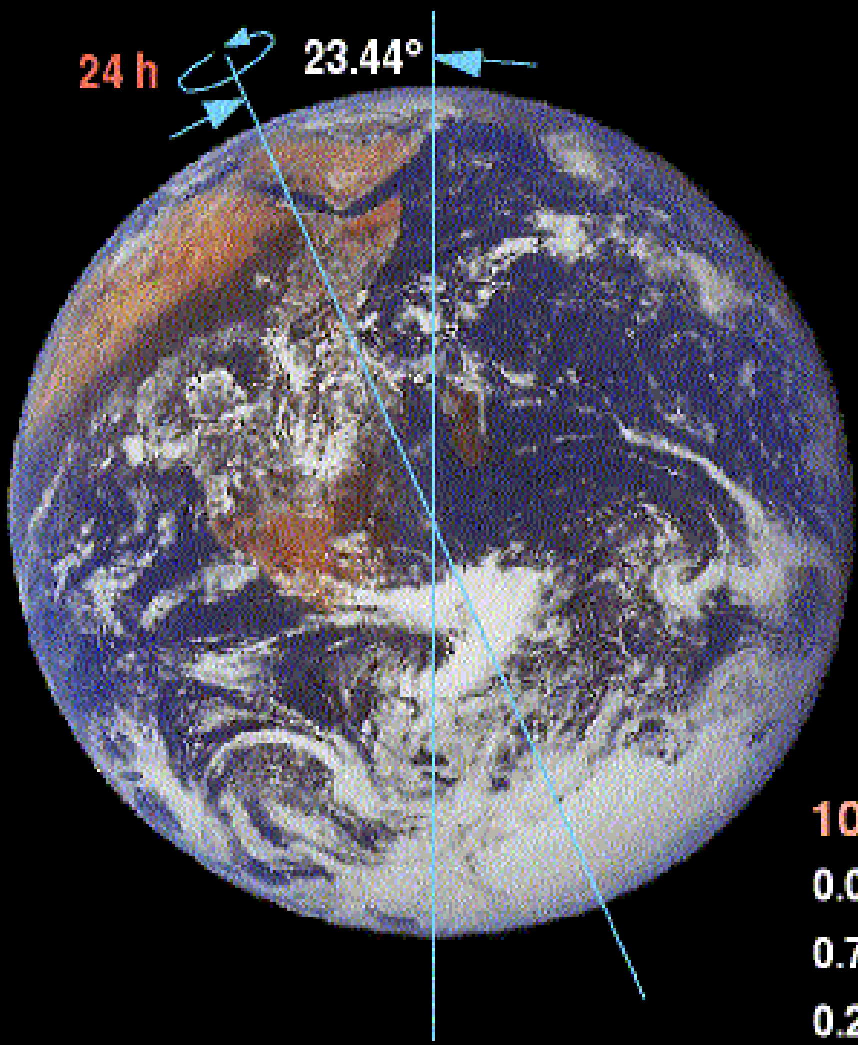


Mars Science Laboratory *Curiosity*

Outline

- Basics – orbit, topography, atmospheric composition
- Basics – dust, dust everywhere
- History of Mars planetary missions 1962-today
- Satellite measurments of atmospheric temperature
- Surface T, P and u,v observations
- Pressure record – annual cycle, baroclinic waves
- Pressure record – diurnal variations (atmospheric tides)
- Mars General Circulation Models (GCMs)
- Model simulations of atmospheric tides
- I am curious about *Curiosity*!

EARTH	COMPARISON	MARS



YEAR

365 Days		686 Days (667 Sols)

GRAVITY

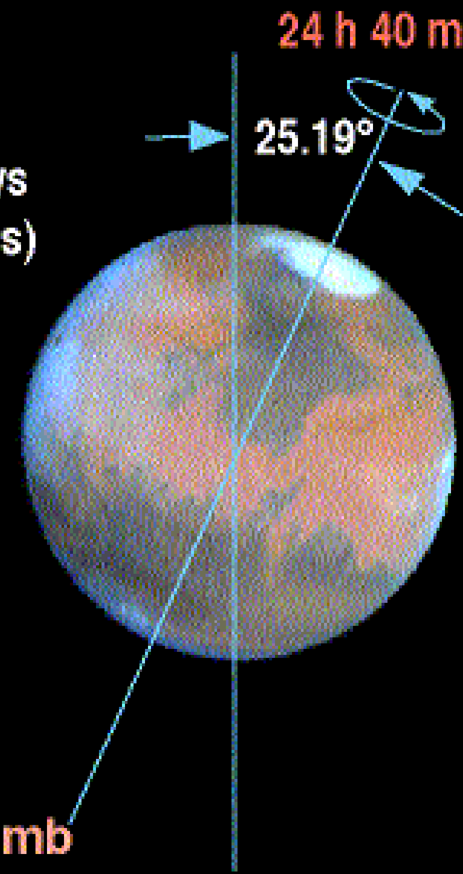
38% of earth

SUNLIGHT

44% of earth

ATMOSPHERE

1013mb	Total	7.6 mb
0.00035	CO_2	0.95
0.781	N_2	0.027
0.210	O_2	0.0013
0 to 0.04	H_2O	0 to 0.00021
0.0093	Ar	0.016

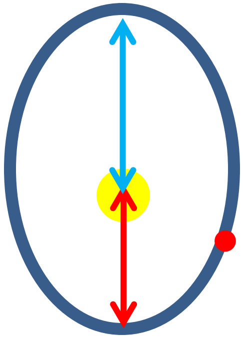


Mars orbit and annual cycle

- Measure time through the year (or position through the orbit) by L_s ("Areocentric longitude") (defined so that $L_s=0^o$ is NH spring equinox "March 21")

- Aphelion 249,209,300 km

- Perihelion 206,669,000 km



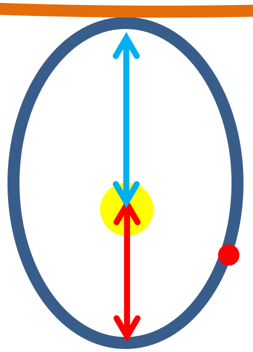
- L_s of perihelion 250^o - late SH spring

Mars orbit and annual cycle

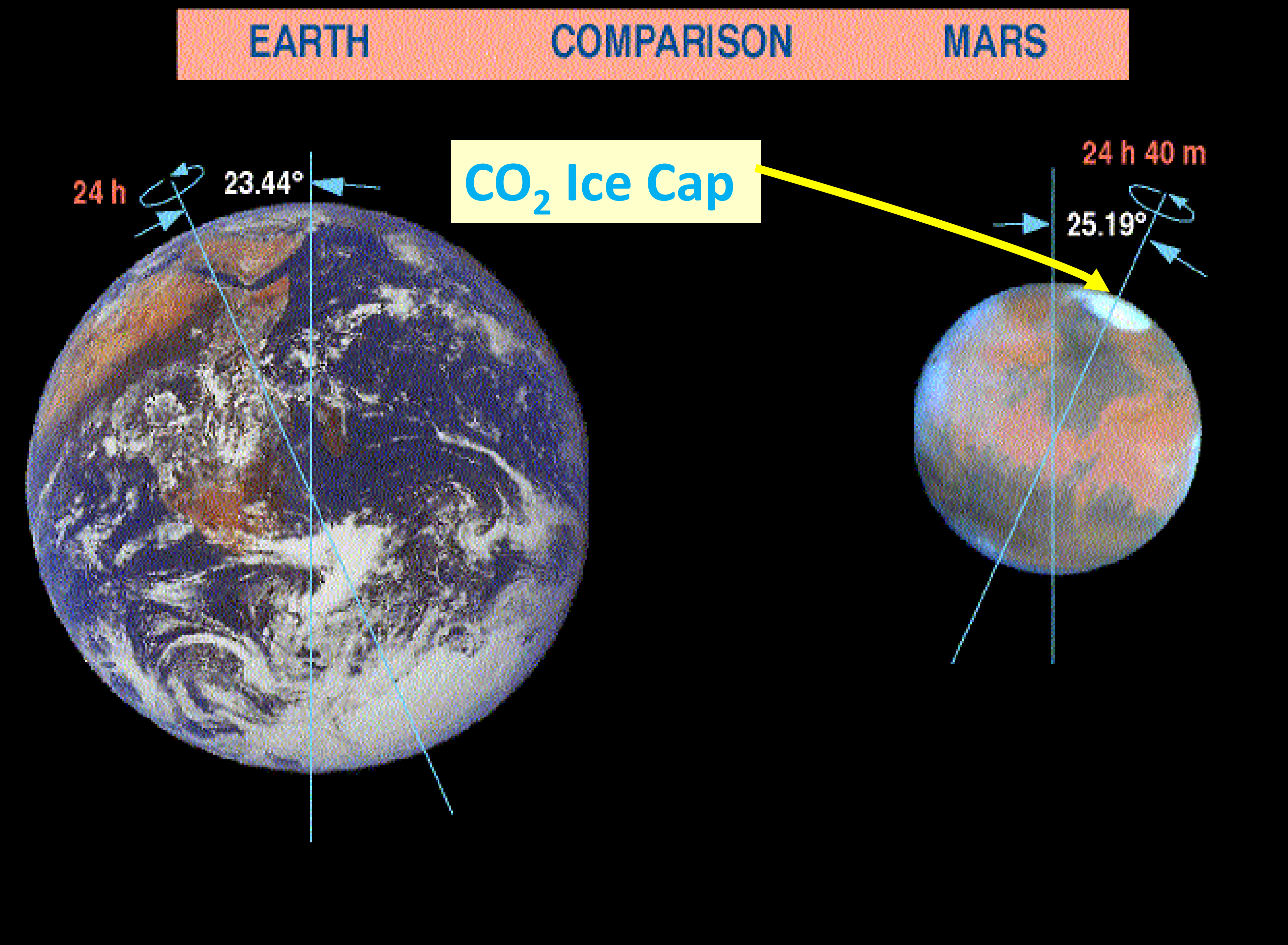
- Measure time through the year (or position through the orbit) by L_s ("Areocentric longitude") (defined so that $L_s=0^o$ is NH spring equinox "March 21")

$R_a^2/R_p^2 = 1.42$ (vs. 1.07 for Earth)

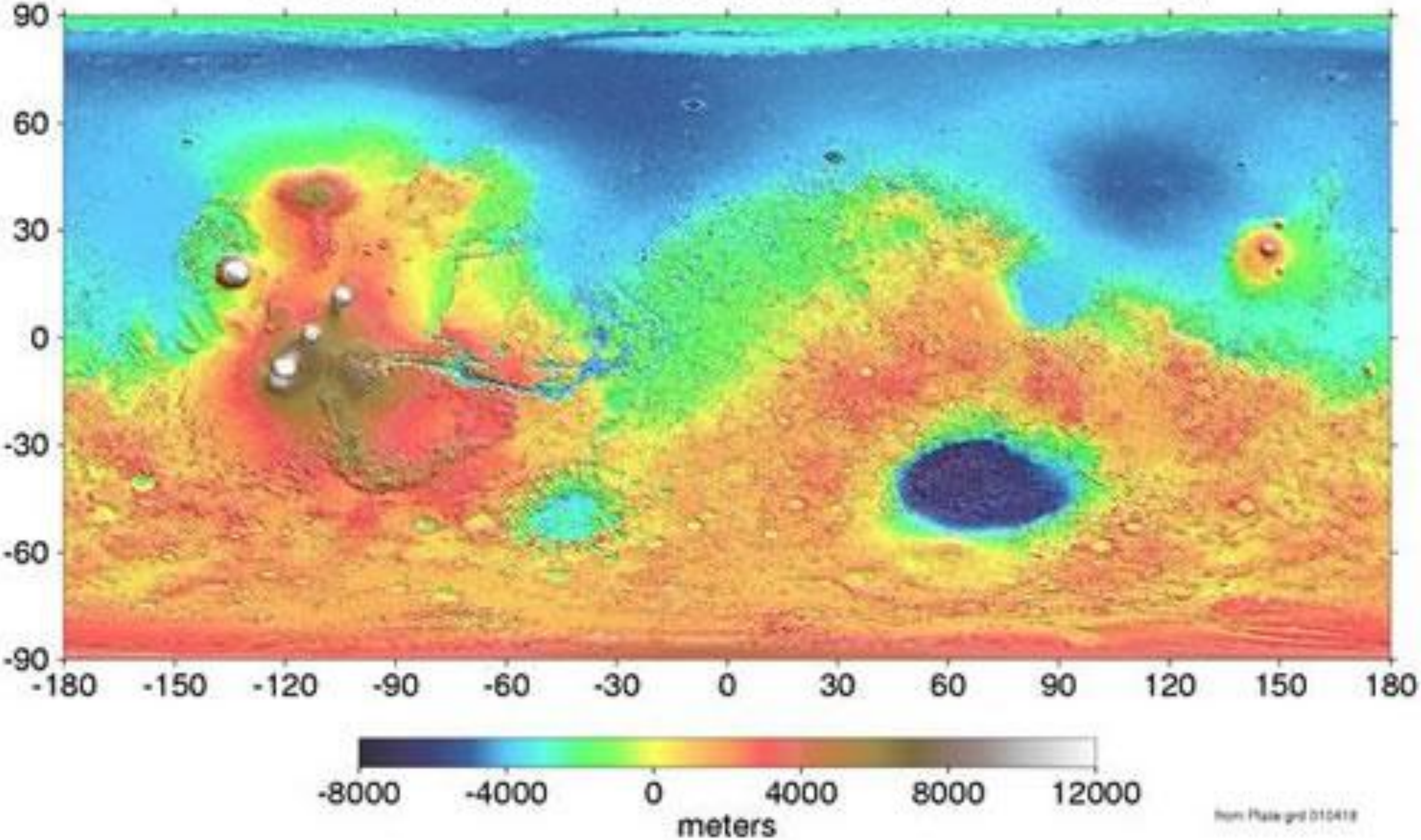
- Aphelion 249,209,300 km
- Perihelion 206,669,000 km

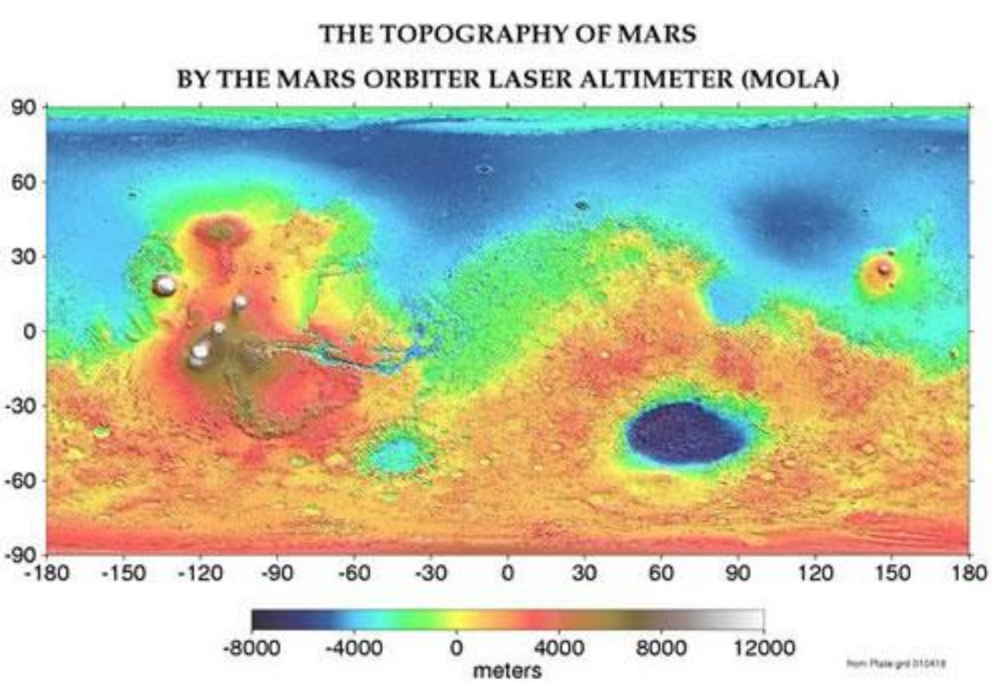


- L_s of perihelion 250^o - late SH spring

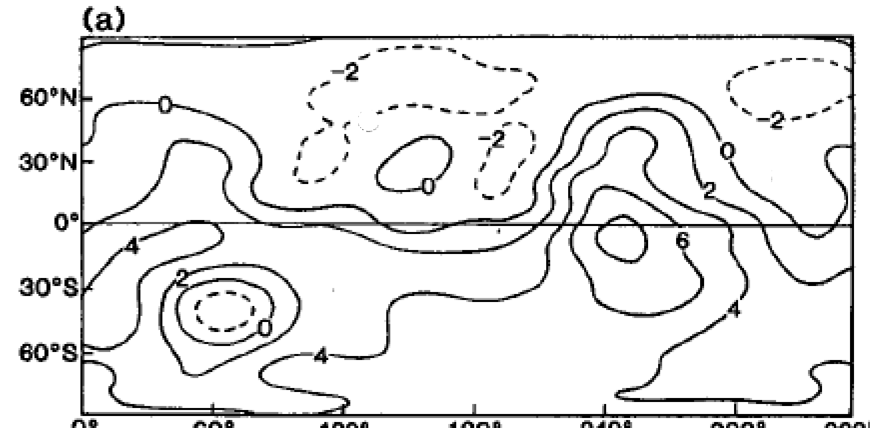

EARTH
COMPARISON
MARS
24 h
23.44°
CO2 Ice Cap
24 h 40 m
25.19°

THE TOPOGRAPHY OF MARS
BY THE MARS ORBITER LASER ALTIMETER (MOLA)



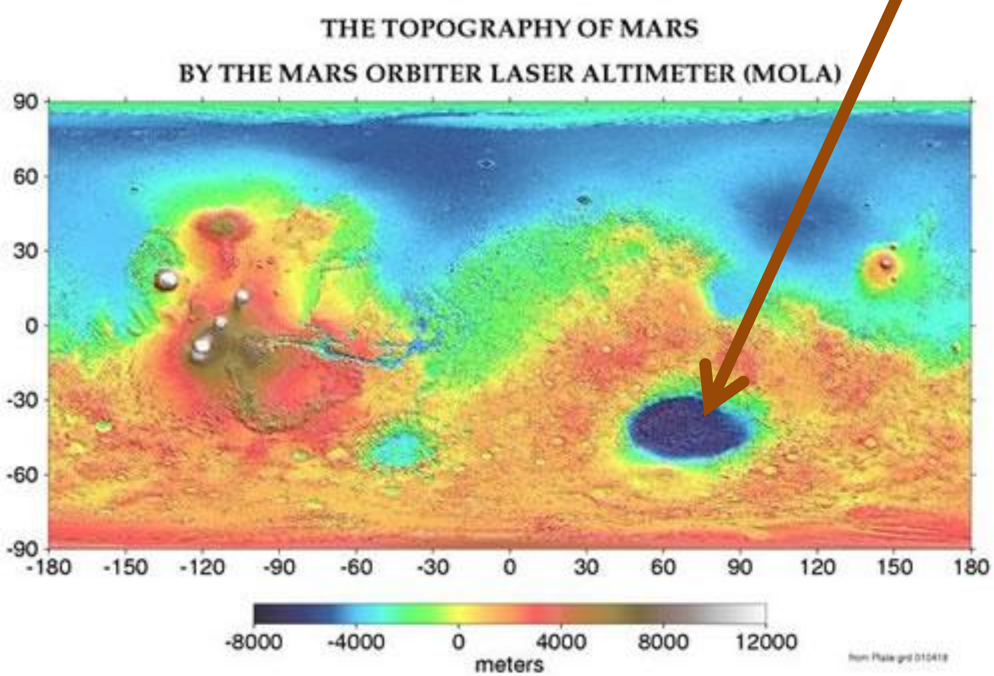


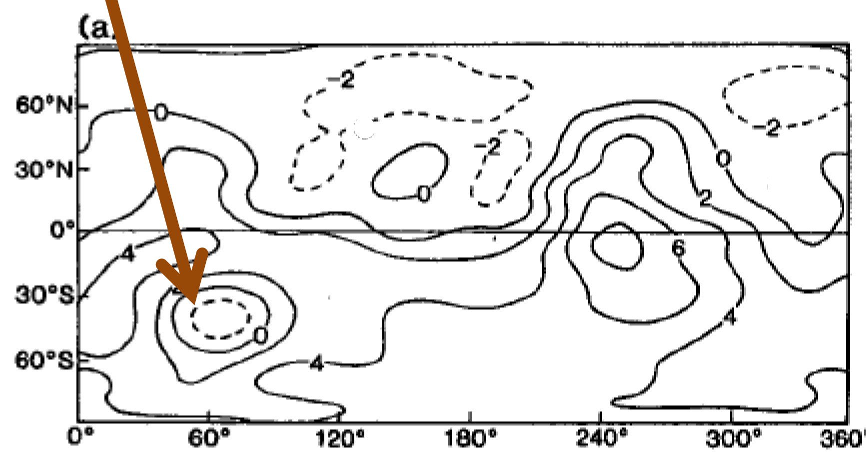
THE TOPOGRAPHY OF MARS
BY THE MARS ORBITER LASER ALTIMETER (MOLA)
90
60
30
0
-30
-60
-90
-180
-150
-120
-90
-60
-30
0
30
60
90
120
150
180
-8000
-4000
0
4000
8000
12000
meters

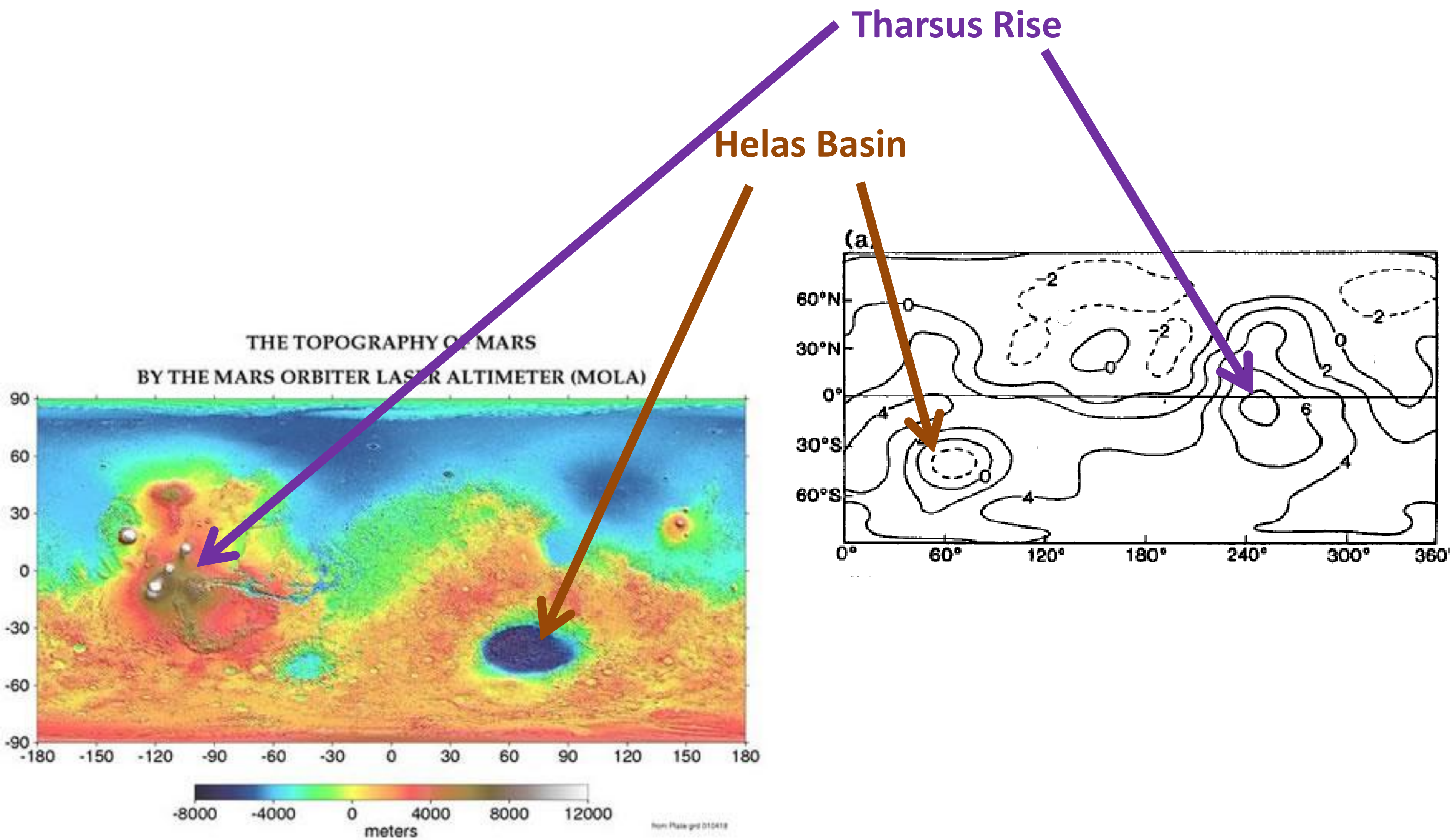


(a)
60°N
30°N
0°
30°S
60°S
0°
60°
120°
180°
240°
300°
360°
-2
0
2
4
6

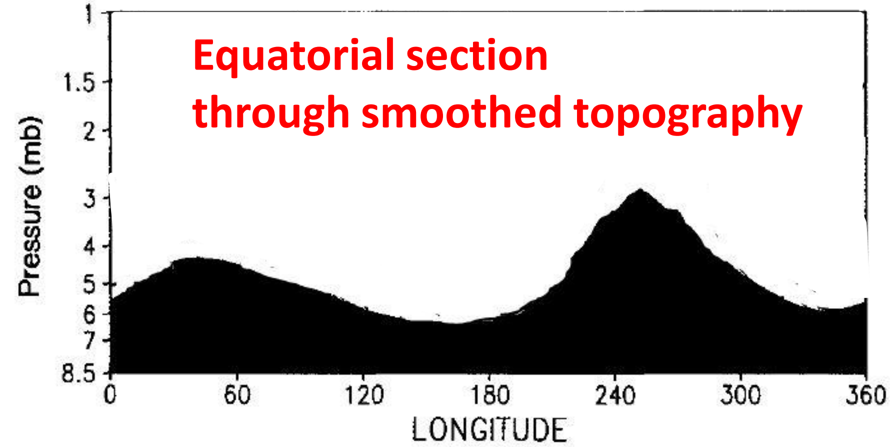
Helas Basin

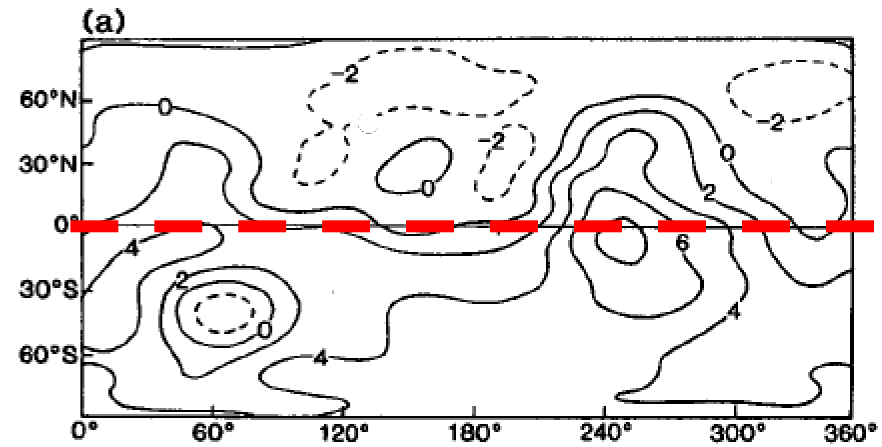

THE TOPOGRAPHY OF MARS
BY THE MARS ORBITER LASER ALTIMETER (MOLA)
90
60
30
0
-30
-60
-90
-180
-150
-120
-90
-60
-30
0
30
60
90
120
150
180
-8000
-4000
0
4000
8000
12000
meters


(a)
60°N
30°N
0°
30°S
60°S
0°
60°
120°
180°
240°
300°
360°
-2
0
2
4
6



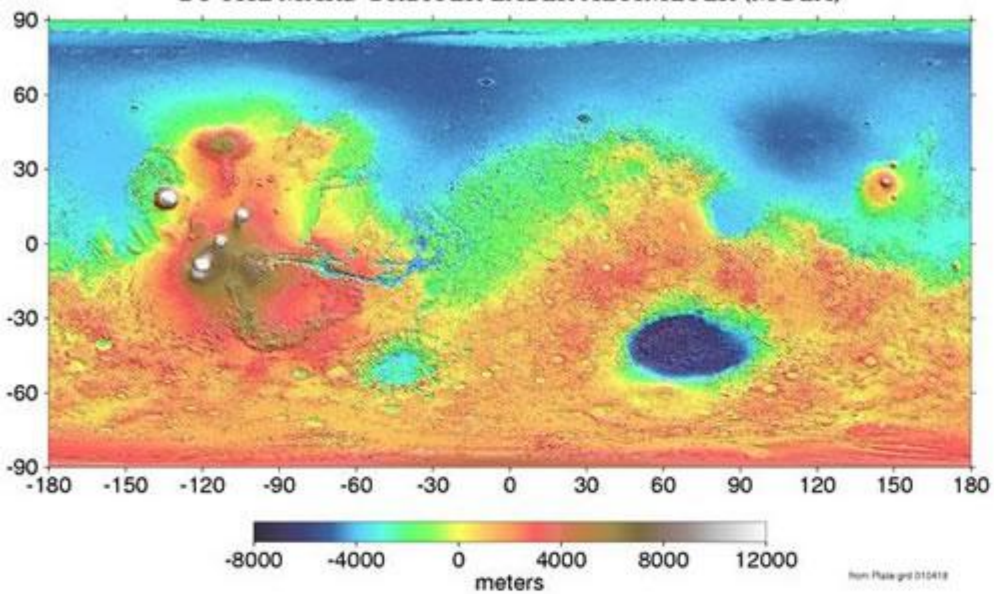
Tharsus Rise
Helas Basin
THE TOPOGRAPHY OF MARS
BY THE MARS ORBITER LASER ALTIMETER (MOLA)
90
60
30
0
-30
-60
-90
-180 -150 -120 -90 -60 -30 0 30 60 90 120 150 180
-8000 -4000 0 4000 8000 12000
meters
(a)
60°N
30°N
0°
30°S
60°S
0° 60° 120° 180° 240° 300° 360°

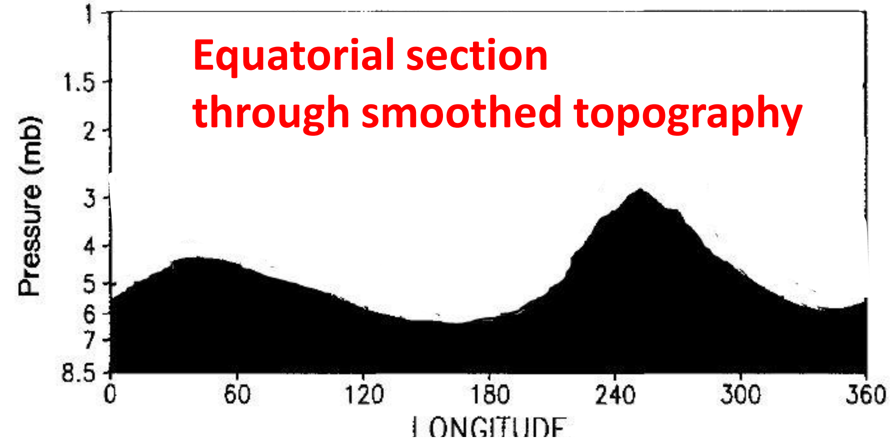


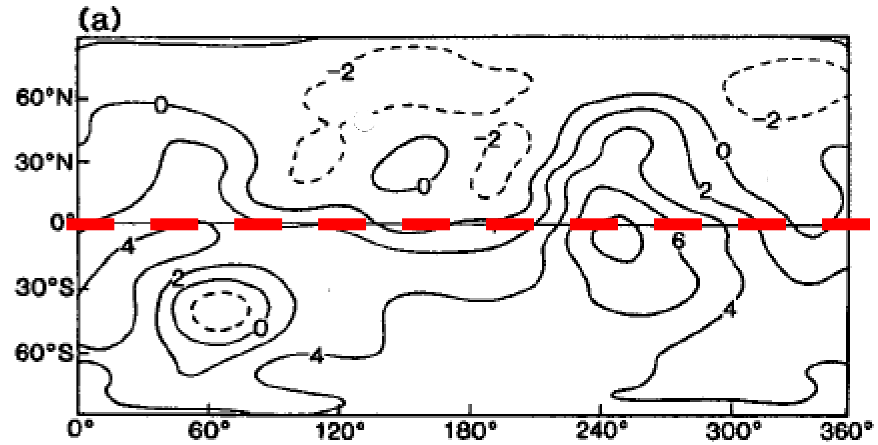


THE TOPOGRAPHY OF MARS

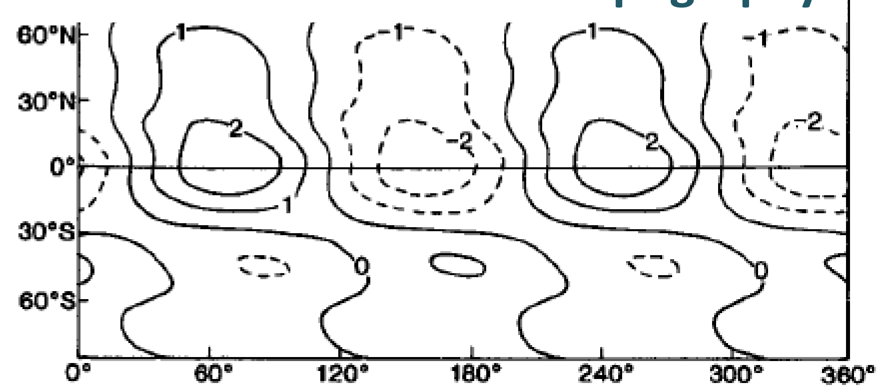
BY THE MARS ORBITER LASER ALTIMETER (MOLA)





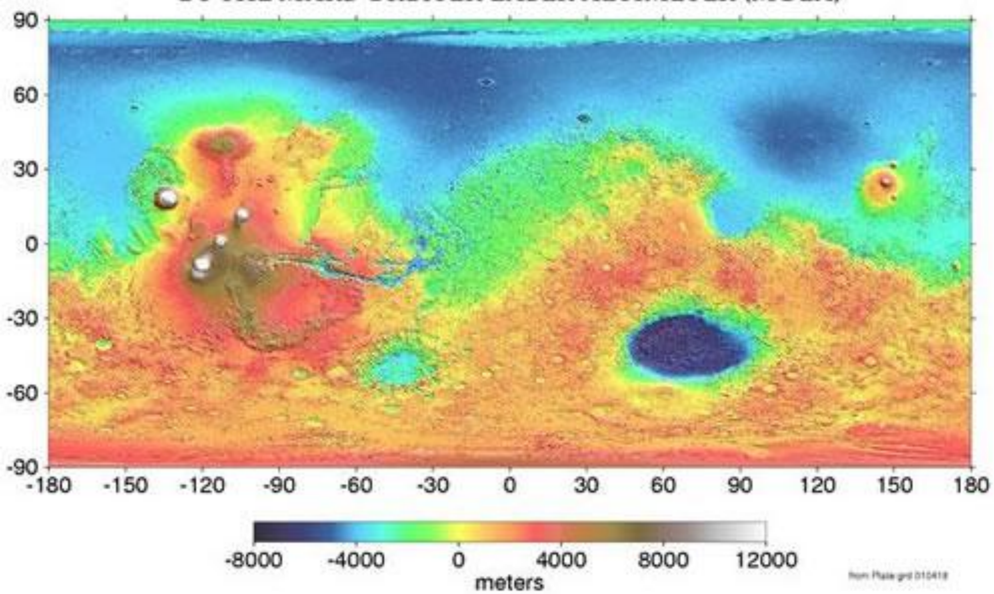


Zonal wavenumber 2 topography



THE TOPOGRAPHY OF MARS

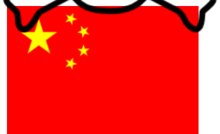
BY THE MARS ORBITER LASER ALTIMETER (MOLA)



- 1962 *Mars 2MV-3 No.1*   Lander
- 1969 *M-69   1&2*   Landers
- 1971 *Kosmos 419*   Orbiter
- 1971 *Mars 2* Orbiter & Lander/Rover
- 1971 *Mars 3*   Orbiter & Lander/Rover
- 1973 *Mars 4*   Orbiter
- 1973 *Mars 5*   Orbiter
- 1973 *Mars 6*   Lander
- 1973 *Mars 7*   Lander
- 1988 *Phobos 1*   Lander
- 1988 *Phobos 2*   Lander
- 1996 *Mars 96* Orbiter, Lander
- 2011 *Fobos-Grunt*   Phobos sample return, Orbiter



- 1962 *Mars 2MV-3 No.1* Lander
- 1969 *M-69* 1&2 Landers
- 1971 *Kosmos 419* Orbiter
- 1971 *Mars 2* Orbiter & Lander/Rover
- 1971 *Mars 3* Orbiter & Lander/Rover
- 1973 *Mars 4* Orbiter
- 1973 *Mars 5* Orbiter
- 1973 *Mars 6* Lander
- 1973 *Mars 7* Lander
- 1988 *Phobos 1* Lander
- 1988 *Phobos 2* Lander
- 1996 *Mars 96* Orbiter, Lander”
- 2011 *Fobos-Grunt* Phobos sample return, Orbiter



- 1973 *Mariner 8* Orbiter
- 1973 *Mariner 9* Orbiter
- 1975 *Viking 1* Orbiter & Lander
- 1975 *Viking 2* Orbiter & Lander
- 1992 *Mars Observer* Orbiter
- 1996 *Mars Global Surveyor* Orbiter
- 1996 *Mars Pathfinder* Lander/Rover
- 1998 *Mars Climate Orbiter*
- 1999 *Mars Polar Lander* Lander
- 2001 *Mars Odyssey* Orbiter
- 2003 *Spirit* Rover
- 2003 *Opportunity* Rover
- 2005 *Mars Reconnaissance Orbiter*
- 2007 *Phoenix* Lander

- **1973 *Mariner 8* Orbiter**
- **1973 *Mariner 9* Orbiter**
- **1975 *Viking 1* Orbiter & Lander**
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- 1973 *Mariner 8* Orbiter
- 1973 *Mariner 9* Orbiter
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- 1996 *Mars Pathfinder* Lander/Rover

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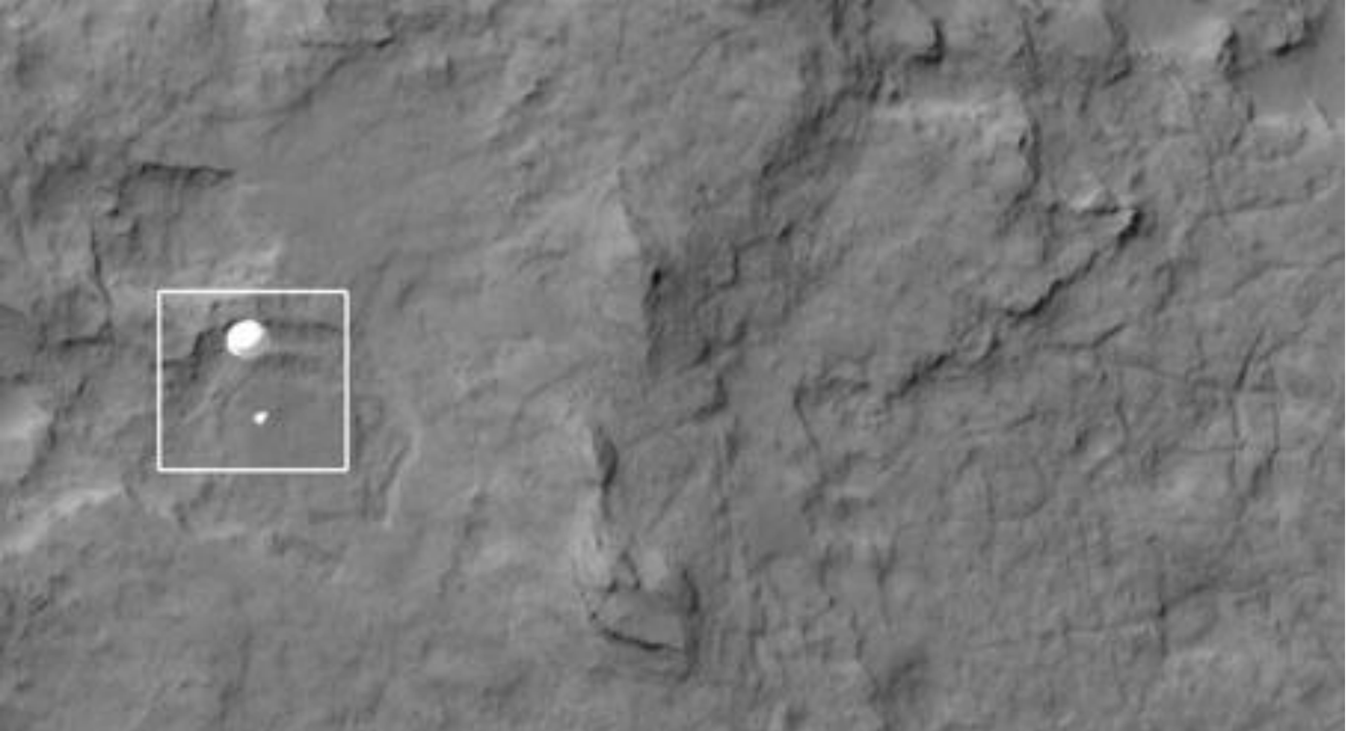
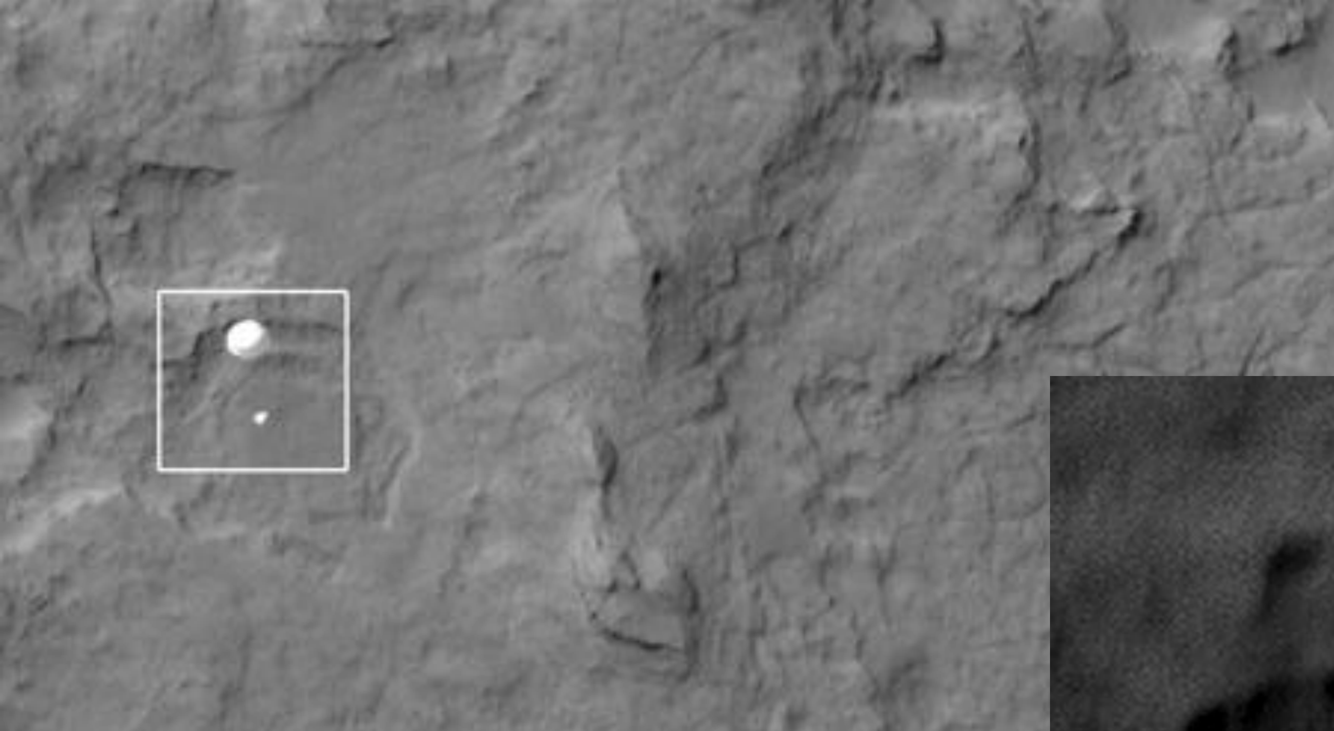
- 2003 *Spirit* Rover
- 2003 *Opportunity* Rover
- 2005 *Mars Reconnaissance Orbiter*
- 2007 *Phoenix* Lander

NASA's Mars Phoenix Lander can be seen parachuting down to Mars, in this image captured by the High Resolution Imaging Science Experiment (HiRISE) camera on NASA's Mars Reconnaissance Orbiter. This is the first time that a spacecraft has imaged the final descent of another spacecraft onto a planetary body.



NASA's Curiosity Rover Caught in the Act of Landing

An image from the High Resolution Imaging Science Experiment (HiRISE) camera aboard NASA's Mars Reconnaissance orbiter captured the Curiosity rover ...



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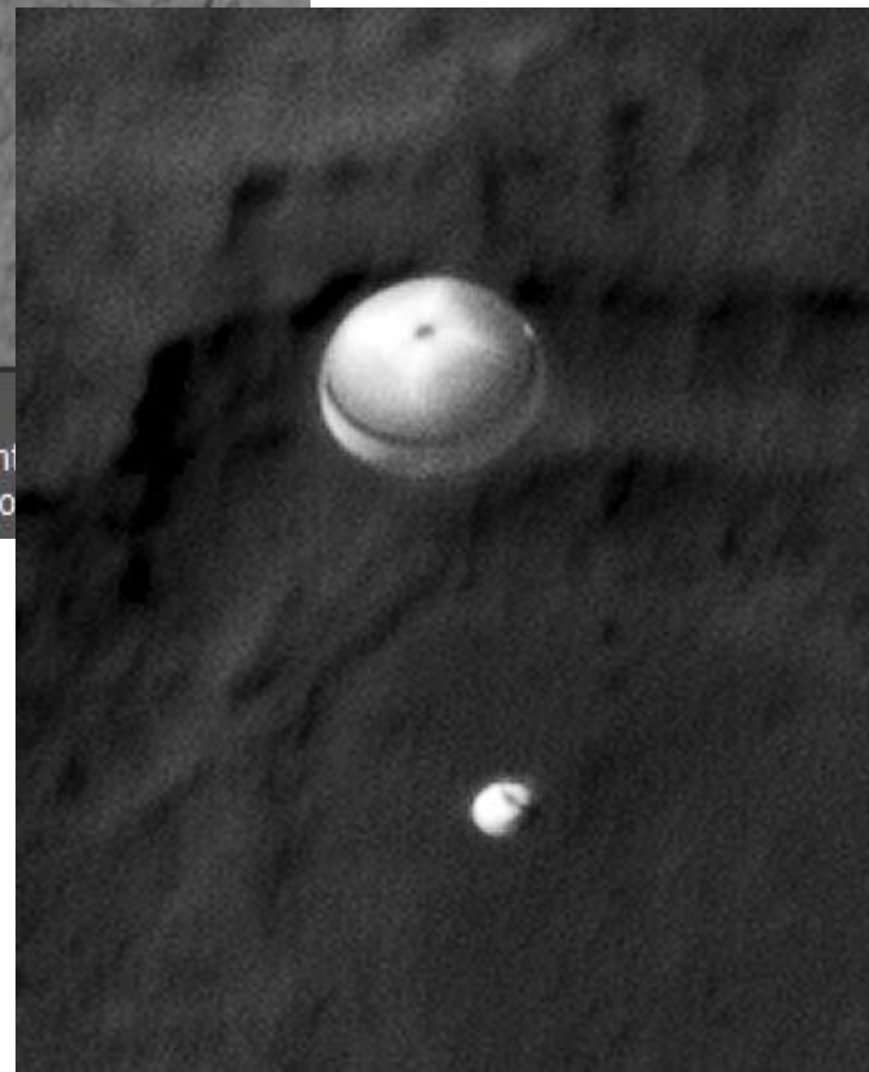
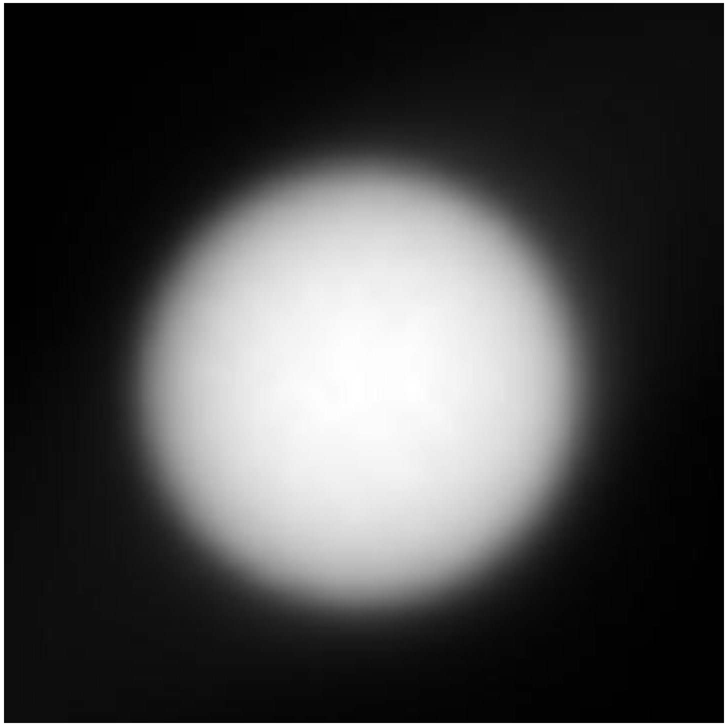
An image from the High Resolution Imaging Science Experiment
aboard NASA's Mars Reconnaissance orbiter captured the Curio





Phobos eclipses the Sun, imaged by the *Opportunity* rover

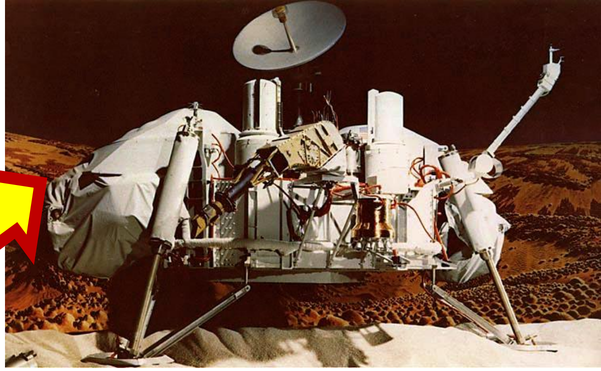
- 1975 *Viking 1*   Orbiter & Lander
- 1975 *Viking 2*   Orbiter & Lander

- 1996 *Mars Pathfinder*   Lander/Rover

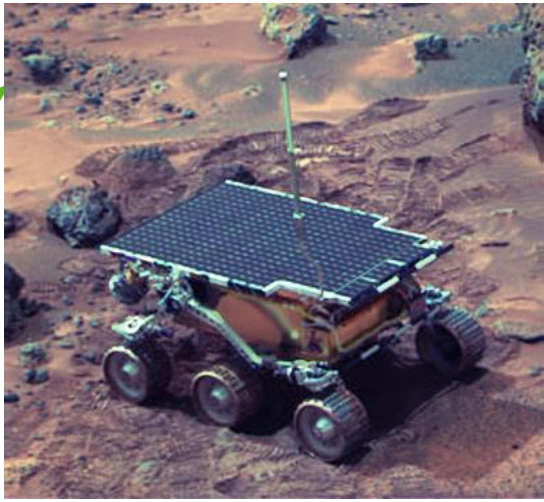
- 2003 *Spirit*   Rover
- 2003 *Opportunity* Rover

- 2007 *Phoenix*   Lander

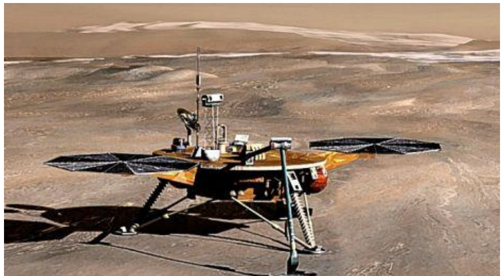
Surface Meteorological Data



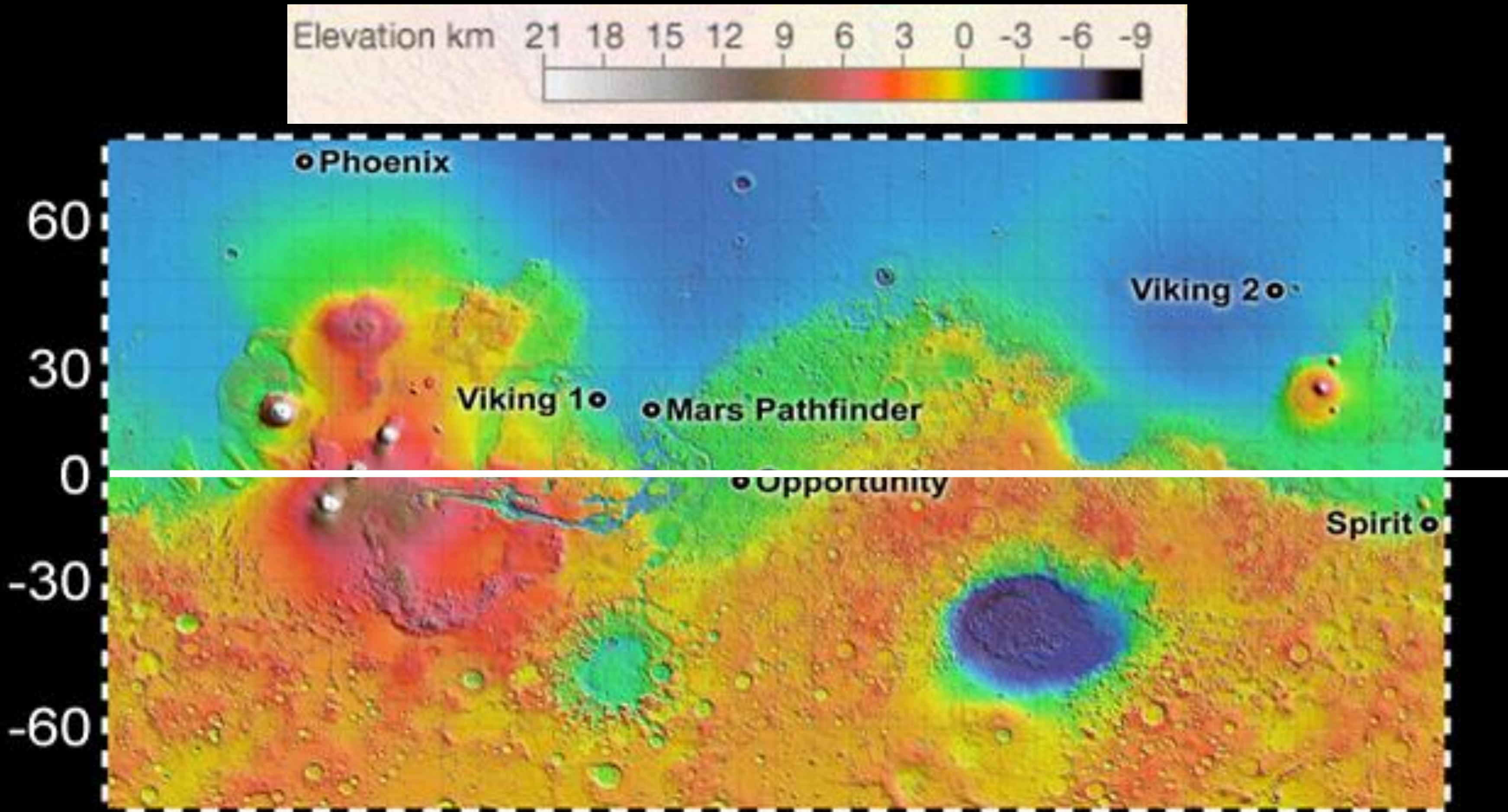
- 1975 *Viking 1* Orbiter & Lander
- 1975 *Viking 2* Orbiter & Lander



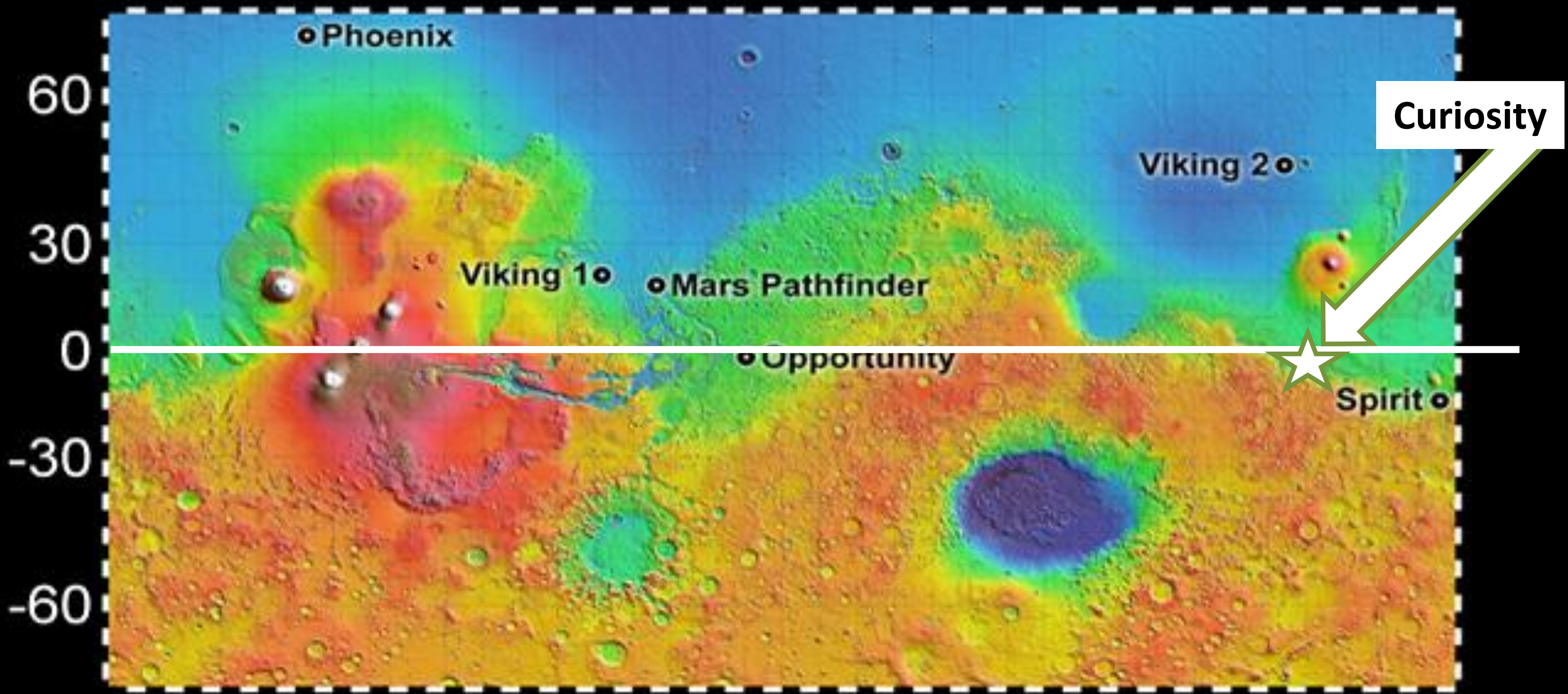
- 1996 *Mars Pathfinder* Lander/Rover
- 2003 *Spirit* Rover
- 2003 *Opportunity* Rover



- 2007 *Phoenix* Lander

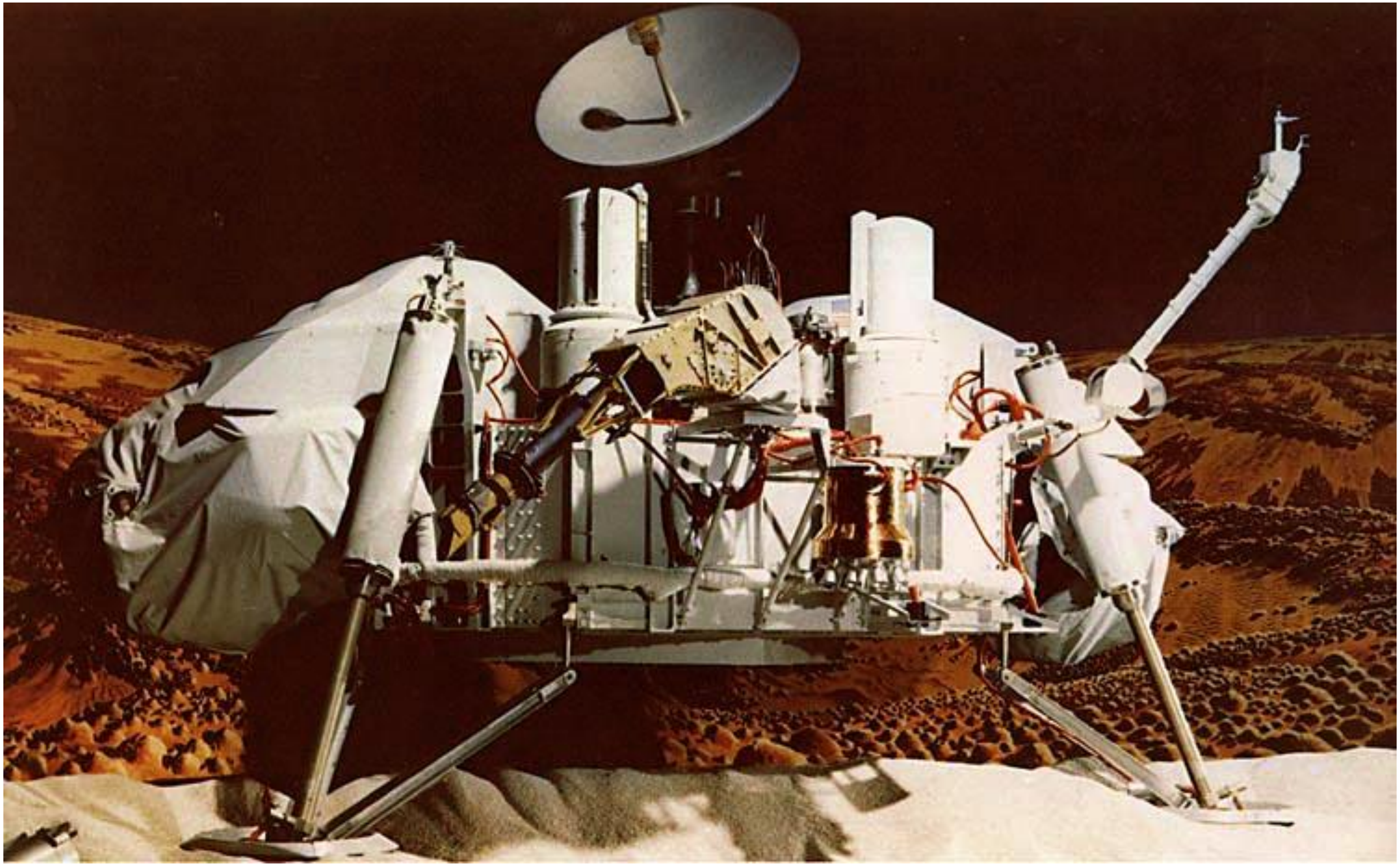


Elevation km
21
18
15
12
9
6
3
0
-3
-6
-9
Phoenix
Viking 2
Viking 1
Mars Pathfinder
Opportunity
Spirit
60
30
0
-30
-60



Phoenix
Viking 1
Mars Pathfinder
Opportunity
Viking 2
Curiosity
Spirit
60
30
0
-30
-60

Viking 1 and *Viking 2* Landers
Landed July 20 and September 3, 1976

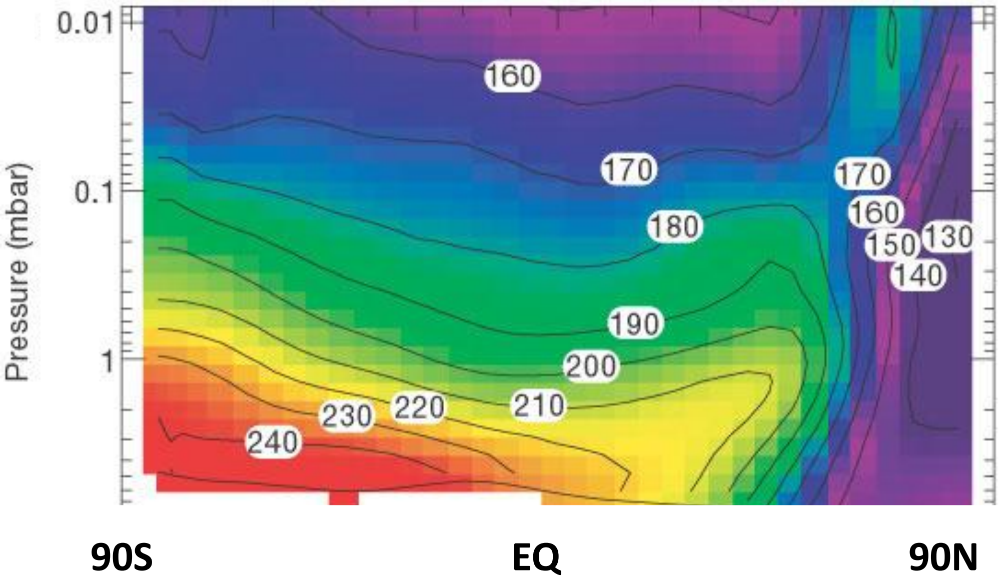


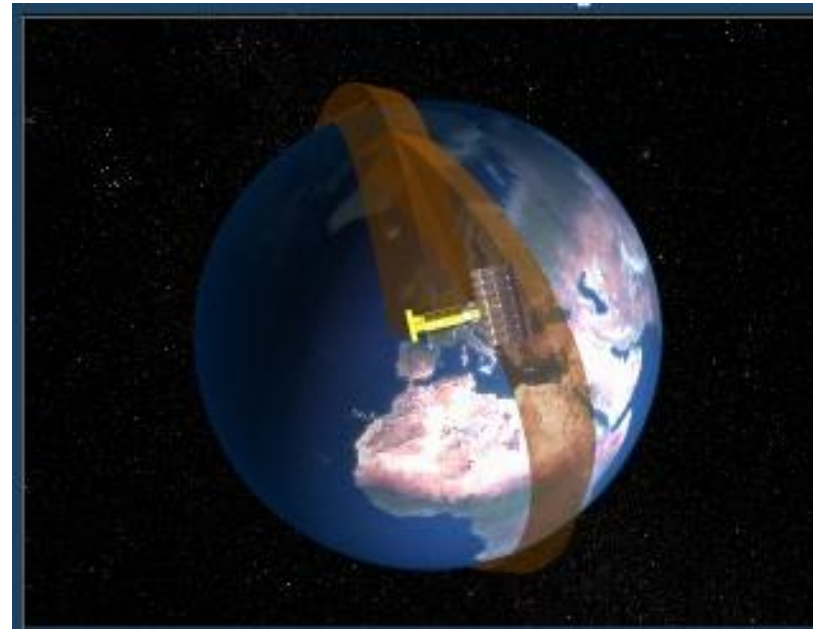
Viking Landers (VL1 & VL2)

- **VL1   22ºN**
- **Start Time : 1976-07-20**
- **Stop Time : 1982-11-13**

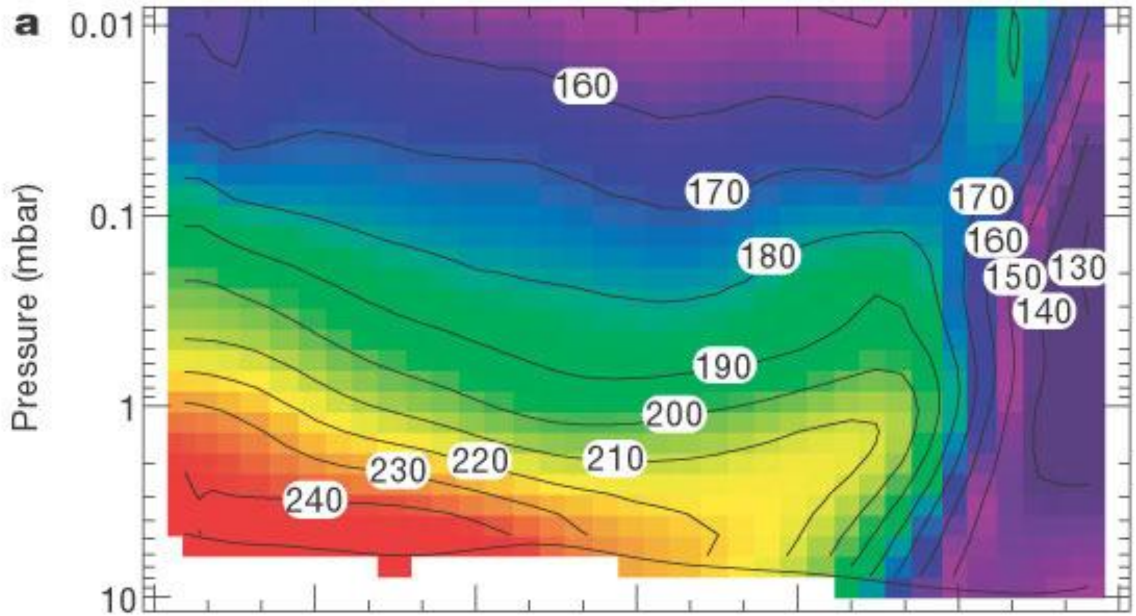
- **VL2 48ºN**
- **Start Time : 1976-09-03**
  Stop Time : 1980-04-11

This picture was taken by the Viking Lander 1 on February 11, 1978 on Sol 556. The large rock just left of the center is about two meters wide. The top of the rock is covered with red soil. Those portions of the rock not covered are similar in color to basaltic rocks on Earth. Therefore, this may be a fragment of a lava flow that was ejected by an impact crater.

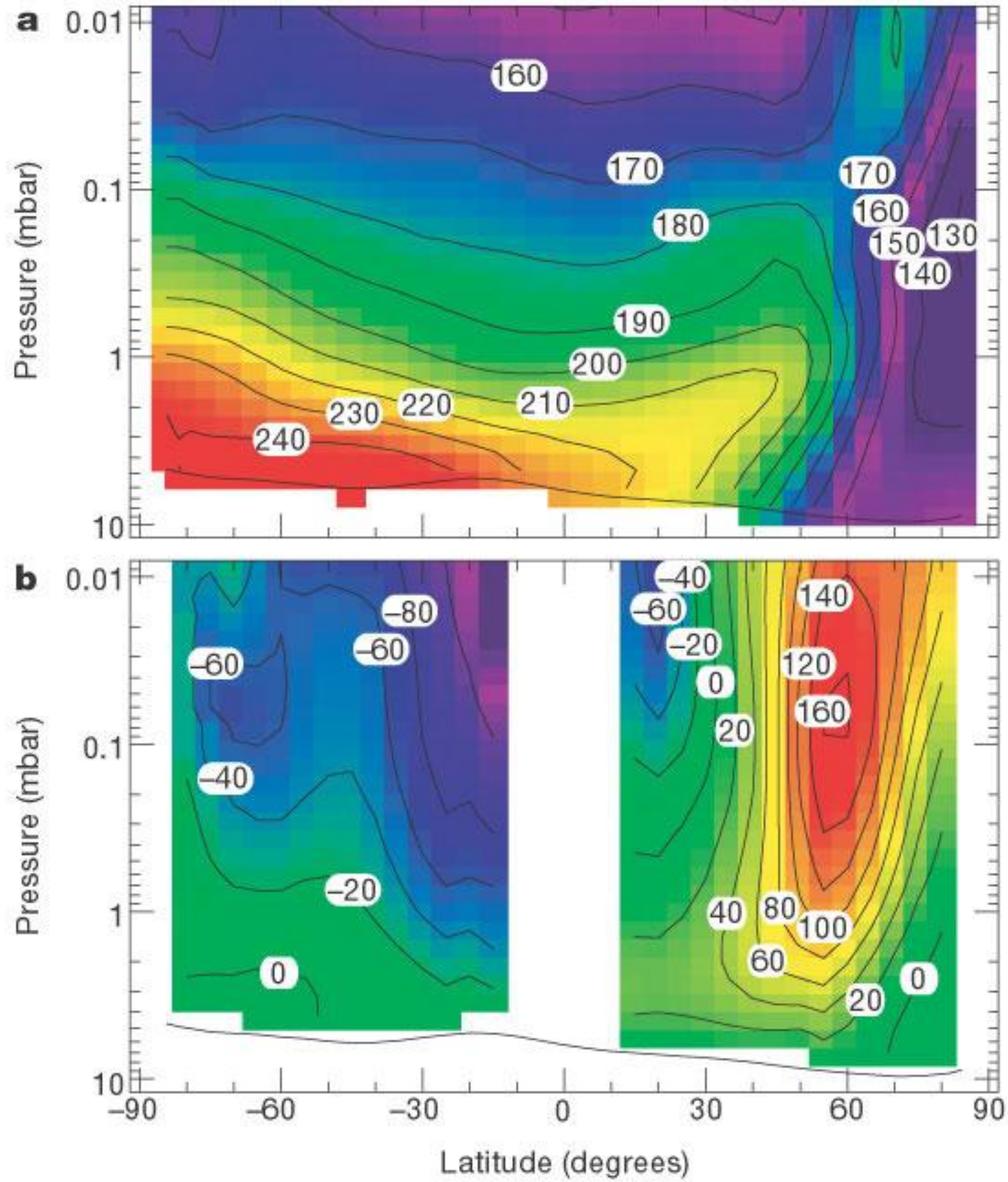




Mars Global Surveyer – Thermal Emission Spectrometer Data



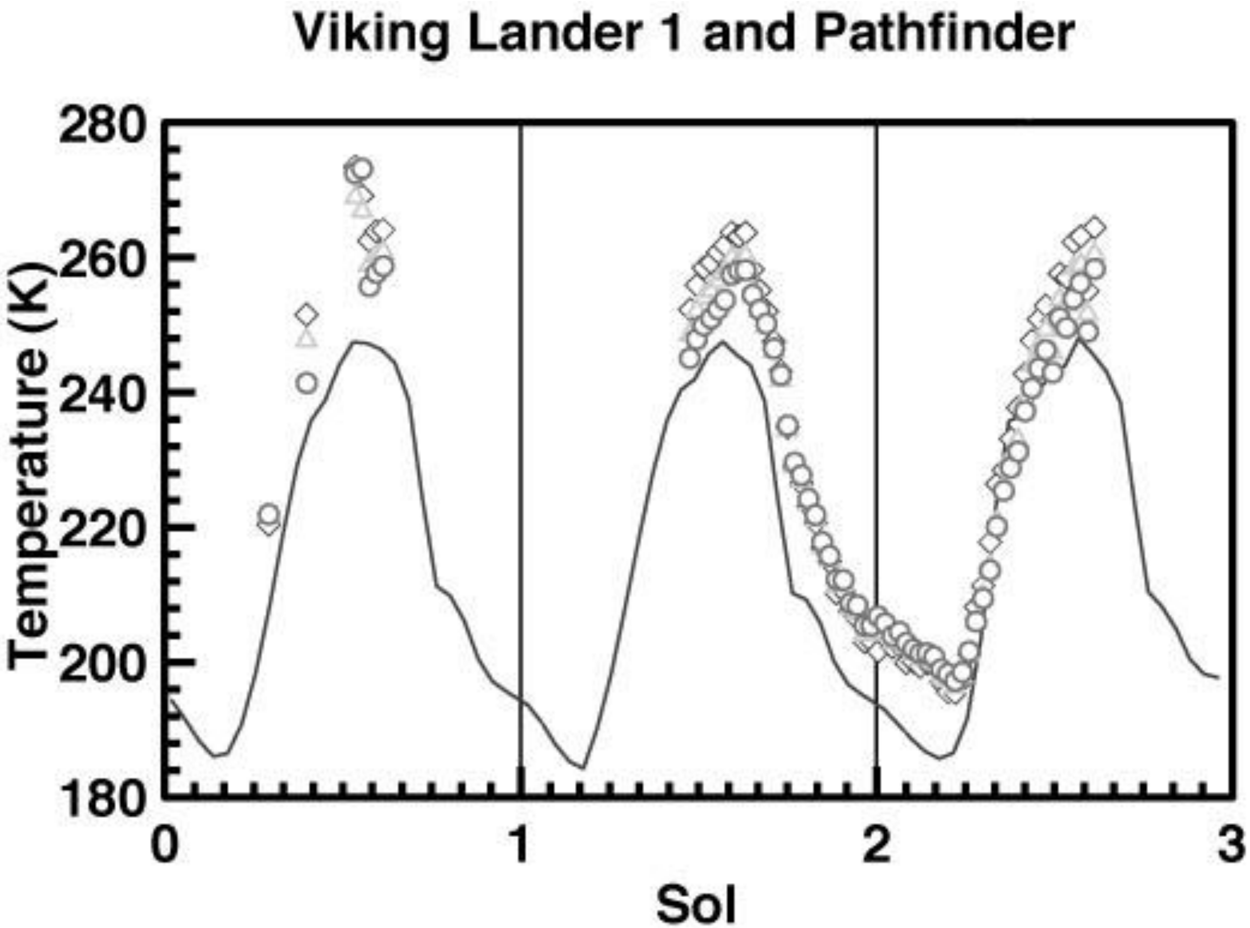
Summer Pole **Equator** **Winter Pole**

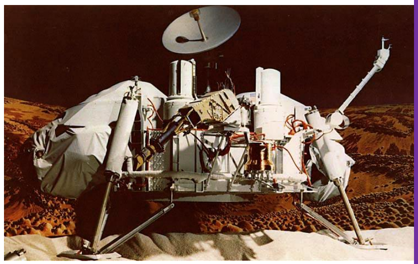


T

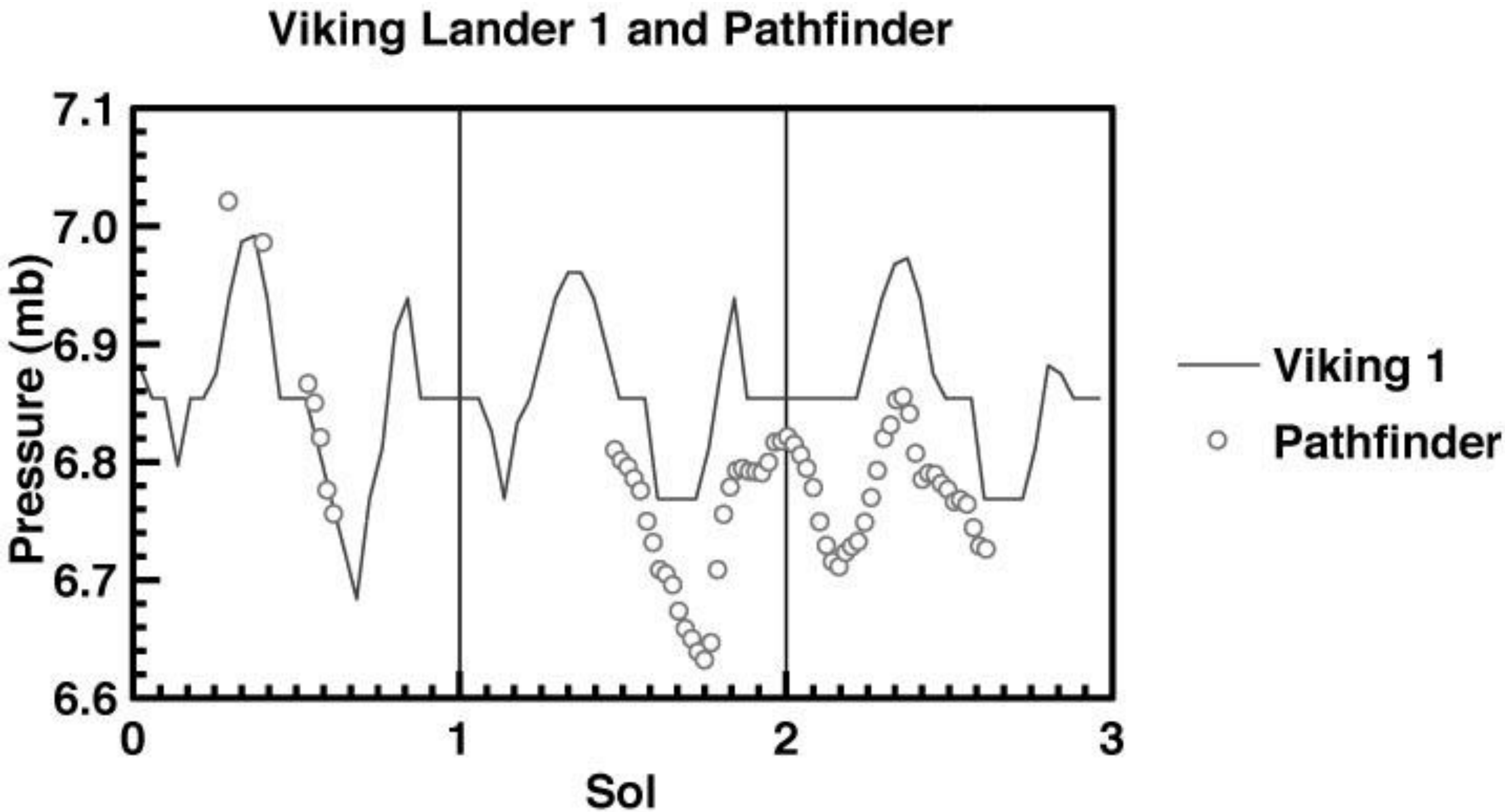
Geostrophic u

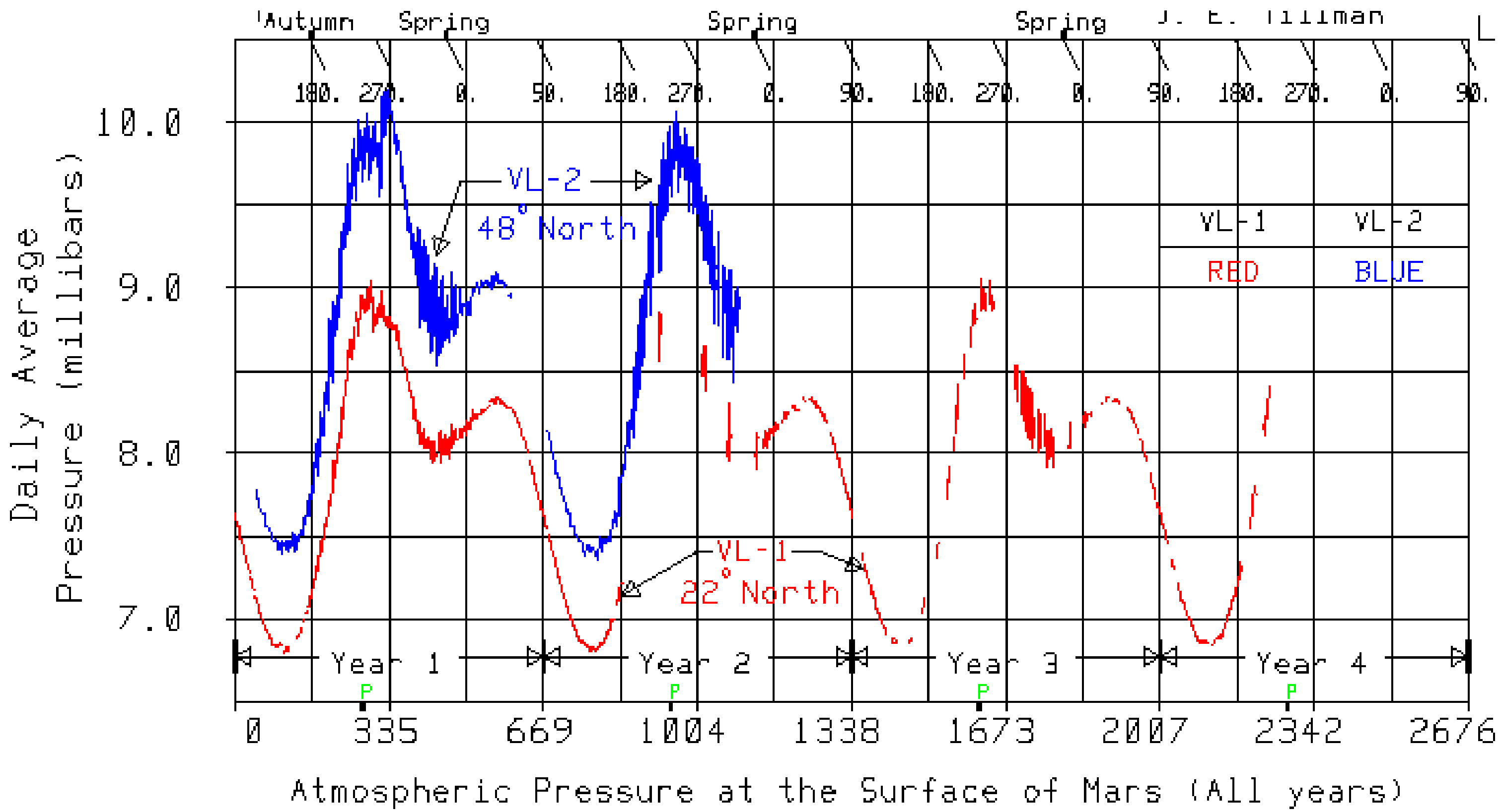
~60K diurnal range of surface air temperature at ~20N



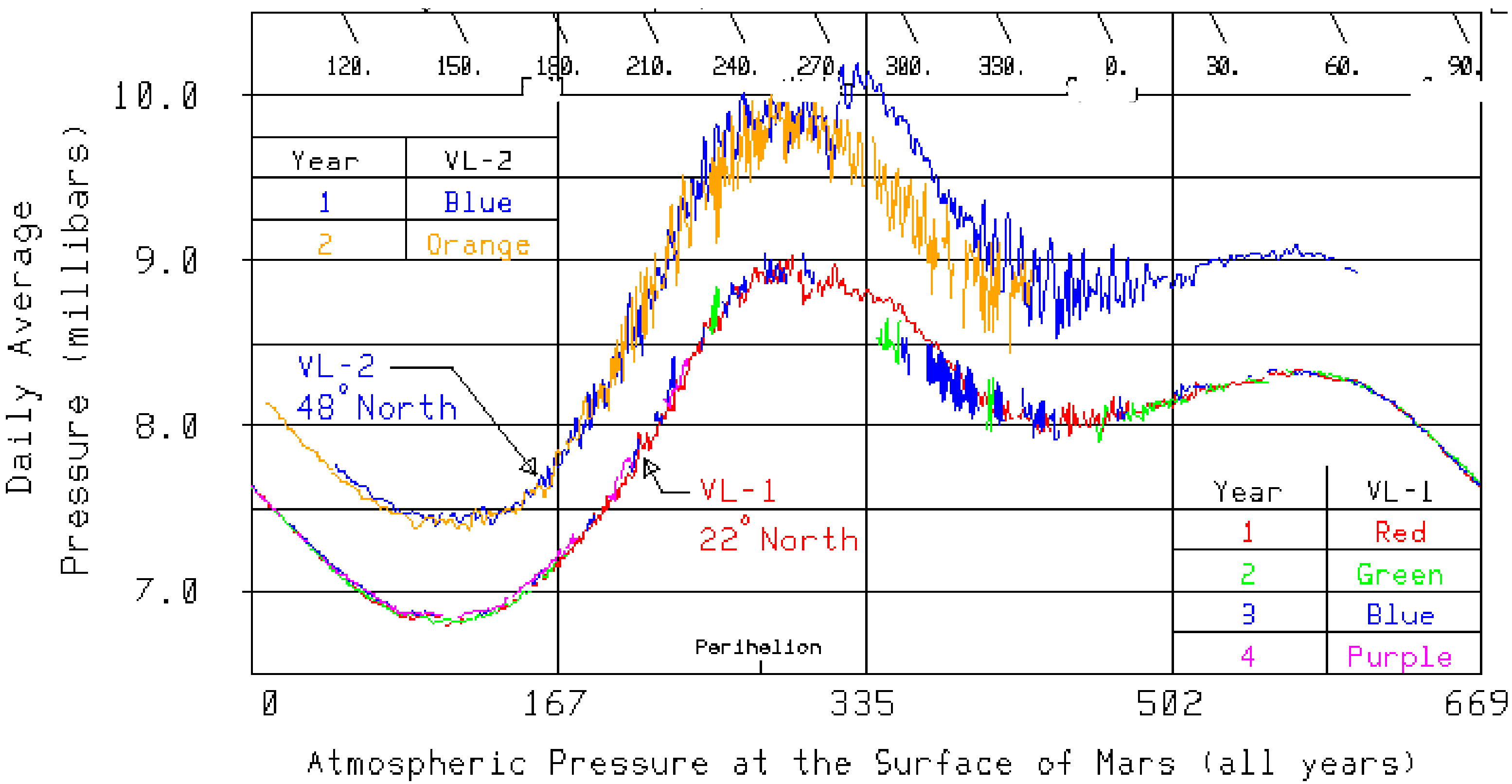


~30 Pa diurnal range of surface pressure at ~20N



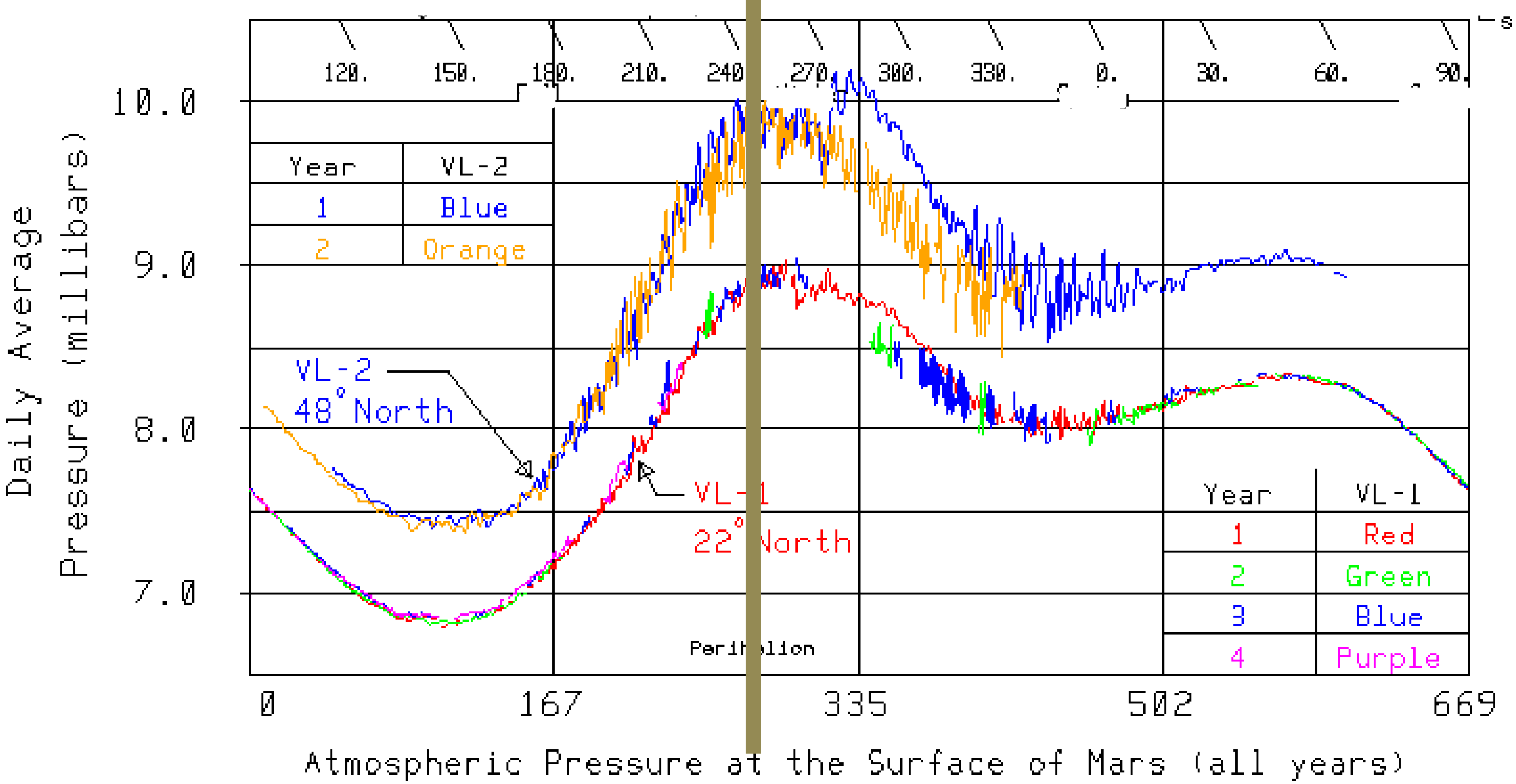


Autumn
Spring
Spring
Spring
J. E. Tillman
Ls
180.
270.
0.
90.
10.0
9.0
8.0
7.0
Daily Average
Pressure (millibars)
VL-2
48° North
VL-1
22° North
VL-1
VL-2
RED
BLUE
Year 1
Year 2
Year 3
Year 4
P
0
335
669
1004
1338
1673
2007
2342
2676
Atmospheric Pressure at the Surface of Mars (All years)

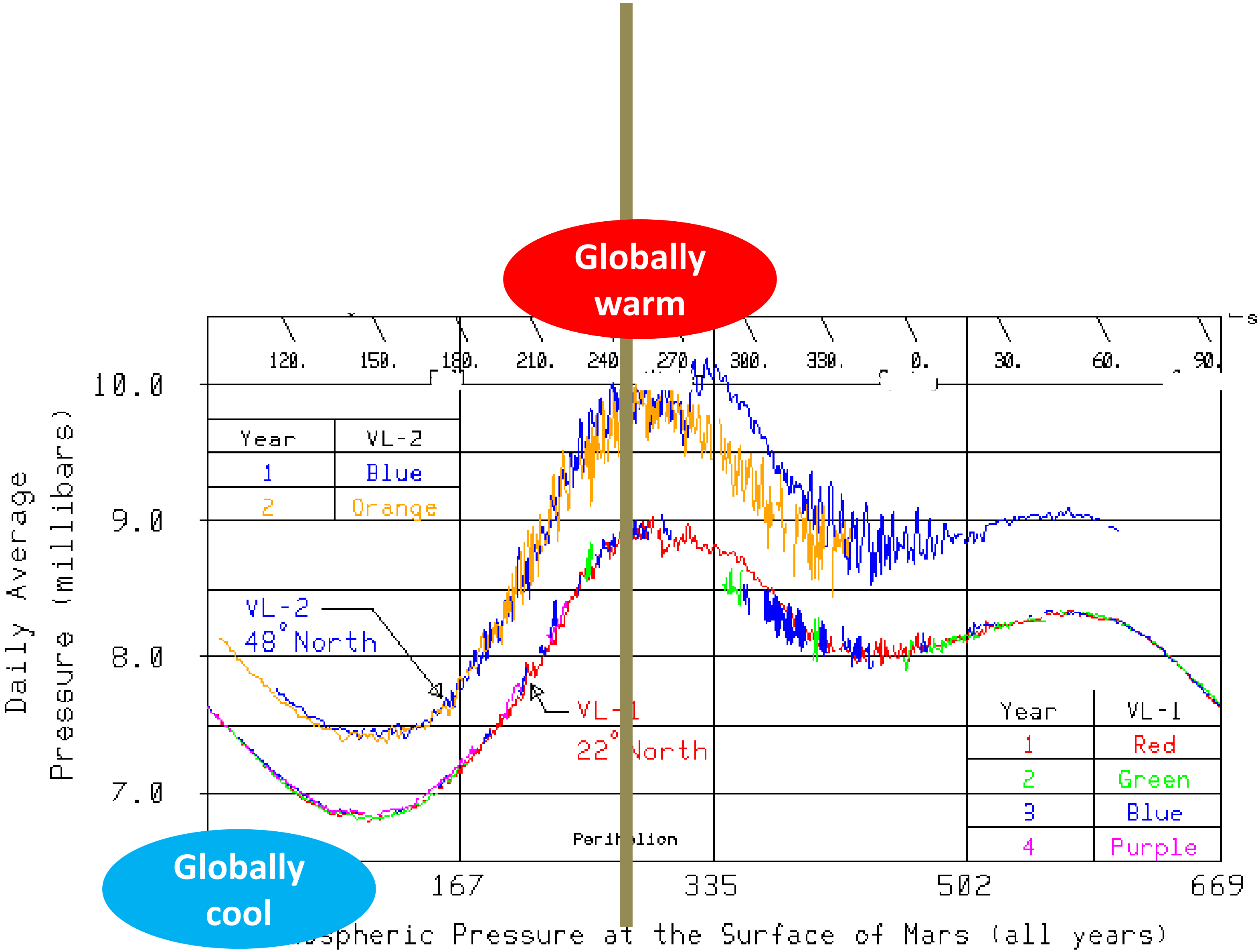


120.
150.
180.
210.
240.
270.
300.
330.
0.
30.
60.
90.
Ls
10.0
9.0
8.0
7.0
Daily Average Pressure (millibars)
Year
VL-2
1
Blue
2
Orange
VL-2
48° North
VL-1
22° North
Year
VL-1
1
Red
2
Green
3
Blue
4
Purple
Perihelion
0
167
335
502
669
Atmospheric Pressure at the Surface of Mars (all years)

Perihelion

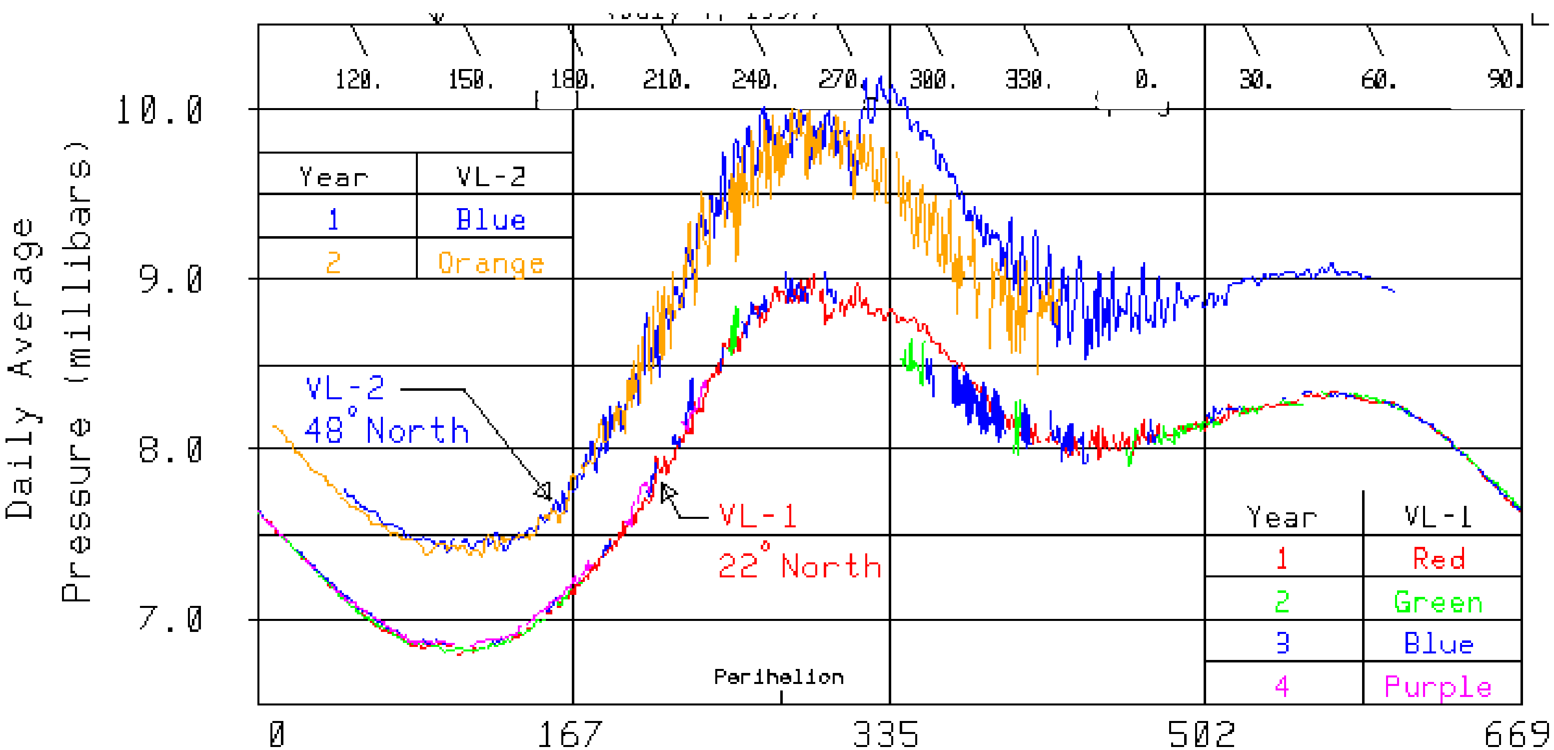


10.0
9.0
8.0
7.0
Daily Average Pressure (millibars)
120. 150. 180. 210. 240. 270. 300. 330. 0. 30. 60. 90.
Year | VL-2
1 | Blue
2 | Orange
VL-2 48° North
VL-1 22° North
Year | VL-1
1 | Red
2 | Green
3 | Blue
4 | Purple
Perihelion
0 167 335 502 669
Atmospheric Pressure at the Surface of Mars (all years)

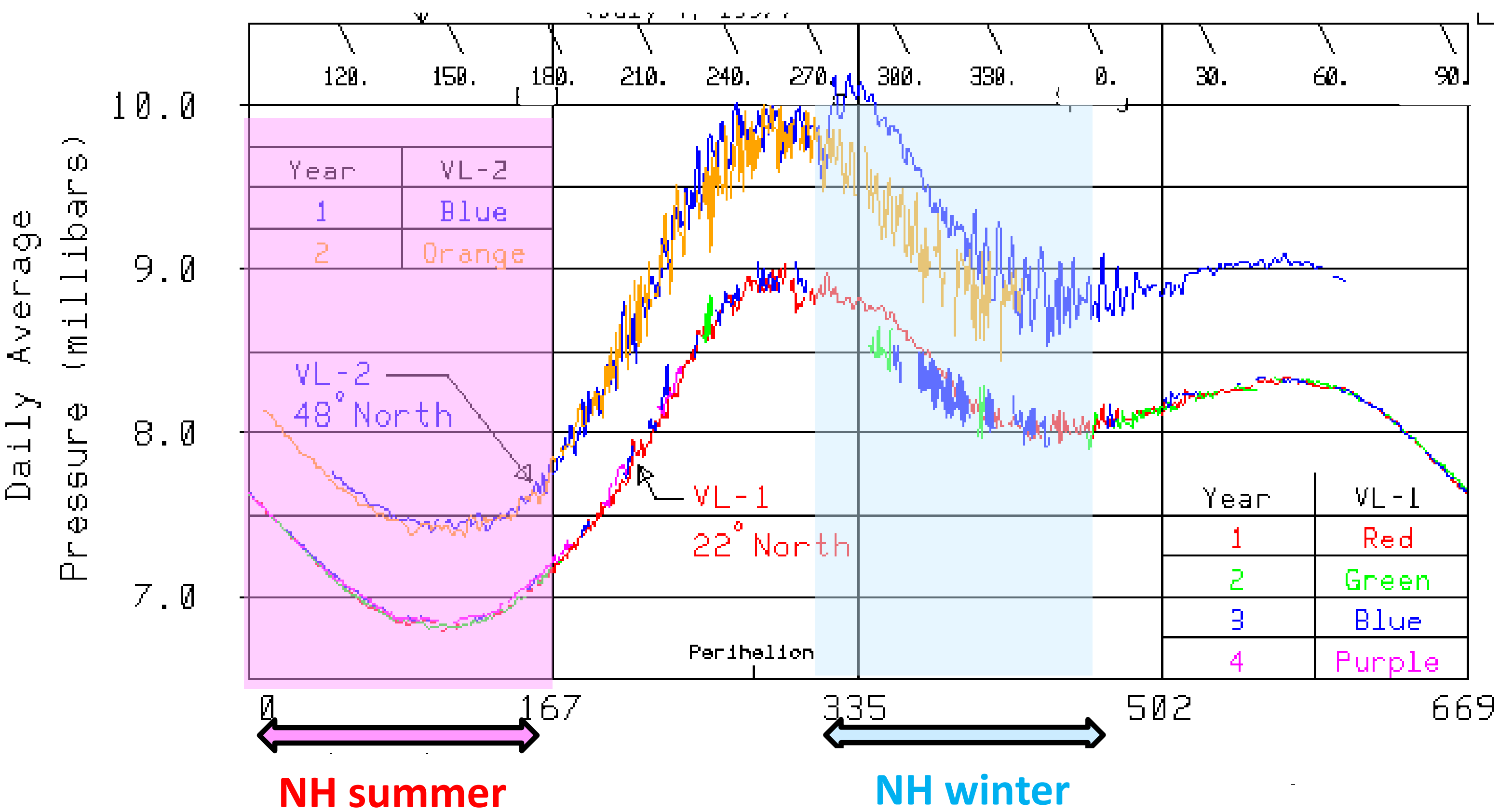

Globally warm
Globally cool
Daily Average Pressure (millibars)
10.0
9.0
8.0
7.0
120.
150.
180.
210.
240.
270.
300.
330.
0.
30.
60.
90.
Ls
Year
VL-2
1
Blue
2
Orange
VL-2
48° North
VL-1
22° North
Year
VL-1
1
Red
2
Green
3
Blue
4
Purple
Perihelion
167
335
502
669
...spheric Pressure at the Surface of Mars (all years)

Annual Cycle of Surface Pressure

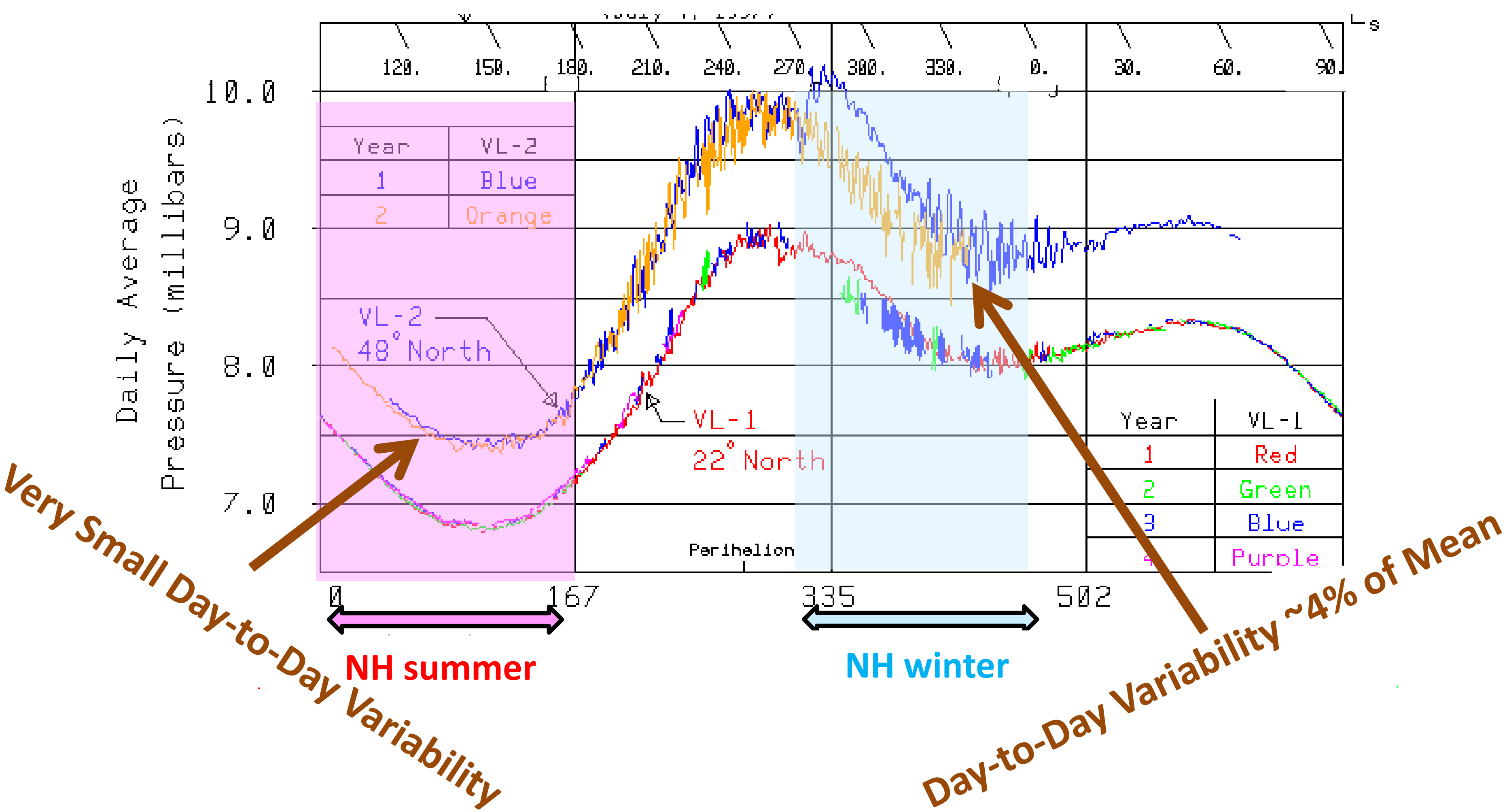
- **The surface pressure everywhere is ~30% higher near perihelion than the minimum which occurs somewhat after aphelion**
- **This is accompanied by a seasonal cycle in the size of the NH and SH polar "ice" caps**
- **We conclude that the CO_2 in the atmosphere is sublimating from/condensing onto the polar caps in such large amounts that the total mass of the atmosphere has a ~30% annual cycle**
- **The global <u>surface pressure is largest</u> when the global <u>atmosphere is warmest</u>**



Atmospheric Pressure at the Surface of Mars (all years)

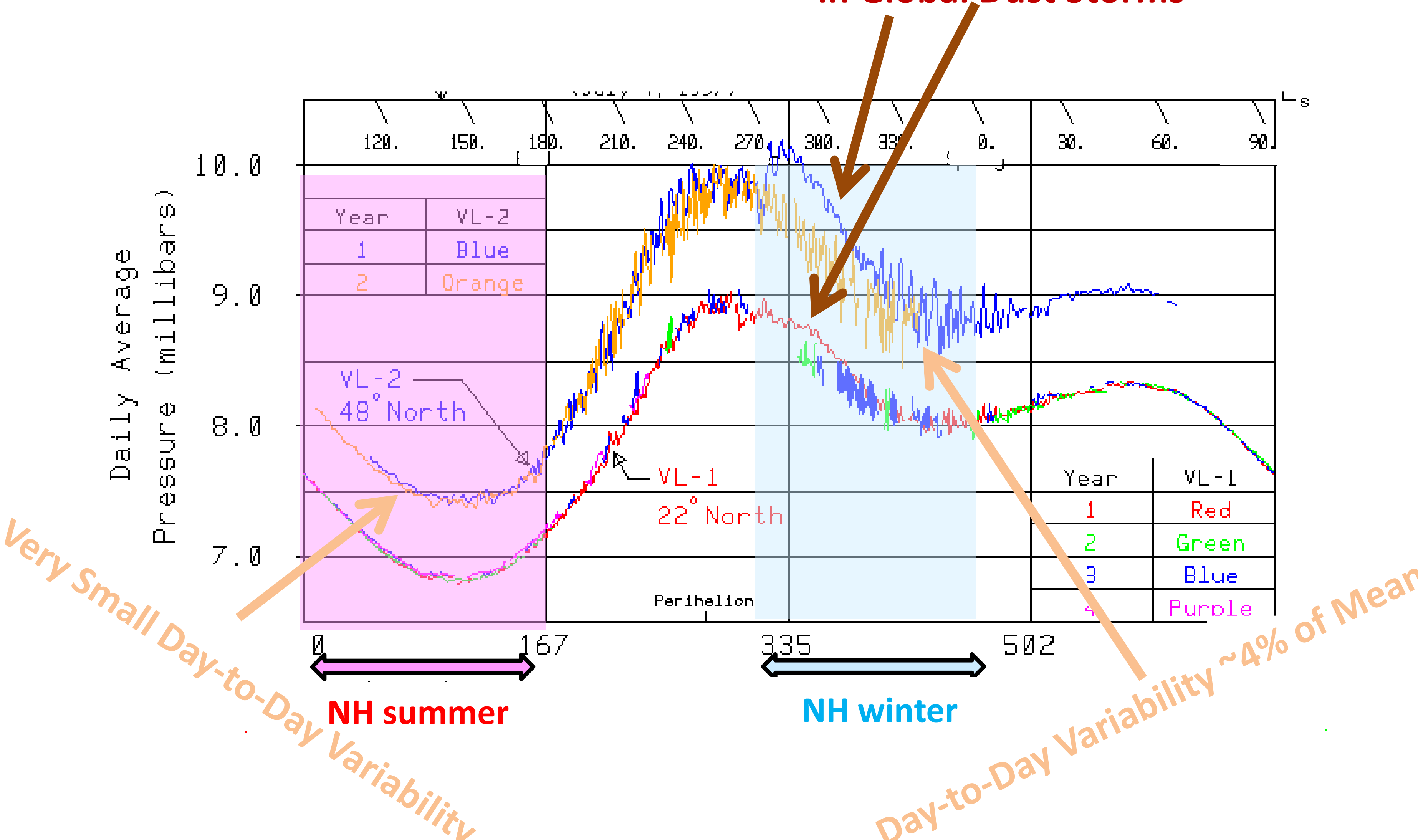


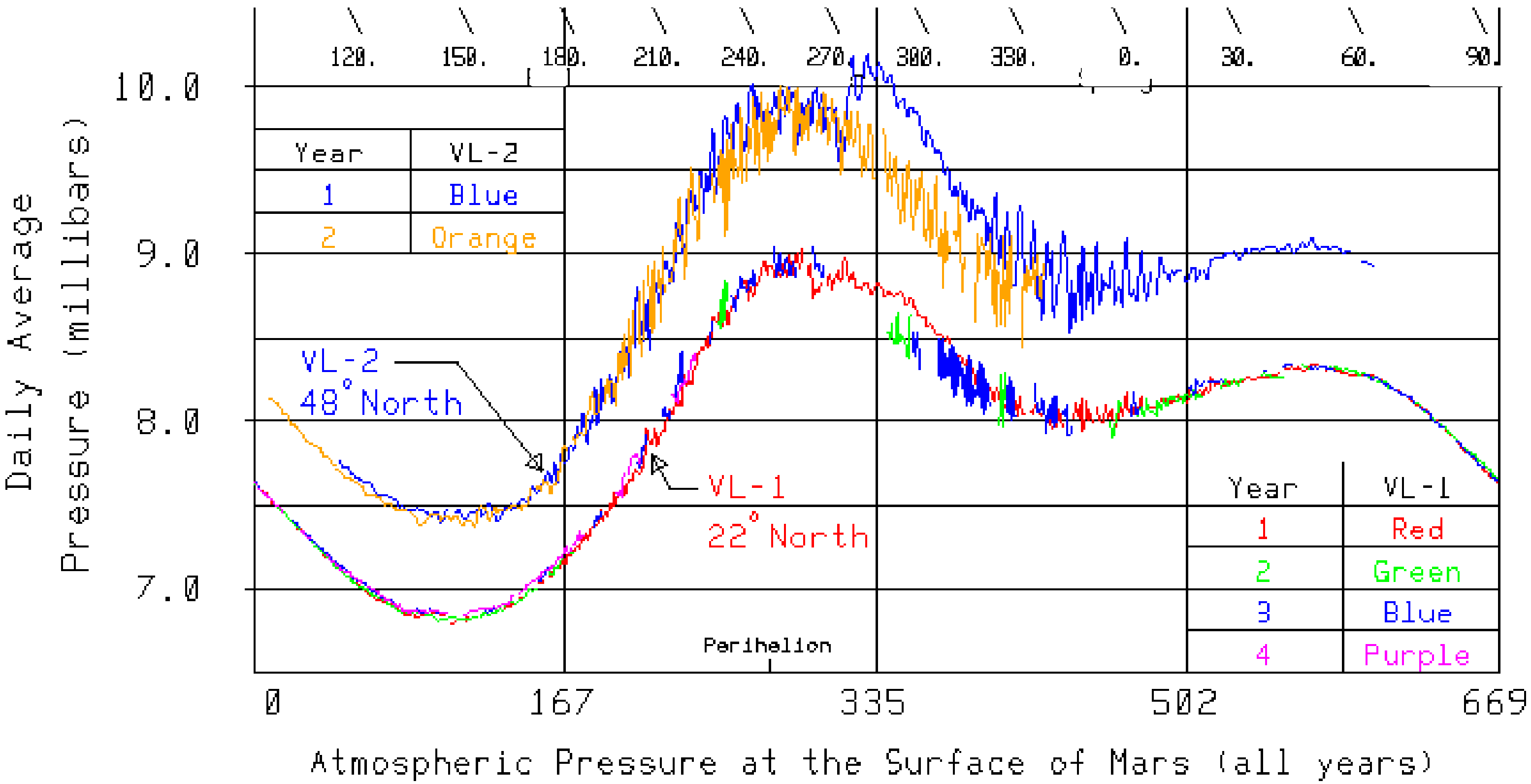
Daily Average Pressure (millibars)
10.0
9.0
8.0
7.0
120.
150.
180.
210.
240.
270.
300.
330.
0.
30.
60.
90.
Ls
Year
VL-2
1
Blue
2
Orange
VL-2
48° North
VL-1
22° North
Perihelion
Year
VL-1
1
Red
2
Green
3
Blue
4
Purple
0
167
335
502
669
NH summer
NH winter



Ls
120.
150.
180.
210.
240.
270.
300.
330.
0.
30.
60.
90.
10.0
9.0
8.0
7.0
Daily Average
Pressure (millibars)
Year	VL-2
1	Blue
2	Orange
VL-2
48° North
VL-1
22° North
Year	VL-1
1	Red
2	Green
3	Blue
4	Purple
Perihelion
0
167
335
502
NH summer
NH winter
Very Small Day-to-Day Variability
Day-to-Day Variability ~4% of Mean

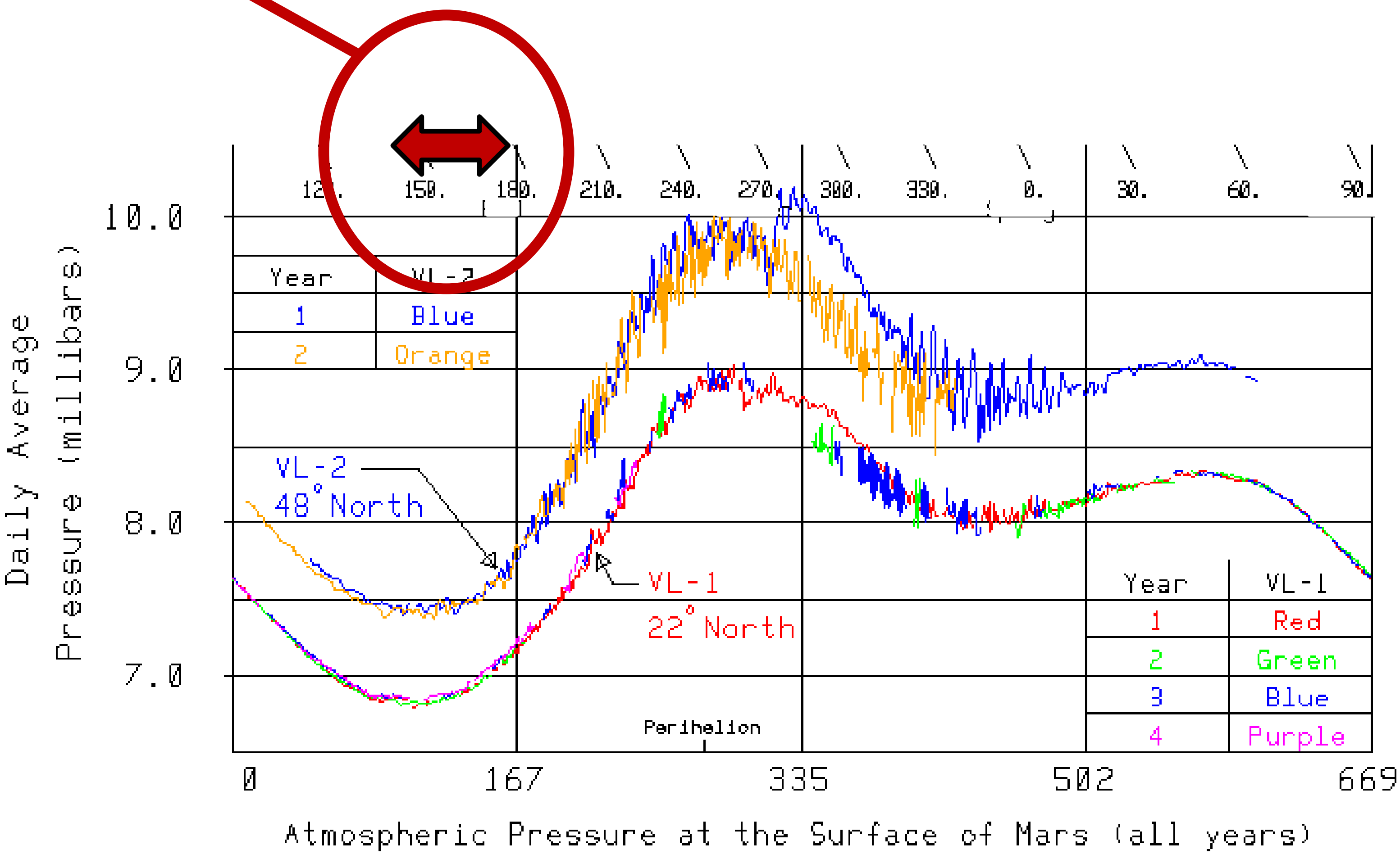
Day-to-Day Variability Nearly Disappears in Global Dust Storms

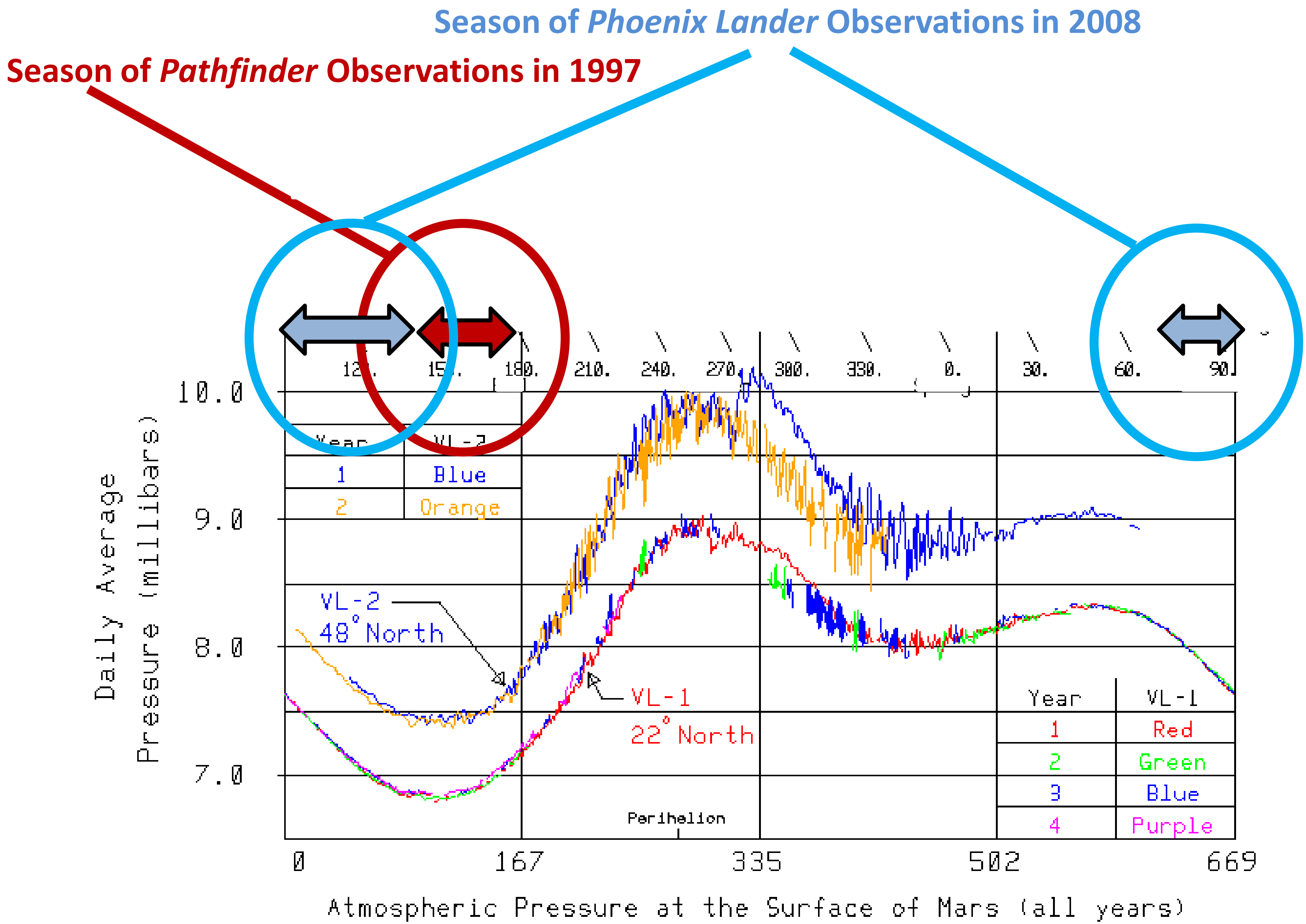




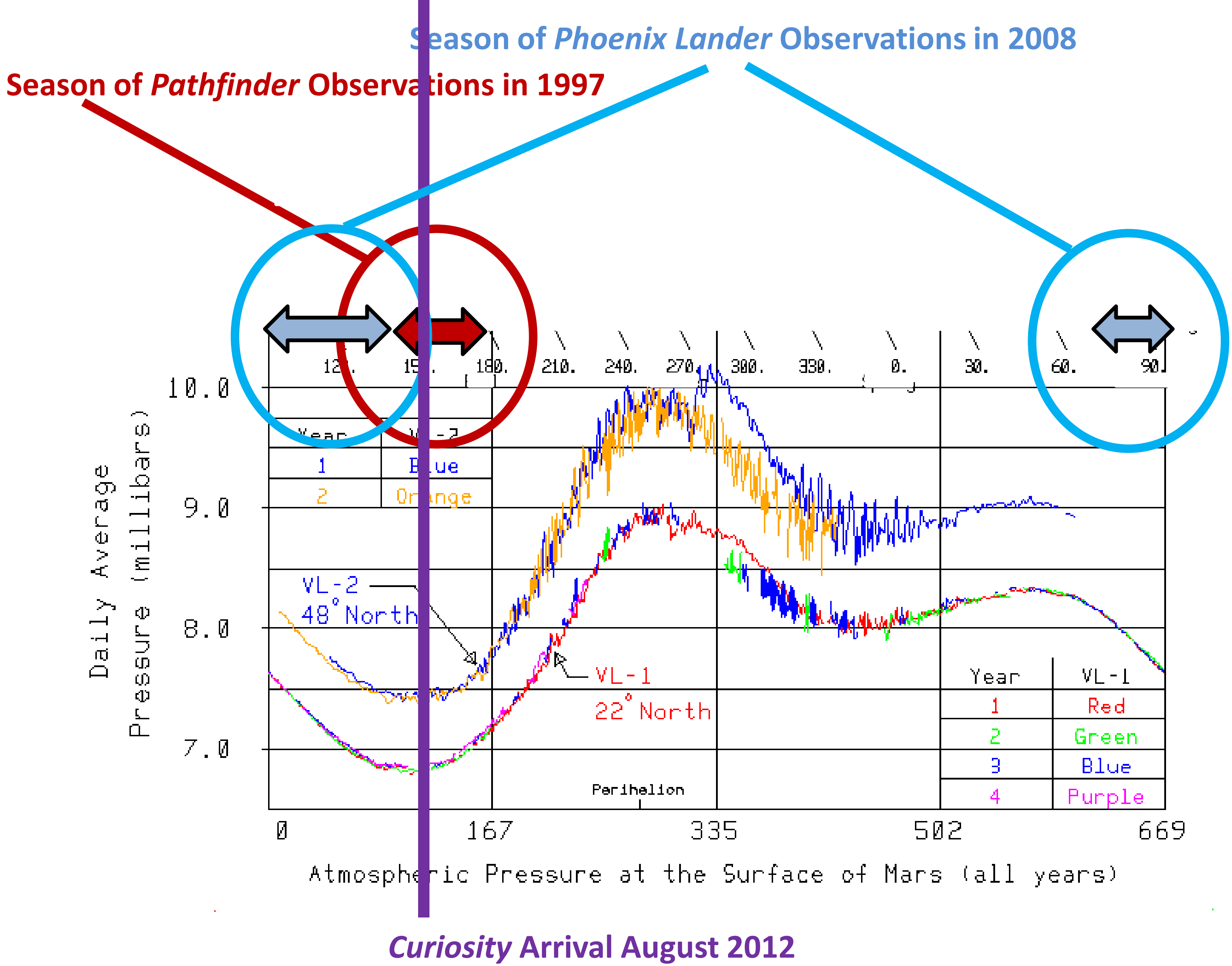
120.
150.
180.
210.
240.
270.
300.
330.
0.
30.
60.
90.
10.0
9.0
8.0
7.0
Daily Average
Pressure (millibars)
Year
VL-2
1
Blue
2
Orange
VL-2
48° North
VL-1
22° North
Year
VL-1
1
Red
2
Green
3
Blue
4
Purple
Perihelion
0
167
335
502
669
Atmospheric Pressure at the Surface of Mars (all years)

Season of *Pathfinder* Observations in 1997



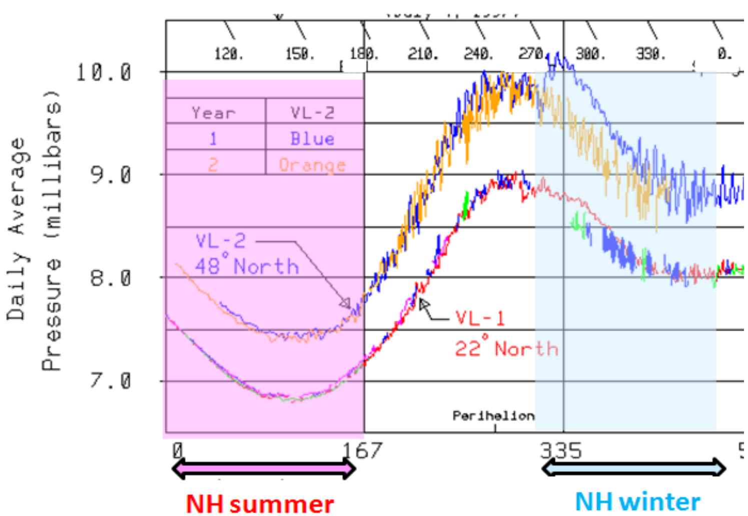


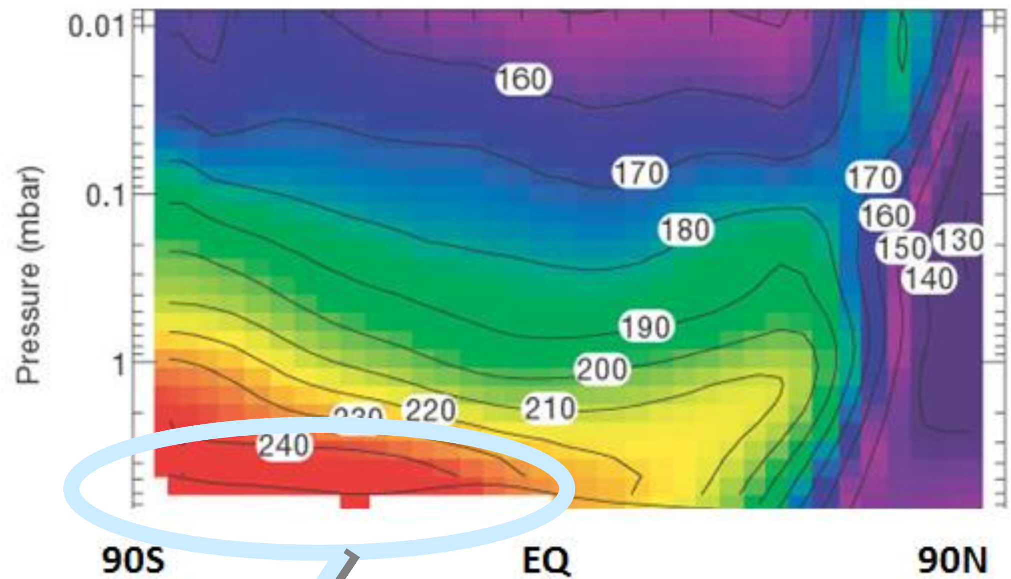
Season of *Phoenix Lander* Observations in 2008
Season of *Pathfinder* Observations in 1997
120.
150.
180.
210.
240.
270.
300.
330.
0.
30.
60.
90.
10.0
9.0
8.0
7.0
Daily Average Pressure (millibars)
Year
VL-2
1
Blue
2
Orange
VL-2 48° North
VL-1 22° North
Year
VL-1
1
Red
2
Green
3
Blue
4
Purple
Perihelion
0
167
335
502
669
Atmospheric Pressure at the Surface of Mars (all years)



Season of Phoenix Lander Observations in 2008
Season of Pathfinder Observations in 1997
Daily Average Pressure (millibars)
10.0
9.0
8.0
7.0
VL-2 48° North
VL-1 22° North
Year
VL-2
1 Blue
2 Orange
Year
VL-1
1 Red
2 Green
3 Blue
4 Purple
Perihelion
0
167
335
502
669
Atmospheric Pressure at the Surface of Mars (all years)
Curiosity Arrival August 2012

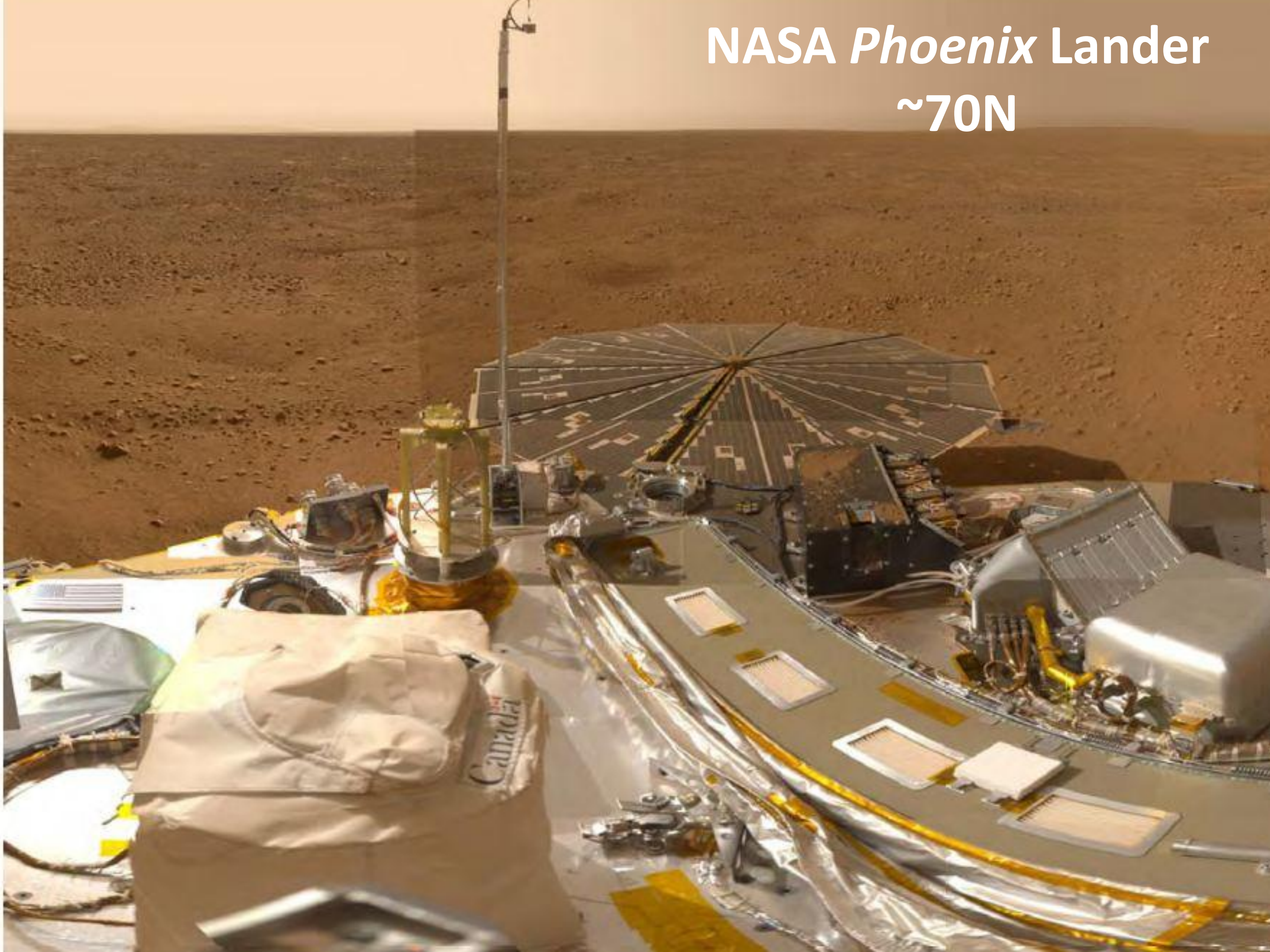
Baroclinic Waves on Mars

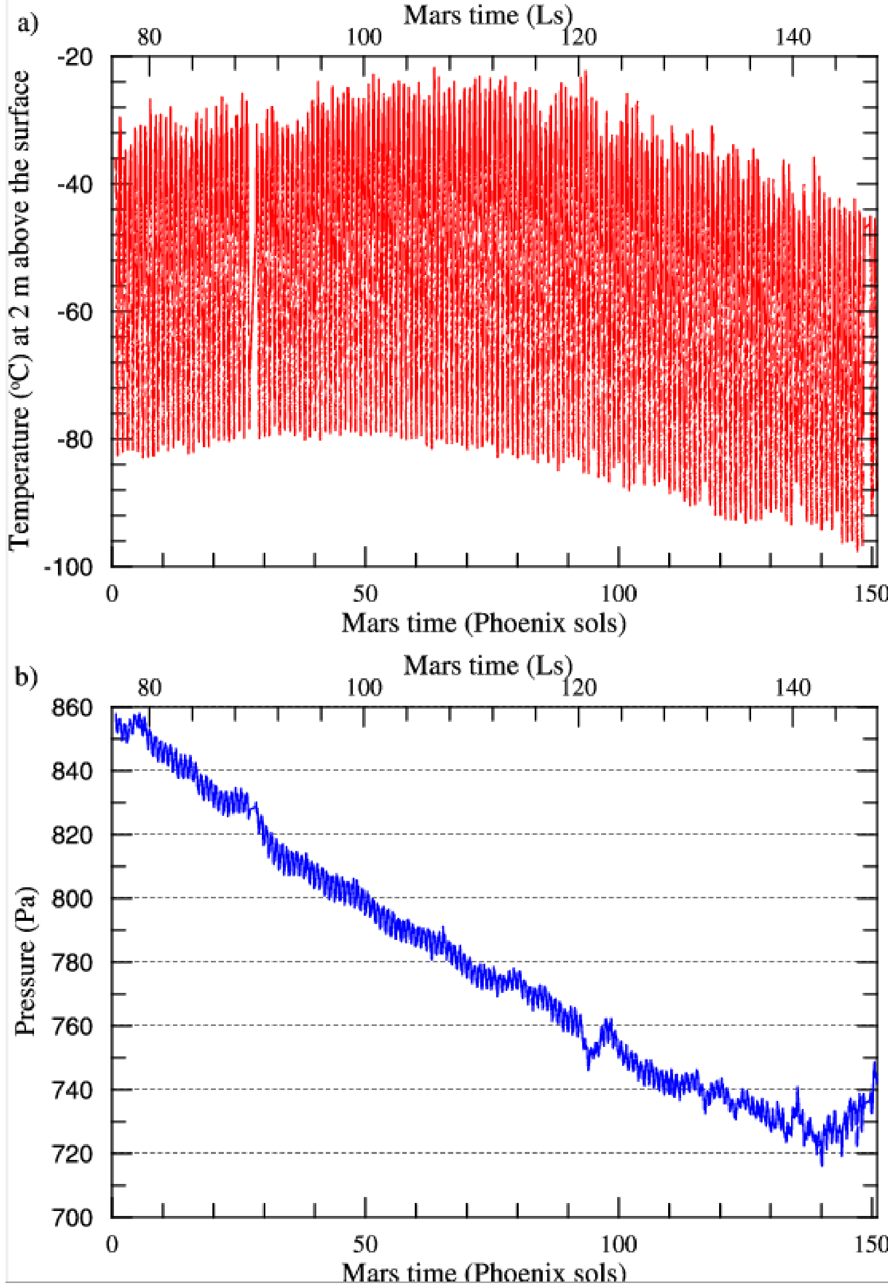




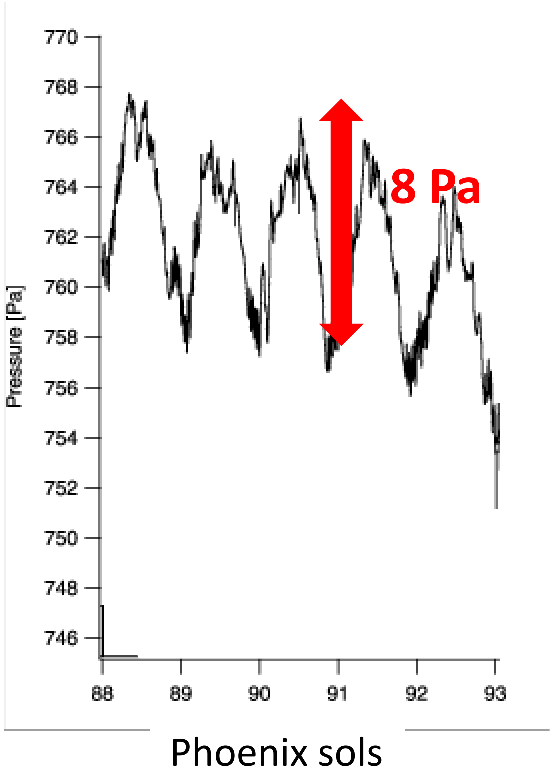
- Baroclinic waves disappear in summer (unlike Earth)

equator-pole gradient (baroclinicity) almost disappears in Martian summer

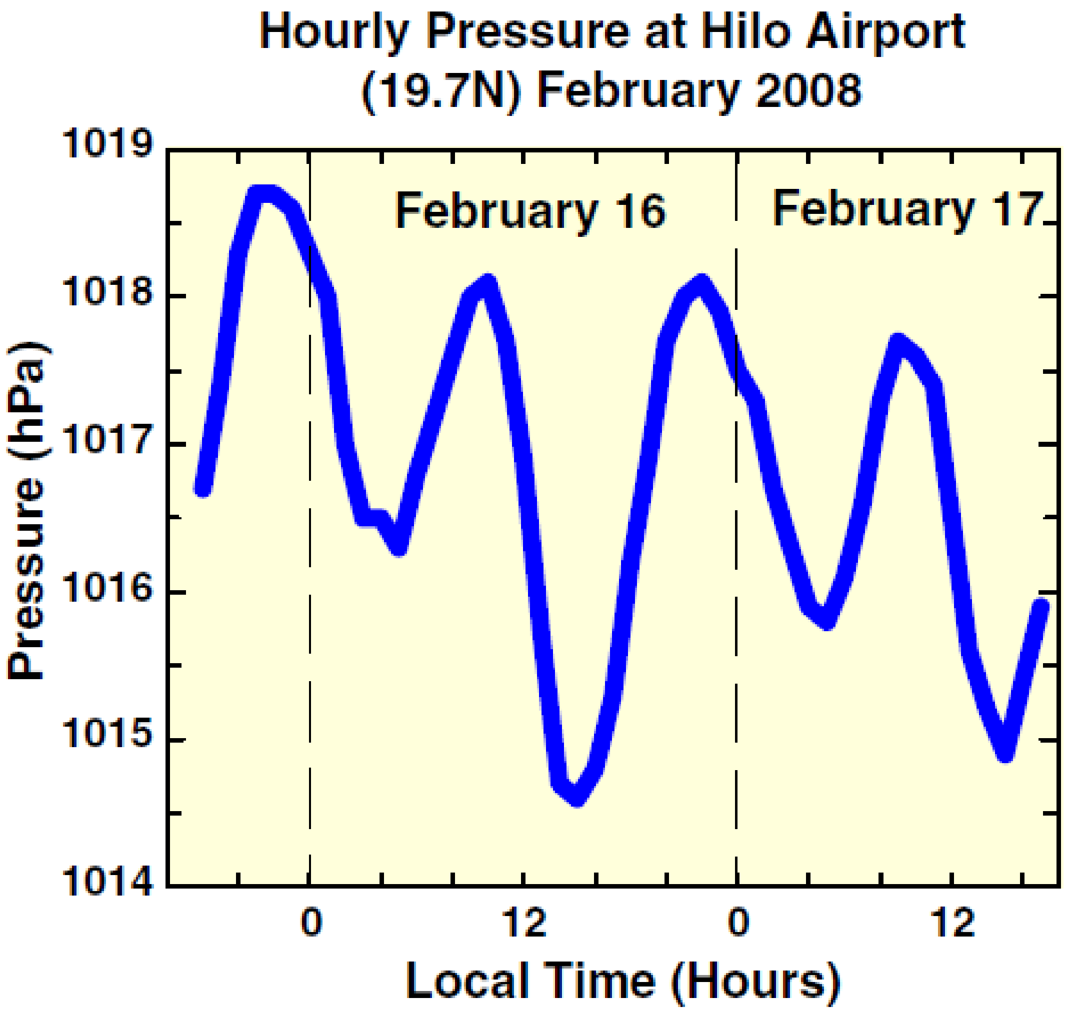

NASA *Phoenix* Lander
~70N
Canada



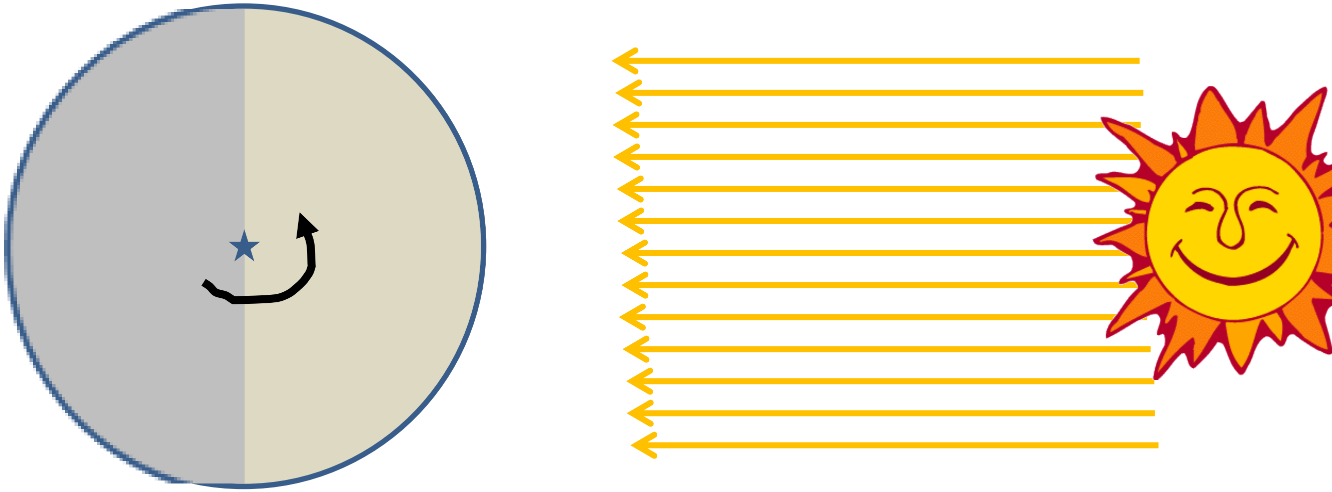
a)
Mars time (Ls)
80
100
120
140
Temperature (ºC) at 2 m above the surface
-20
-40
-60
-80
-100
0
50
100
150
Mars time (Phoenix sols)
b)
Mars time (Ls)
80
100
120
140
Pressure (Pa)
860
840
820
800
780
760
740
720
700
0
50
100
150
Mars time (Phoenix sols)



8 Pa
Pressure [Pa]
770
768
766
764
762
760
758
756
754
752
750
748
746
88
89
90
91
92
93
Phoenix sols


Hourly Pressure at Hilo Airport
(19.7N) February 2008
February 16
February 17
Pressure (hPa)
1019
1018
1017
1016
1015
1014
0
12
0
12
Local Time (Hours)

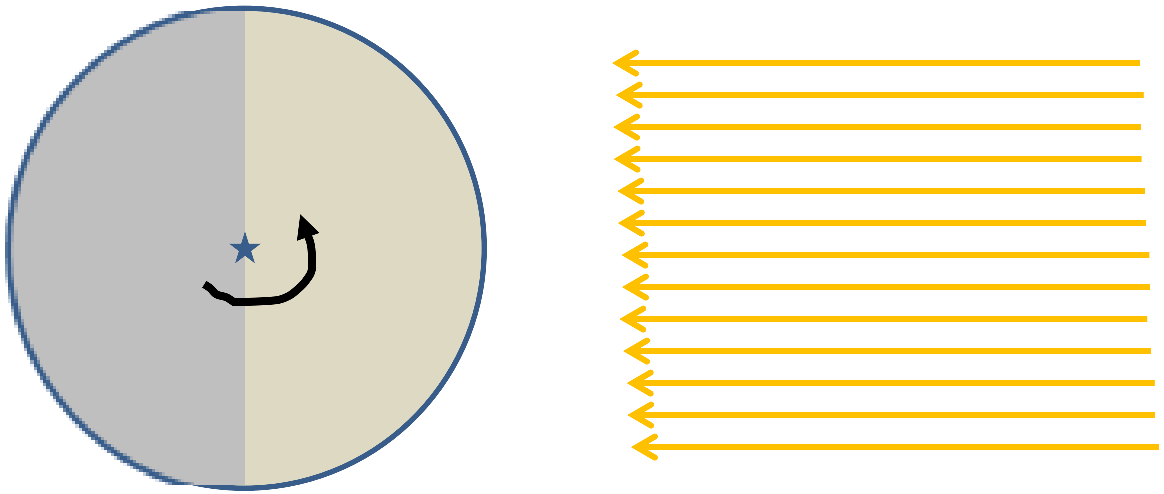
Looking down on North Pole



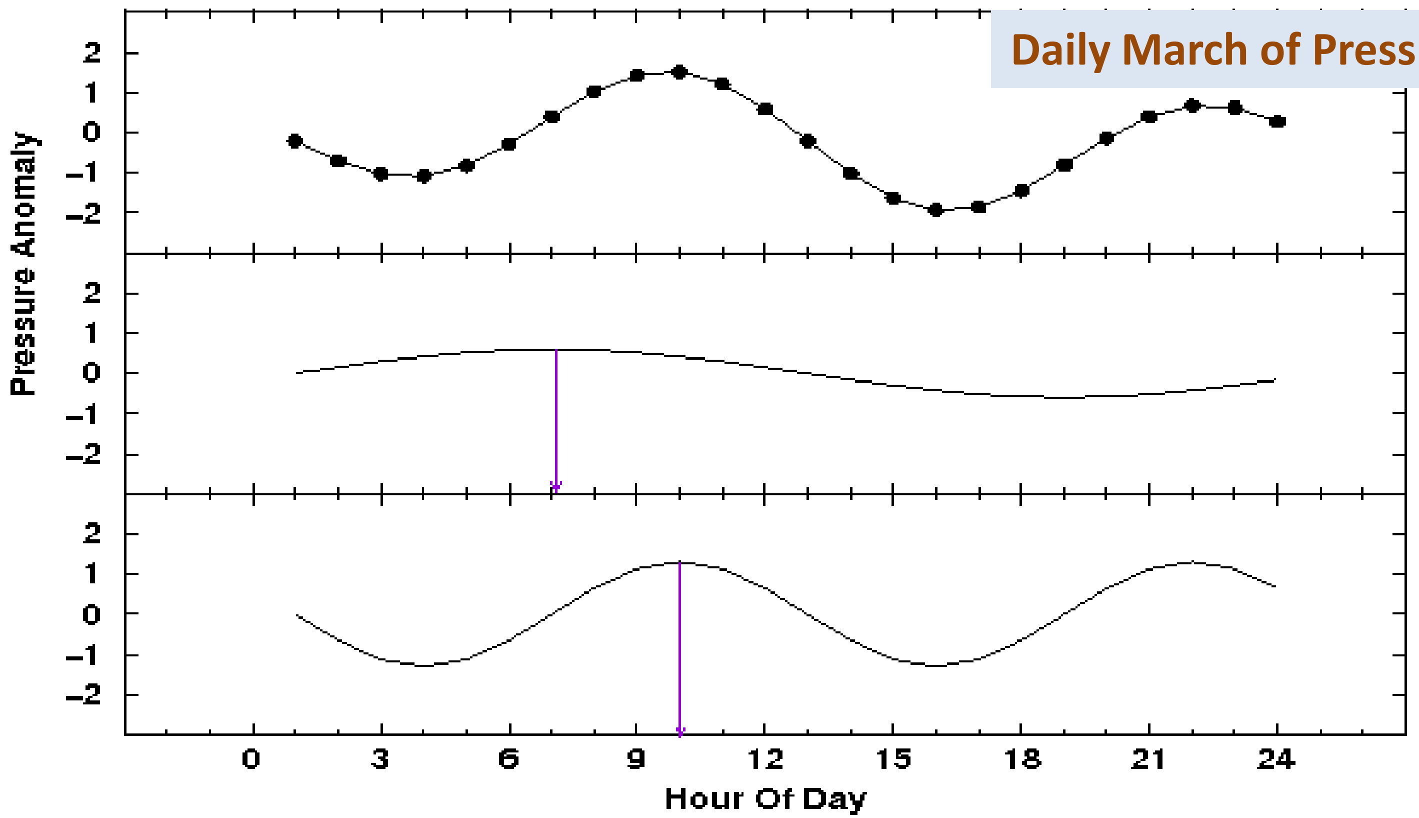
Earth thermal tides vs Mars thermal tides

Similar rotation rate

Less atmosphere mass on Mars ➔ stronger tide in temperature or δP/P



Daily March of Pressure (or T…)

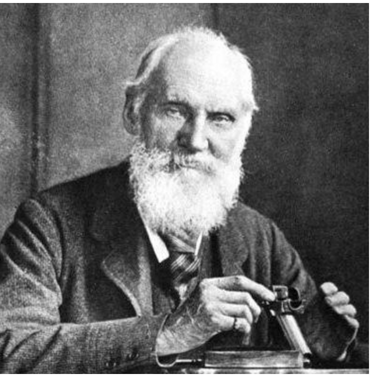


S1(p) solar diurnal (24 hour) harmonic of pressure
S2(p) solar semidiurnal (12 hour) harmonic of pressure

-
-
-

S1(p) solar diurnal (24 hour) harmonic of pressure
S2(p) solar semidiurnal (12 hour) harmonic of pressure

- S2(p) ~twice as large as S1(p) in tropics

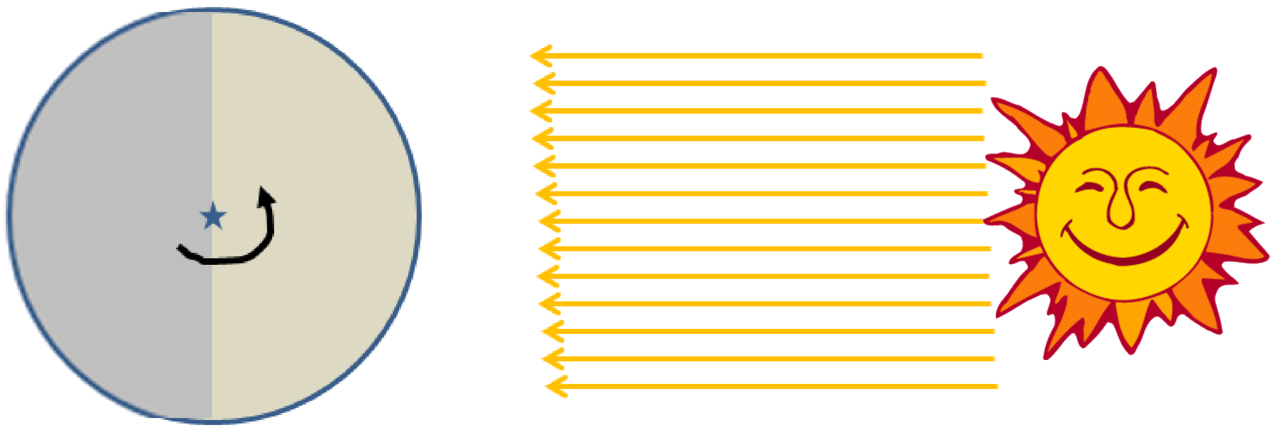


Lord Kelvin proposed global resonance --NO!

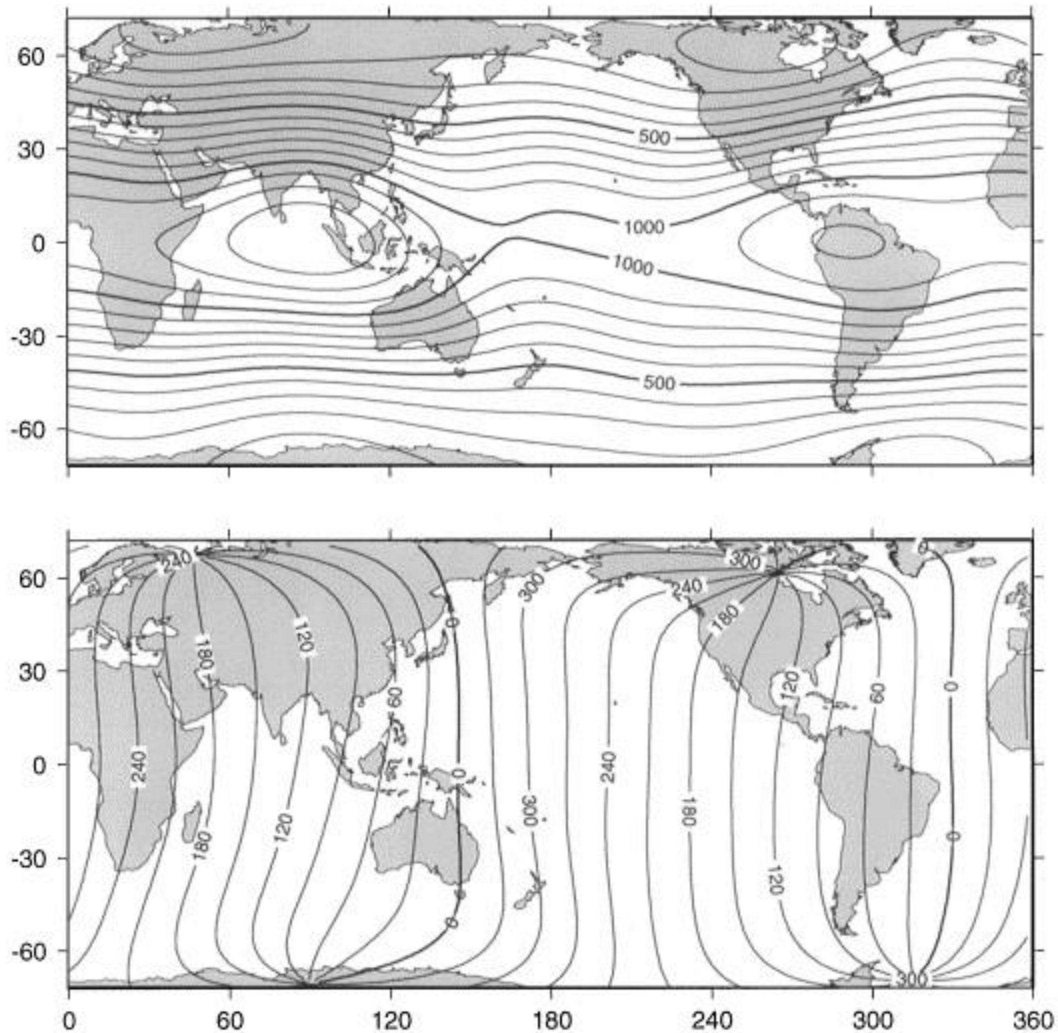
- (although I believe that on Mars the tide is resonant - Hamilton & Garcia 1986; Wilson & Hamilton 1996)

Sun-Synchronous Tides

- Without zonal asymmetry in forcing (absorber distributions; convective heating...), or mean state, or lower boundary (e.g. topography). Leads to a response which has amplitude only dependent on latitude and
- either constant phase (in local time) or uniform westward propagation (in Greenwich time)



Observed Annual Mean Amplitude and Phase for S2(p)

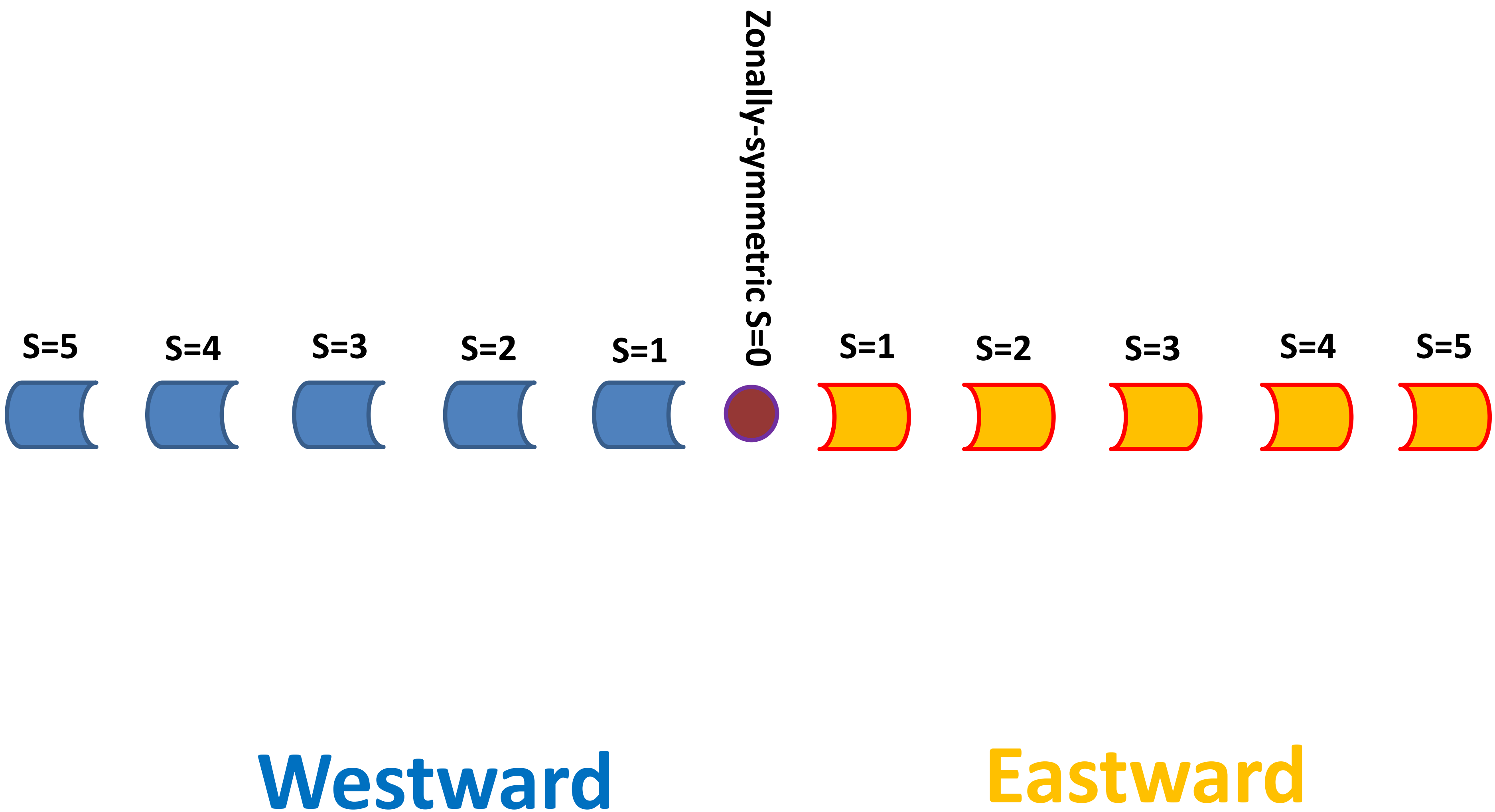


Sun-Synchronous Tides

- Without zonal asymmetry in forcing (absorber distributions; convective heating...), or mean state, or lower boundary (e.g. topography). Leads to a response which has amplitude only dependent on latitude and
- either constant phase (in local time) or uniform westward propagation (in Greenwich time)

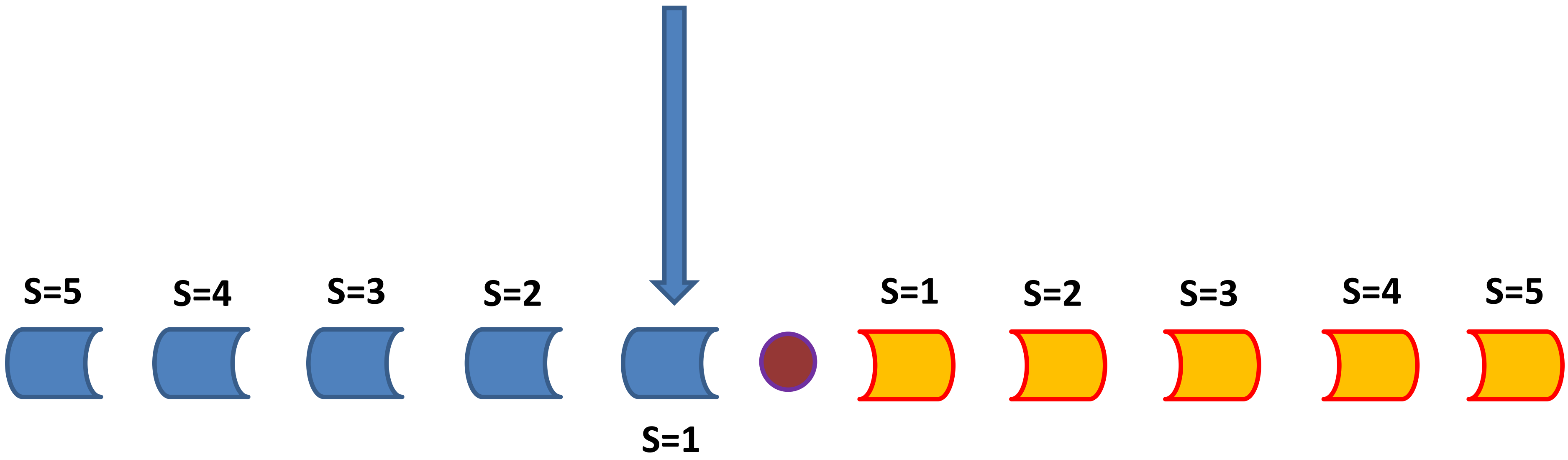
Non-Sun-Synchronous NSS Tides

- Forced by zonal asymmetry in forcing (absorber distributions; convective heating...), or mean state, or lower boundary (e.g. topography)



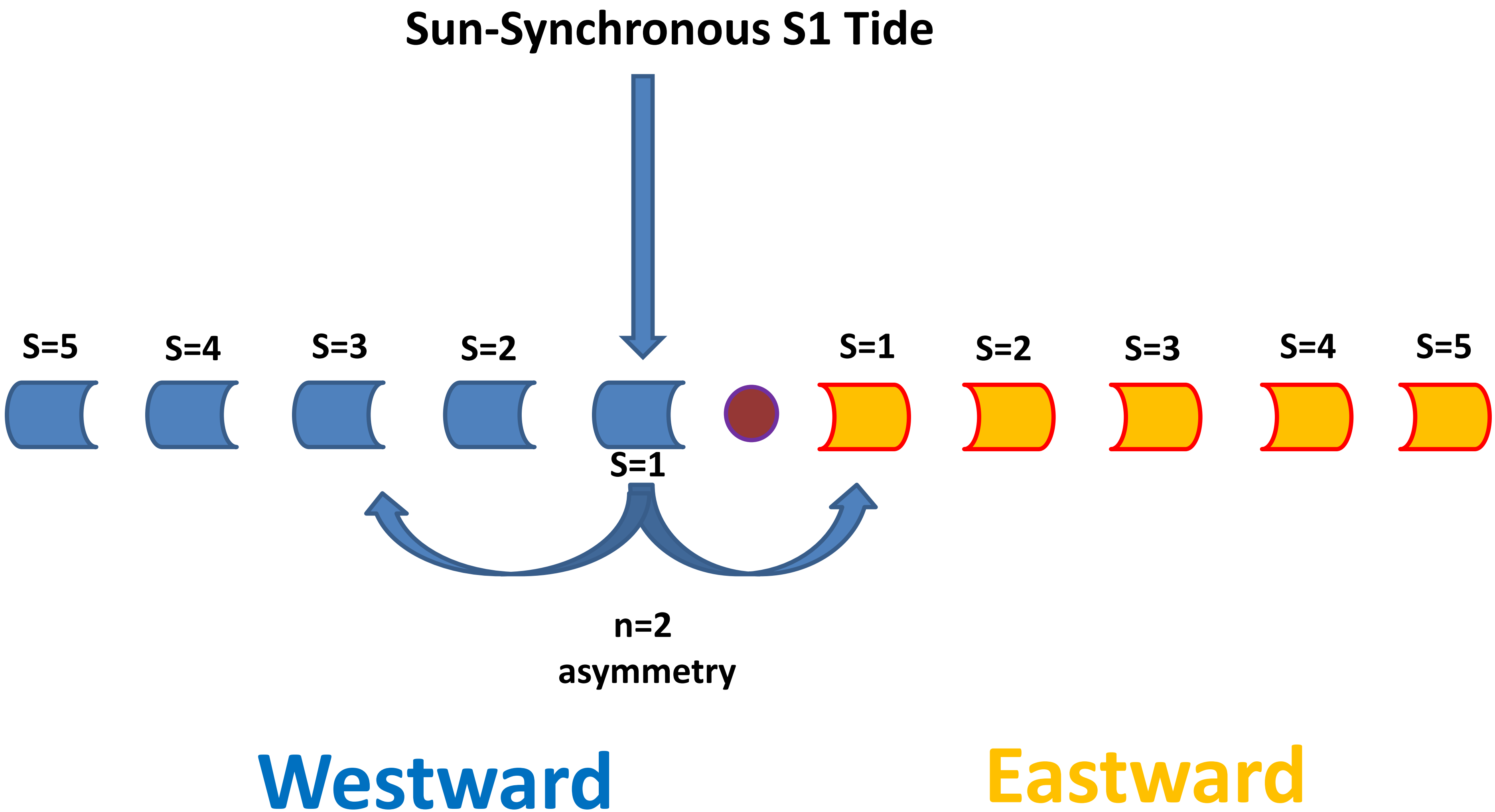
Zonally-symmetric S=0
S=5
S=4
S=3
S=2
S=1
S=1
S=2
S=3
S=4
S=5
Westward
Eastward

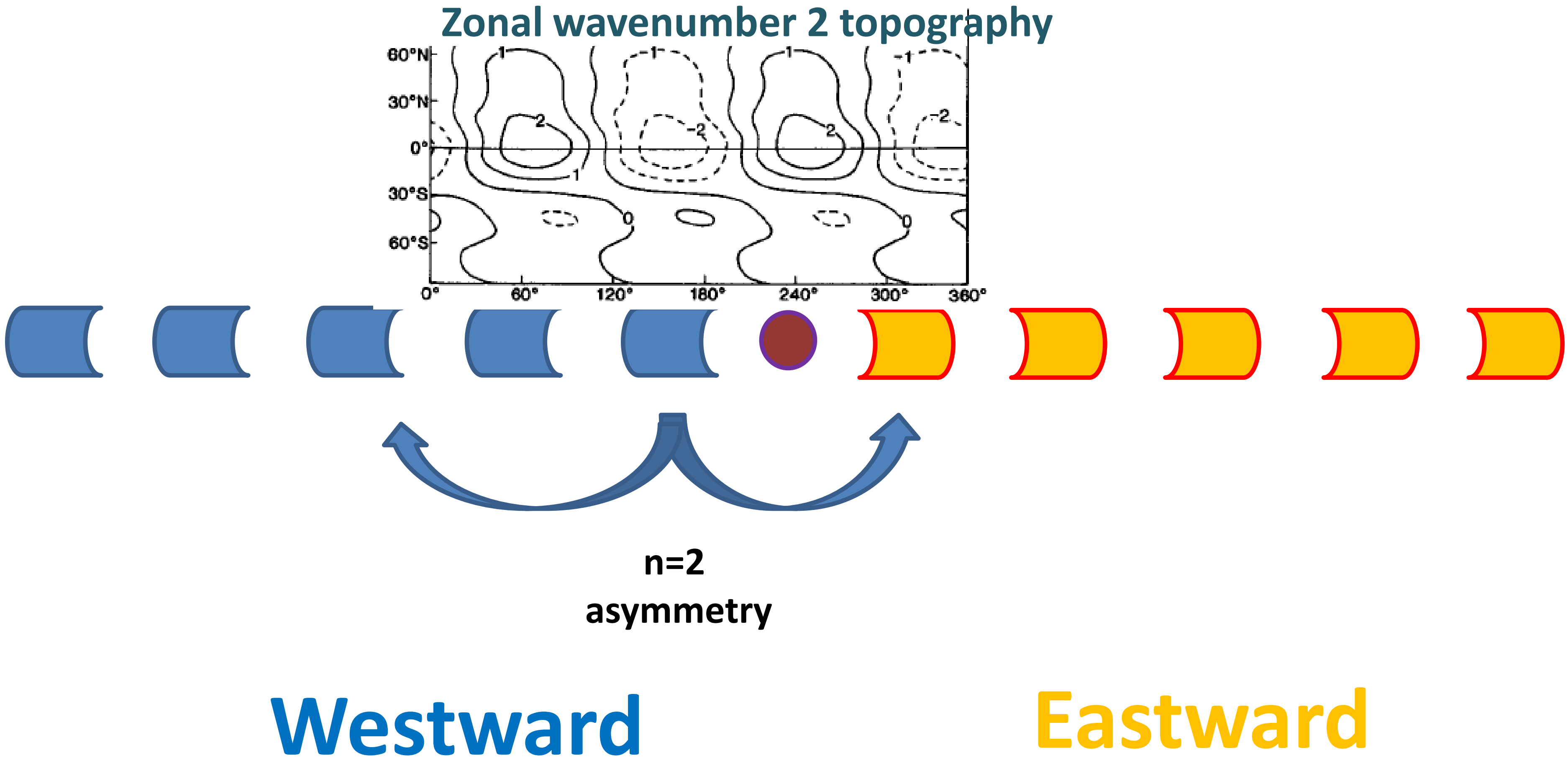
Sun-Synchronous S1 Tide

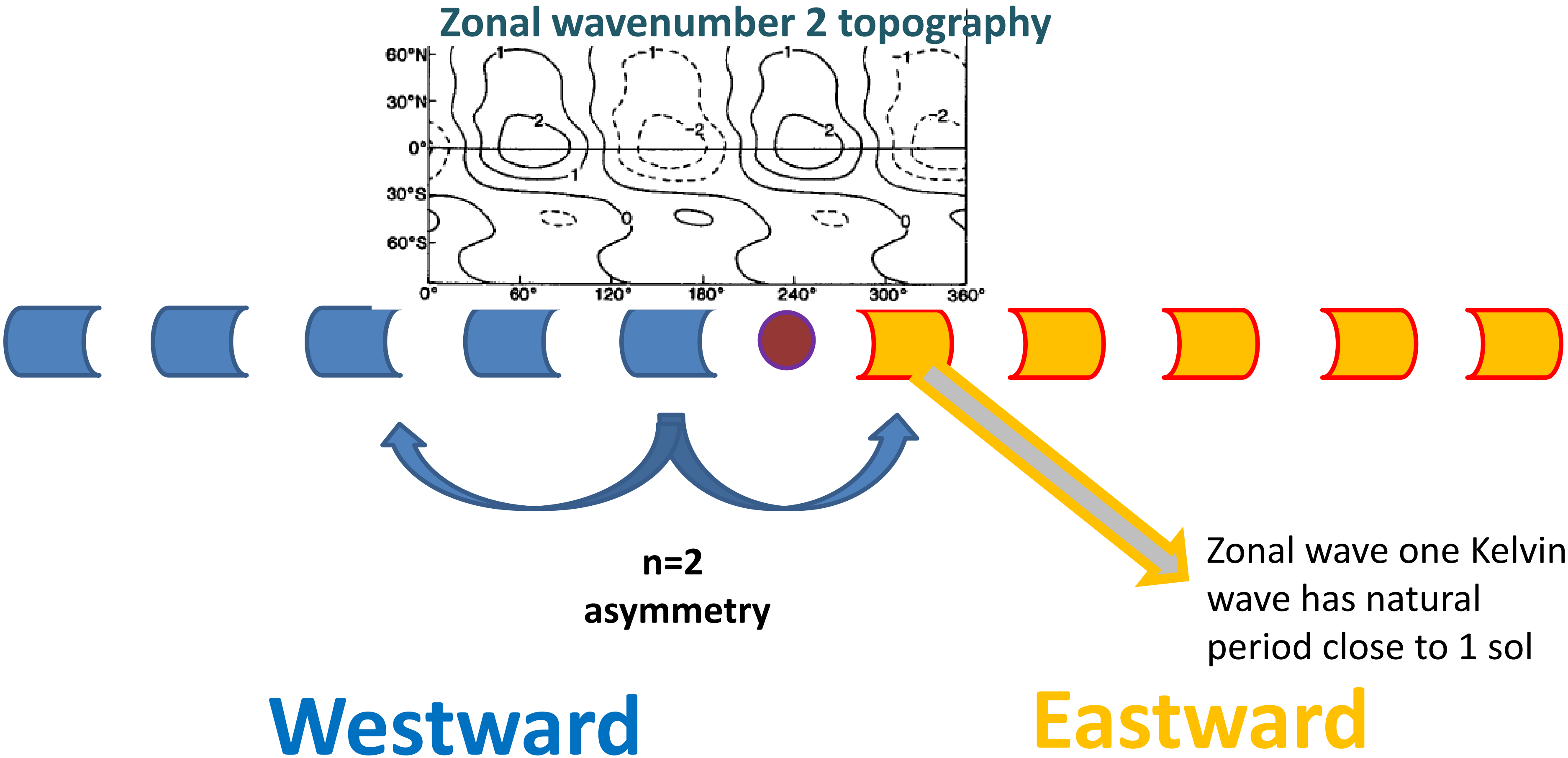


Westward

Eastward


Sun-Synchronous S1 Tide
S=5
S=4
S=3
S=2
S=1
S=1
S=2
S=3
S=4
S=5
n=2
asymmetry
Westward
Eastward

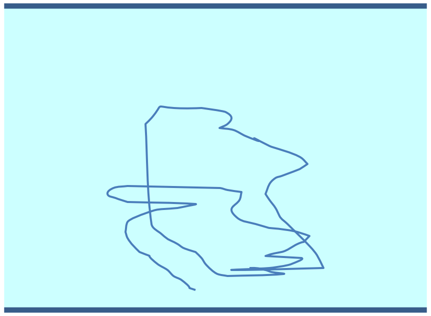

Zonal wavenumber 2 topography
60°N
30°N
0°
30°S
60°S
0°
60°
120°
180°
240°
300°
360°
n=2
asymmetry
Westward
Eastward



Zonal wavenumber 2 topography
60°N
30°N
0°
30°S
60°S
0°
60°
120°
180°
240°
300°
360°
n=2
asymmetry
Zonal wave one Kelvin
wave has natural
period close to 1 sol
Westward
Eastward

RESONANCE OF THE GLOBAL ATMOSPHERE

Inviscid stratified ocean, rigid lid

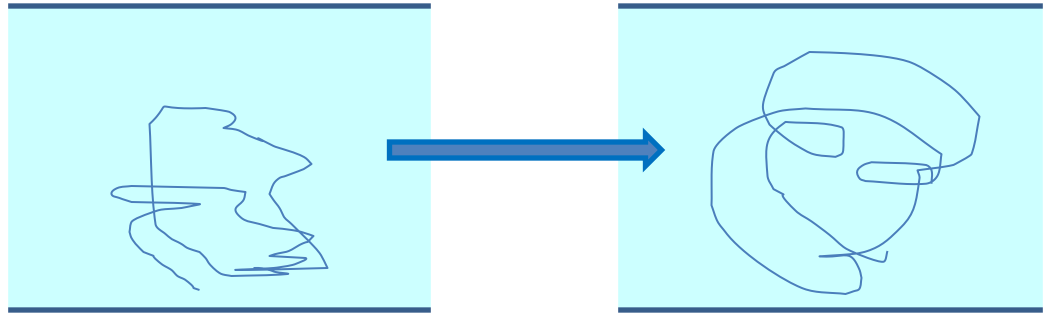


Inviscid stratified atmosphere, radiation condition at “top”

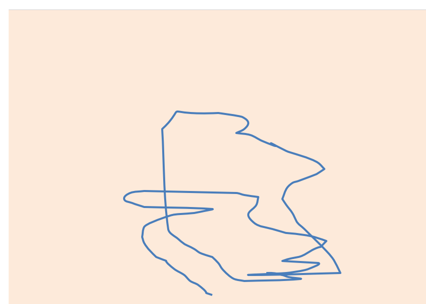
Initially

Inviscid stratified ocean, rigid lid

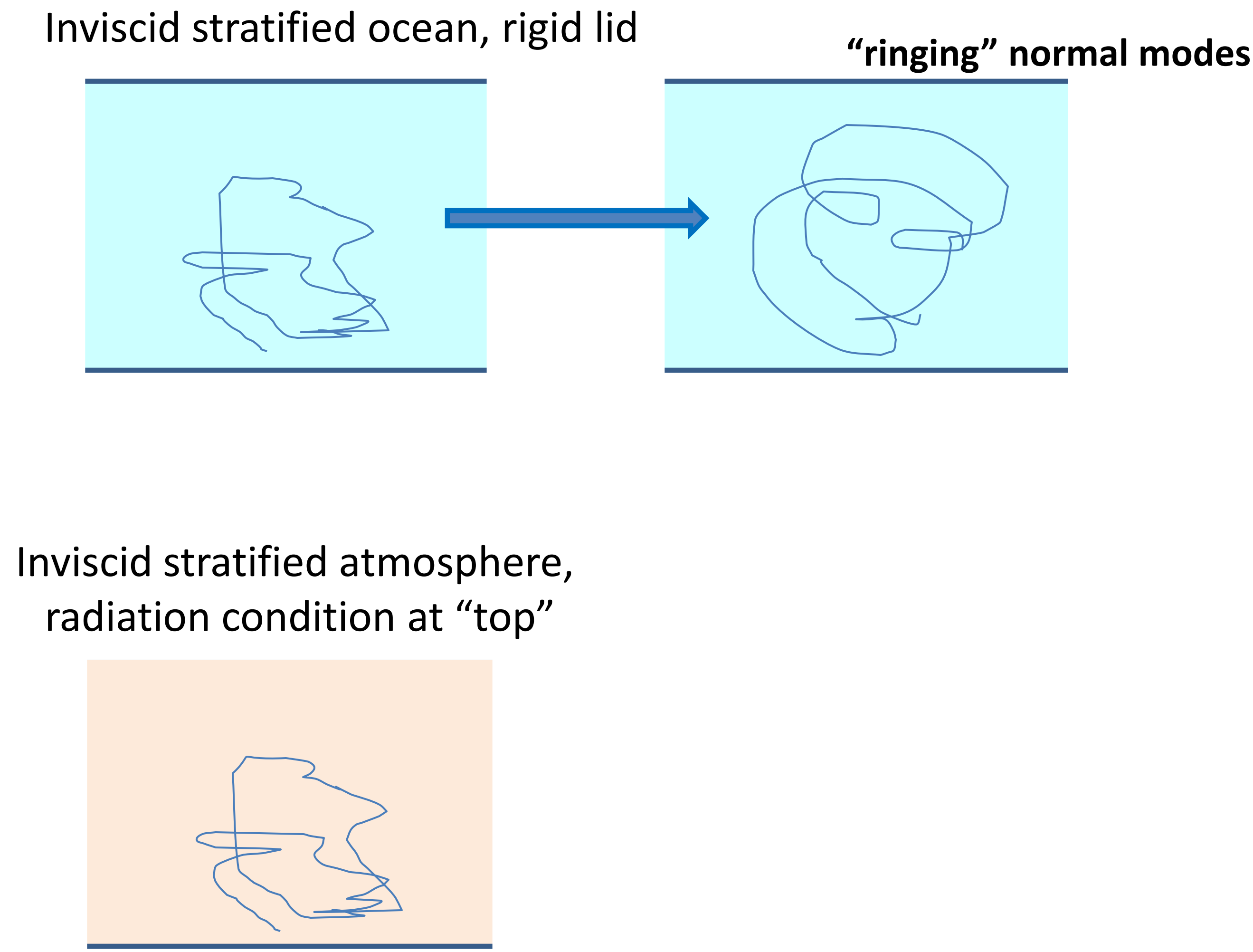
“ringing” normal modes



Inviscid stratified atmosphere, radiation condition at “top”

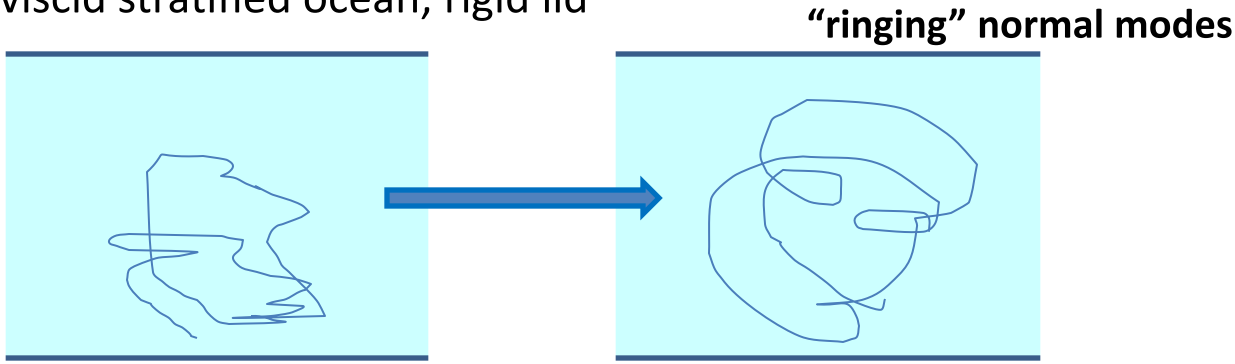


Initially

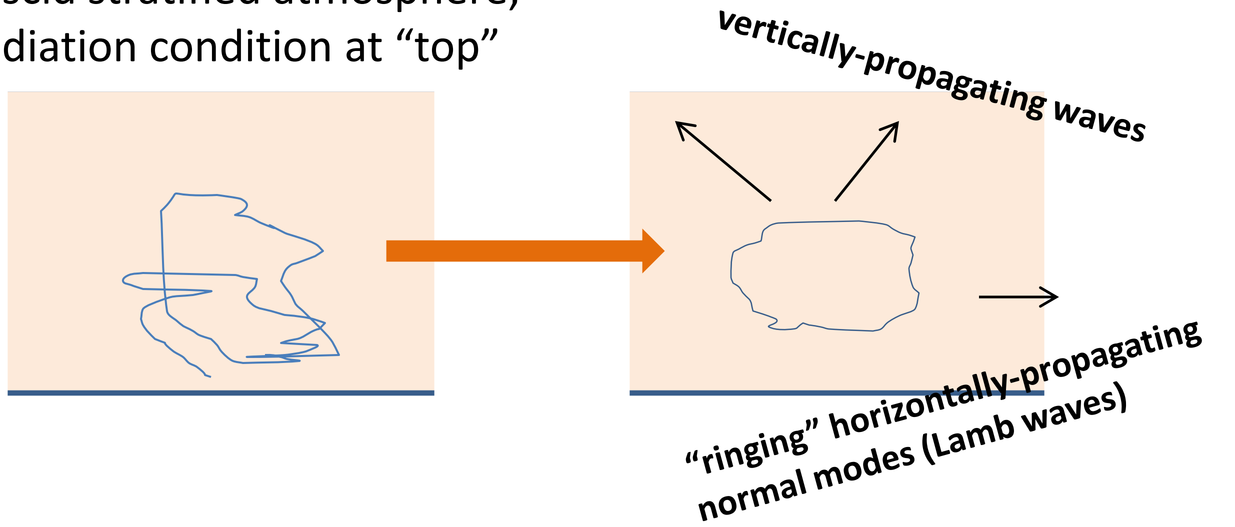

Inviscid stratified ocean, rigid lid
"ringing" normal modes
Inviscid stratified atmosphere,
radiation condition at "top"

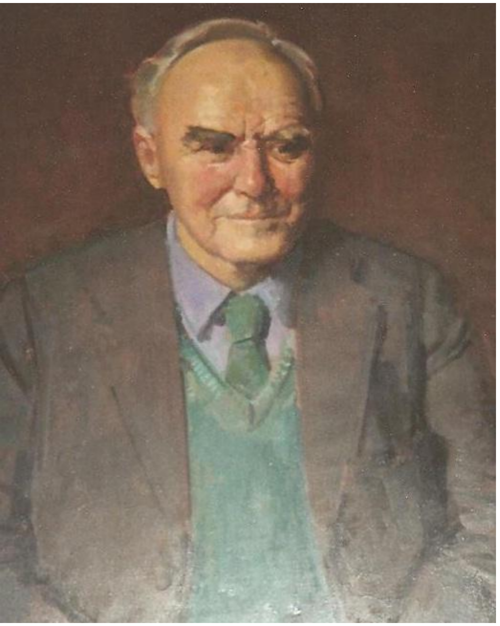
Initially

Inviscid stratified ocean, rigid lid

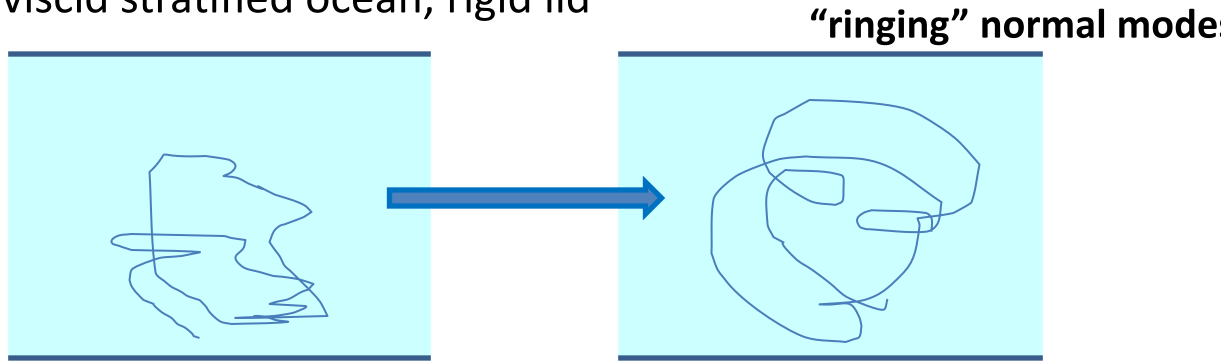


Inviscid stratified atmosphere, radiation condition at "top"

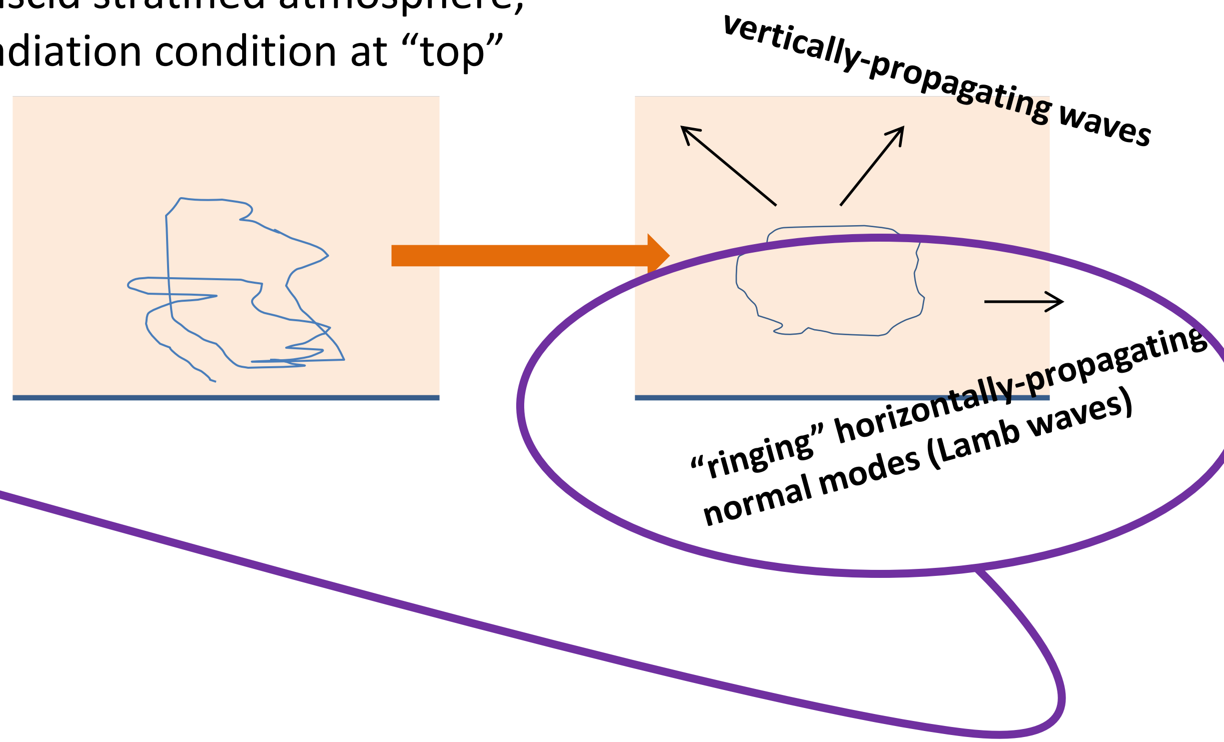




Inviscid stratified ocean, rigid lid



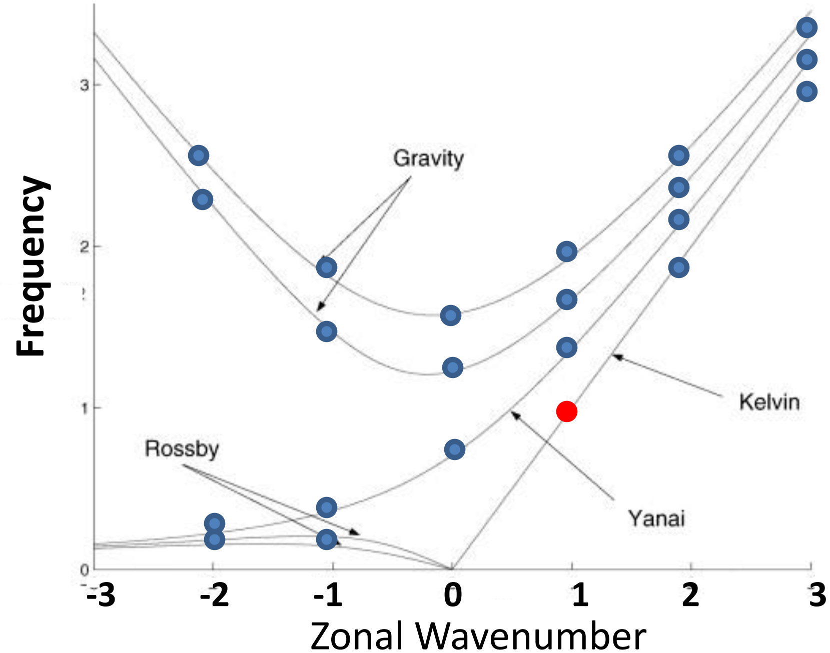
Inviscid stratified atmosphere, radiation condition at “top”



G.I. Taylor **showed that the free oscillations of the atmosphere had frequencies equal to those of a shallow water ocean of depth 10 km**

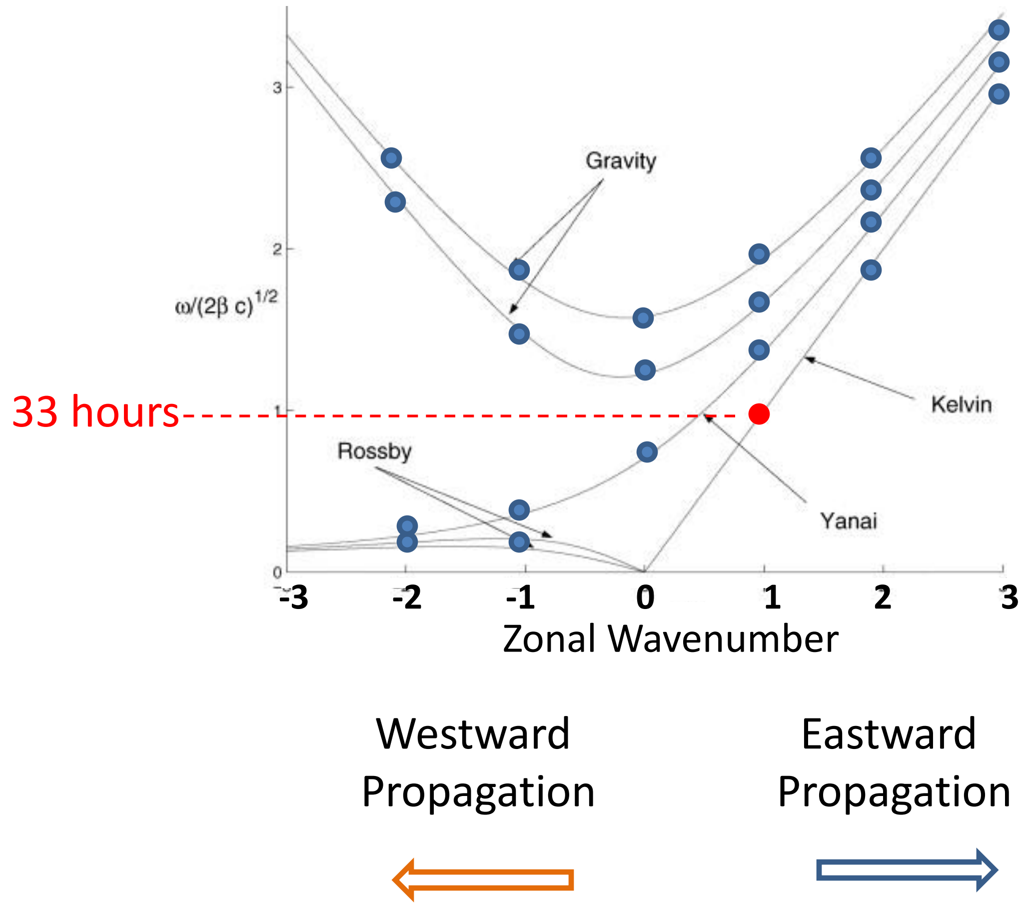
T. Matsuno

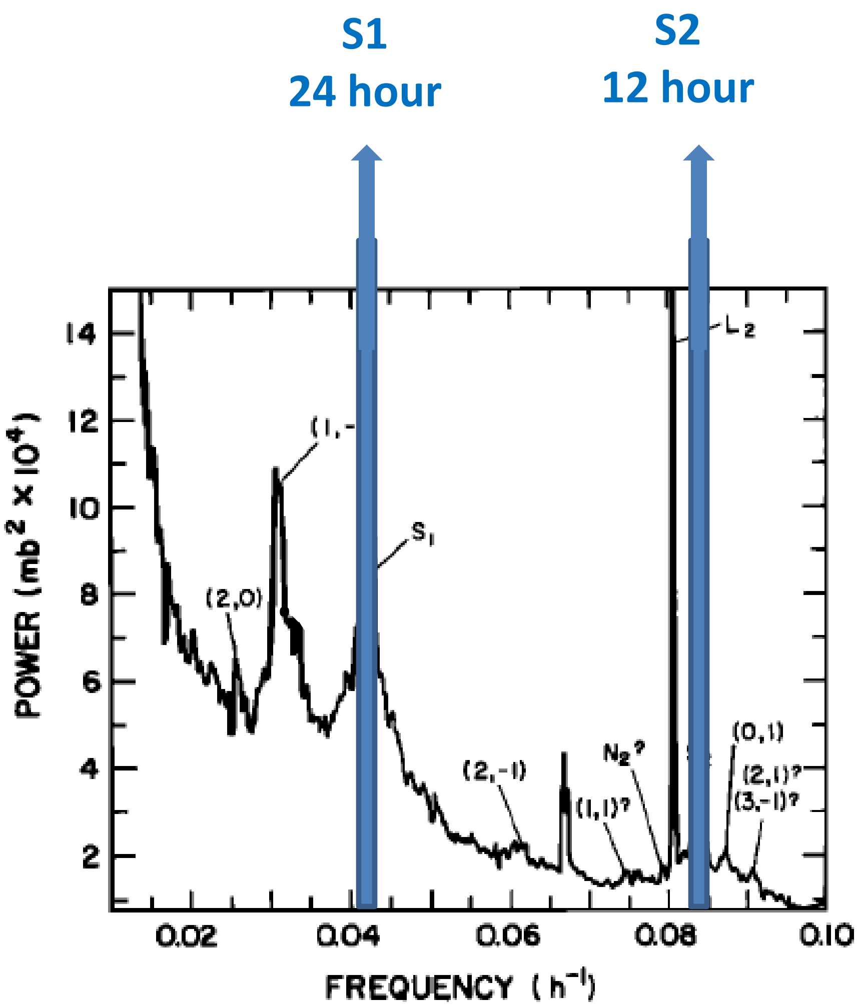
M. Longuet-Higgins

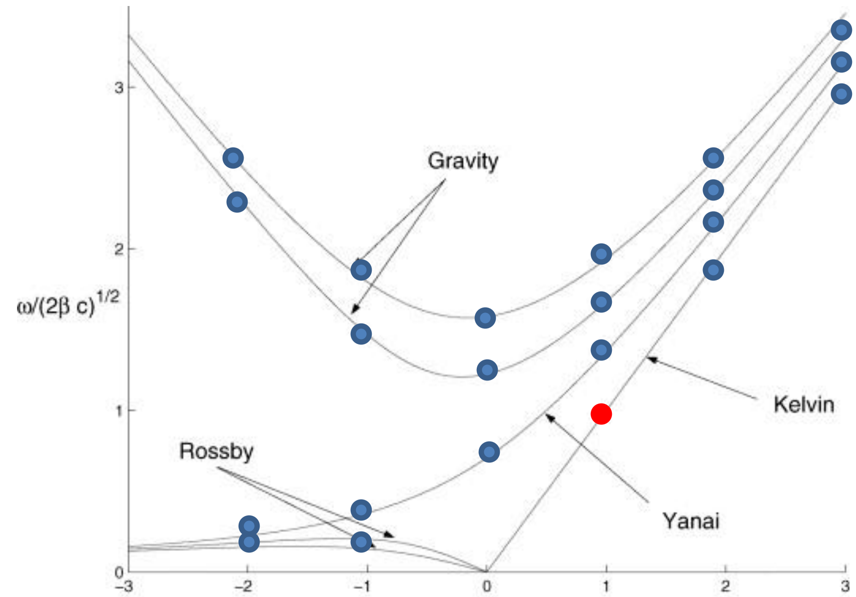


Westward Propagation

Eastward Propagation

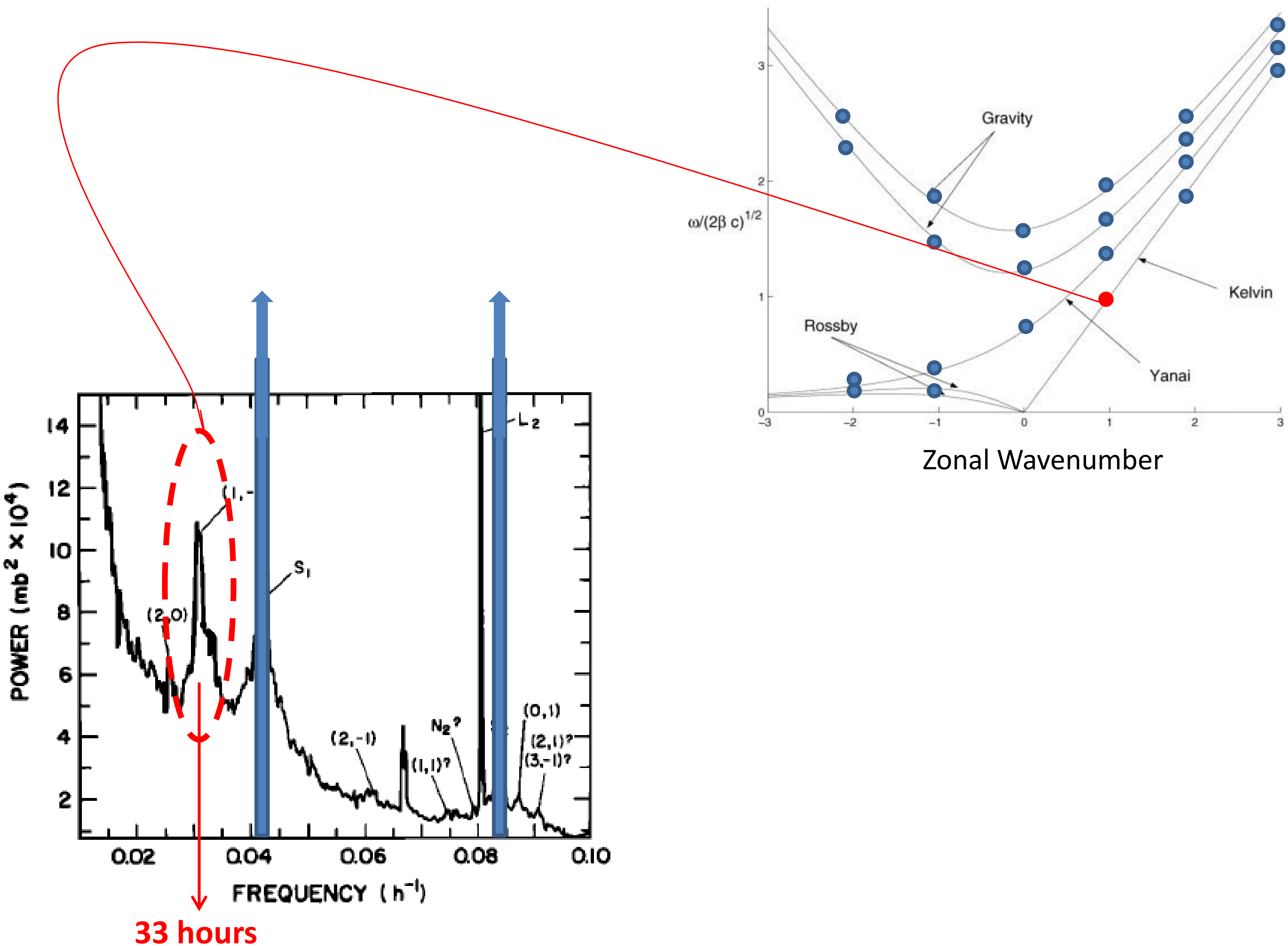

33 hours
ω/(2β c)^1/2
Gravity
Kelvin
Yanai
Rossby
0
1
2
3
-3
-2
-1
0
1
2
3
Zonal Wavenumber
Westward Propagation
Eastward Propagation

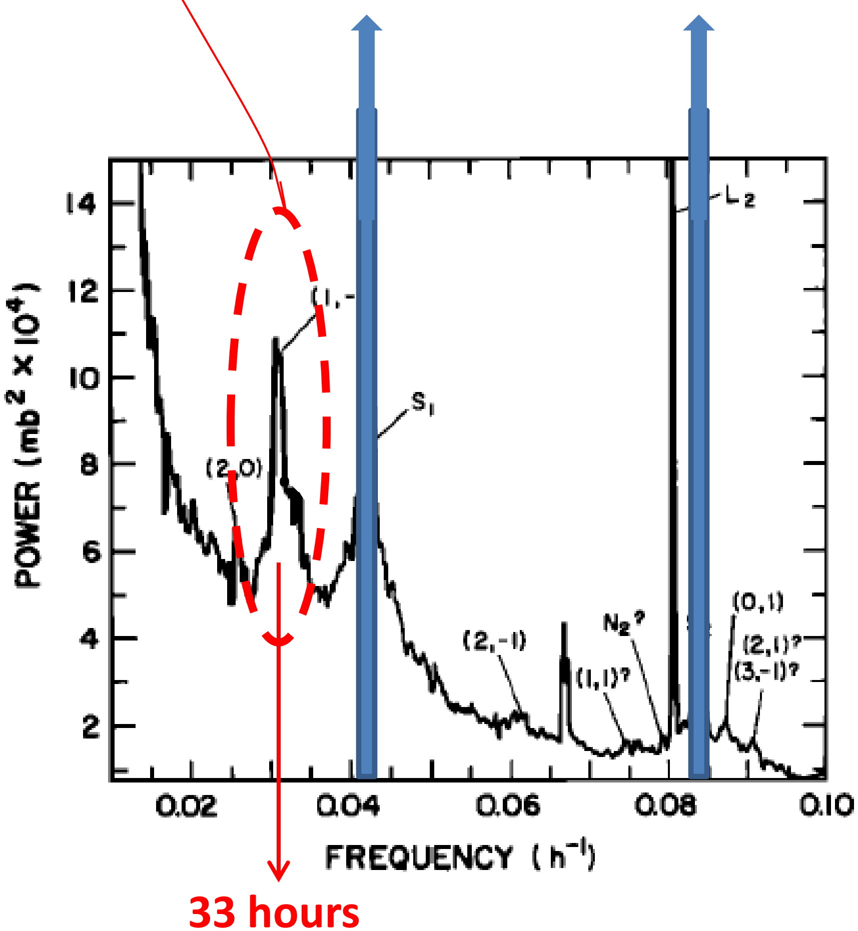


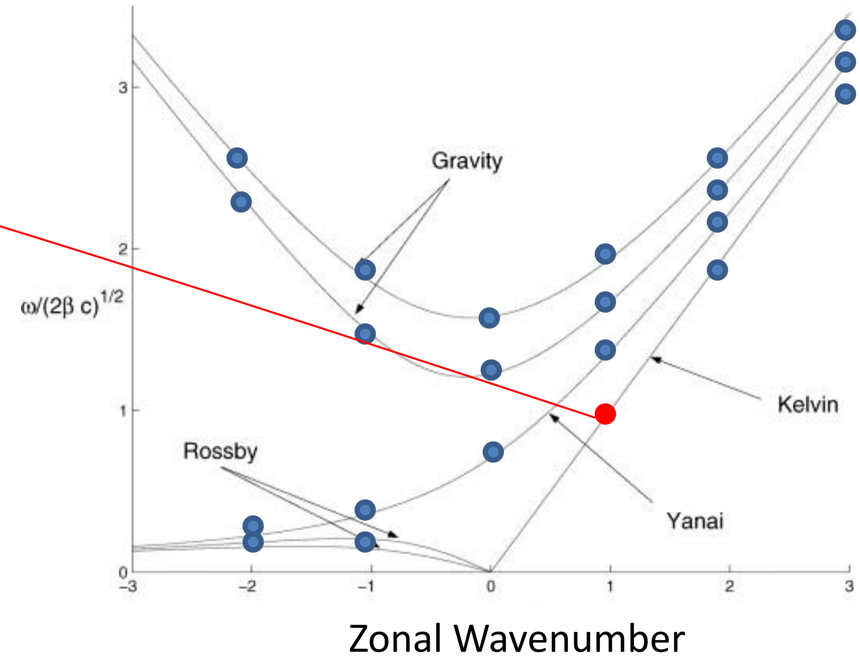


Zonal Wavenumber

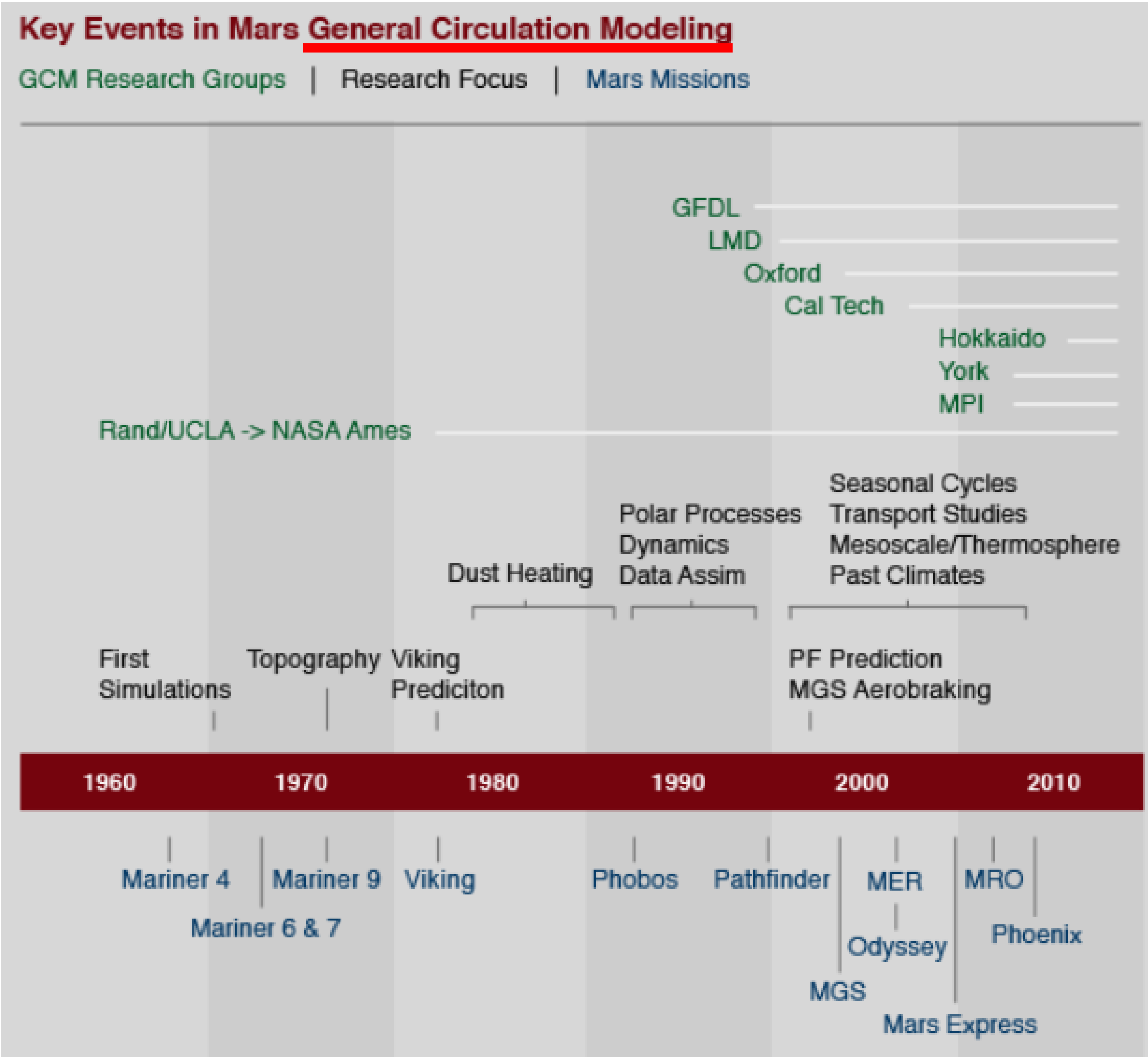
Power spectrum of 77 years of hourly surface pressure observations at Djakarta (6°S)

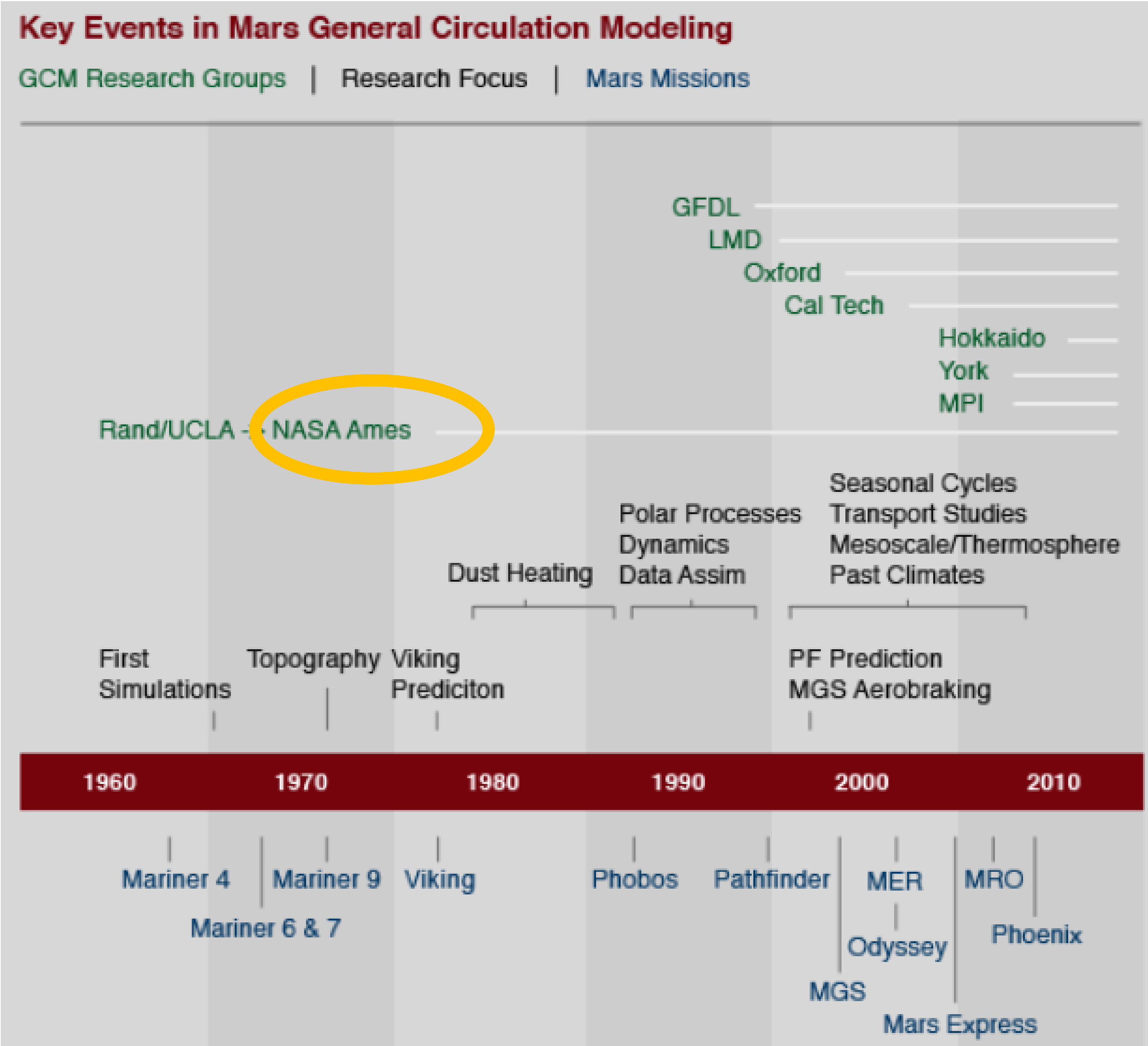

Gravity
Kelvin
Rossby
Yanai
ω/(2β c)^1/2
Zonal Wavenumber
POWER (mb² x 10⁴)
FREQUENCY (h⁻¹)
(2,0)
S₁
L₂
(2,-1)
(1,1)?
N₂?
(0,1)
(2,1)?
(3,-1)?
33 hours





Hamilton & Garcia (1986) noted that on Mars the period of the wave 1 Kelvin normal mode could be close to 1 sol.


Key Events in Mars General Circulation Modeling
GCM Research Groups | Research Focus | Mars Missions
GFDL
LMD
Oxford
Cal Tech
Hokkaido
York
MPI
Rand/UCLA -> NASA Ames
Seasonal Cycles
Transport Studies
Mesoscale/Thermosphere
Past Climates
Polar Processes
Dynamics
Data Assim
Dust Heating
First Simulations
Topography
Viking Prediciton
PF Prediction
MGS Aerobraking
1960
1970
1980
1990
2000
2010
Mariner 4
Mariner 6 & 7
Mariner 9
Viking
Phobos
Pathfinder
MGS
MER
Odyssey
Mars Express
MRO
Phoenix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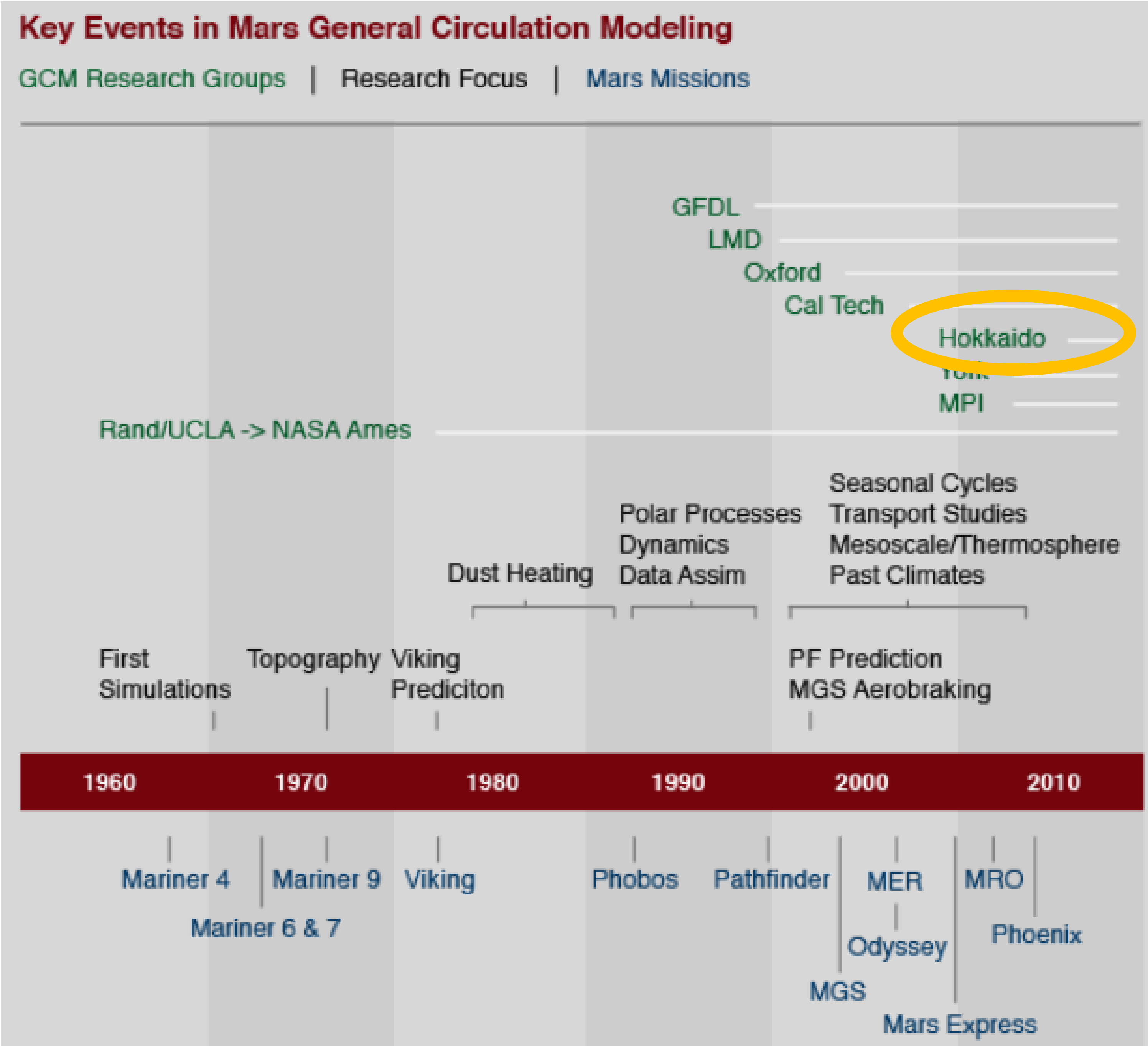
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JGR | Journal of Geophysical Research
Planets

Topographically induced north-south asymmetry of the meridional circulation in the Martian atmosphere

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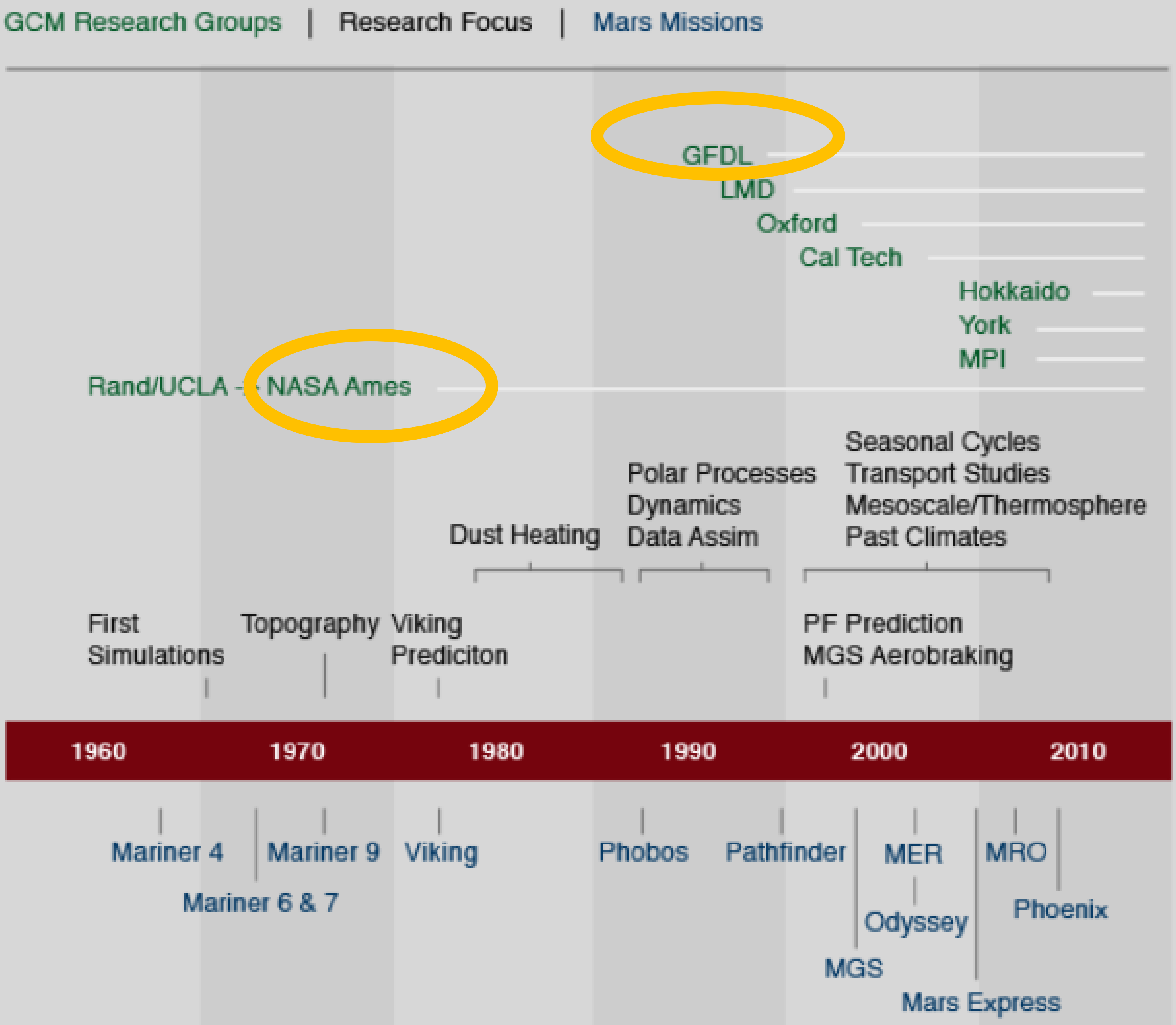
Key Events in Mars General Circulation Modeling



Comprehensive Model Simulation of Thermal Tides in the Martian Atmosphere

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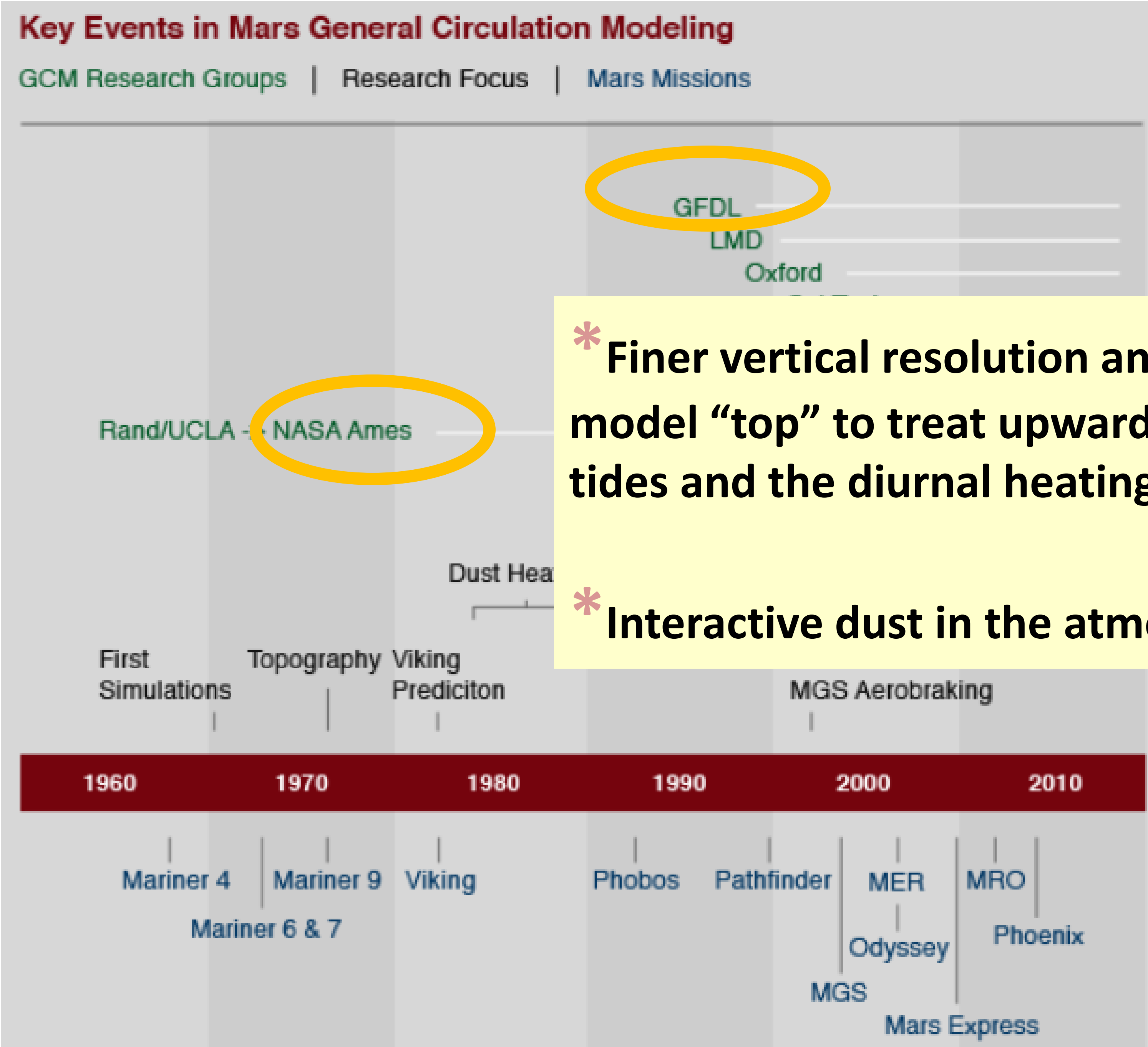
(Manuscript received 20 June 1995, in final form 30 October 1995)

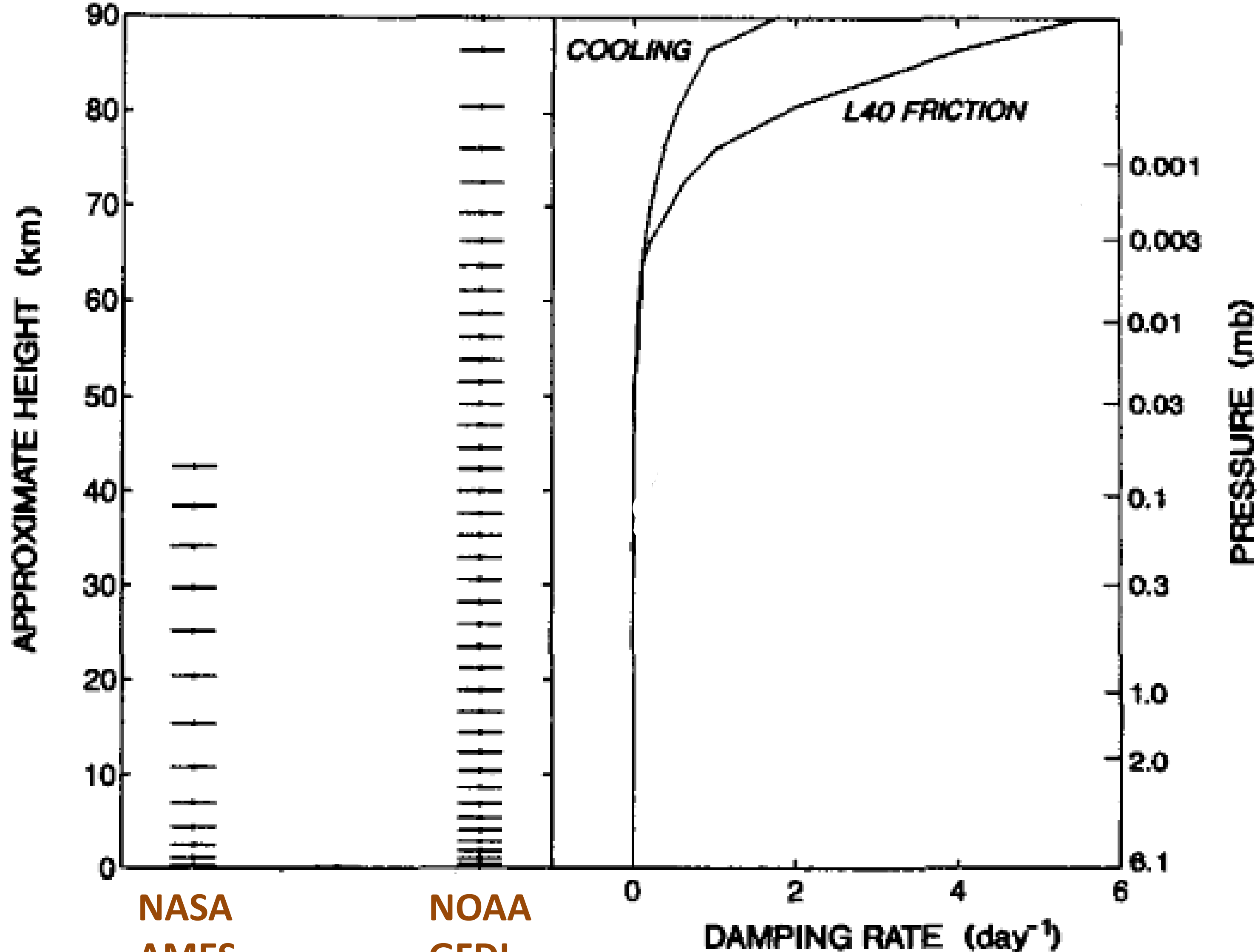
ABSTRACT

This paper discusses the thermotidal oscillations in simulations performed with a newly developed comprehensive general circulation model of the Martian atmosphere. With reasonable assumptions about the effective thermal inertia of the planetary surface and about the distribution of radiatively active atmospheric aerosol, the model produces both realistic zonal-mean temperature distributions and a diurnal surface pressure oscillation of at least roughly realistic amplitude. With any reasonable aerosol distribution, the simulated diurnal pressure oscillation has a very strong zonal variation, in particular a very pronounced zonal wavenumber-2 modulation. This results from a combination of the prominent wave-2 component in the important boundary forcings (topography and surface thermal inertia) and from the fact that the eastward-propagating zonal wave-1 Kelvin normal mode has a period near 1 sol (a Martian mean solar day of 88 775 s). The importance of global resonance

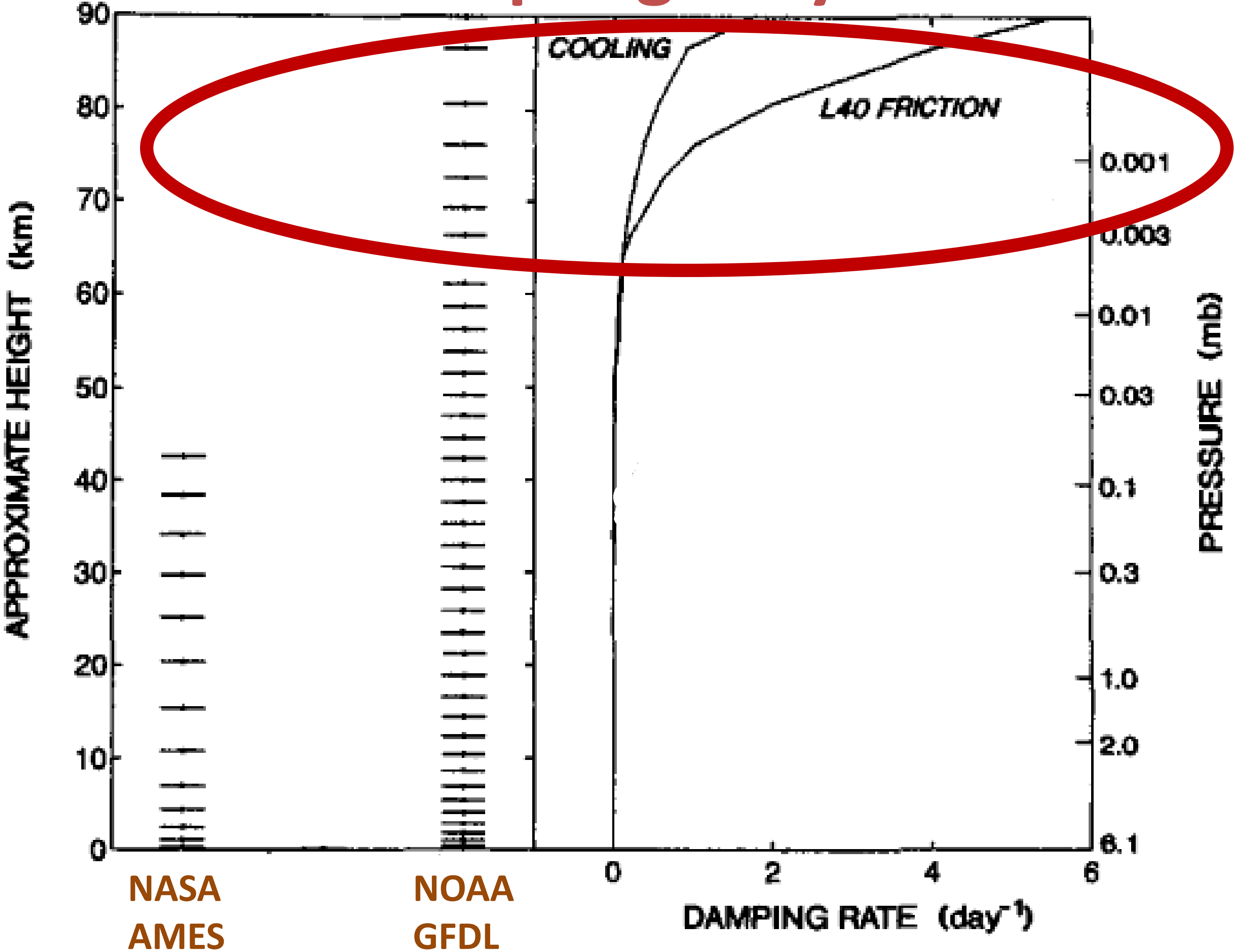


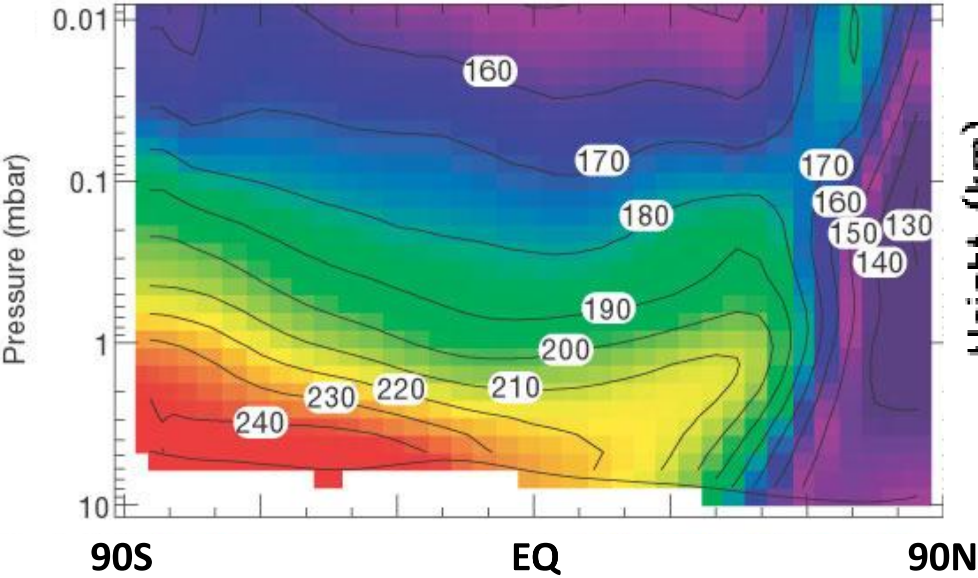
* Finer vertical resolution and higher model "top" to treat upward propagating tides and the diurnal heating near ground

* Interactive dust in the atmosphere

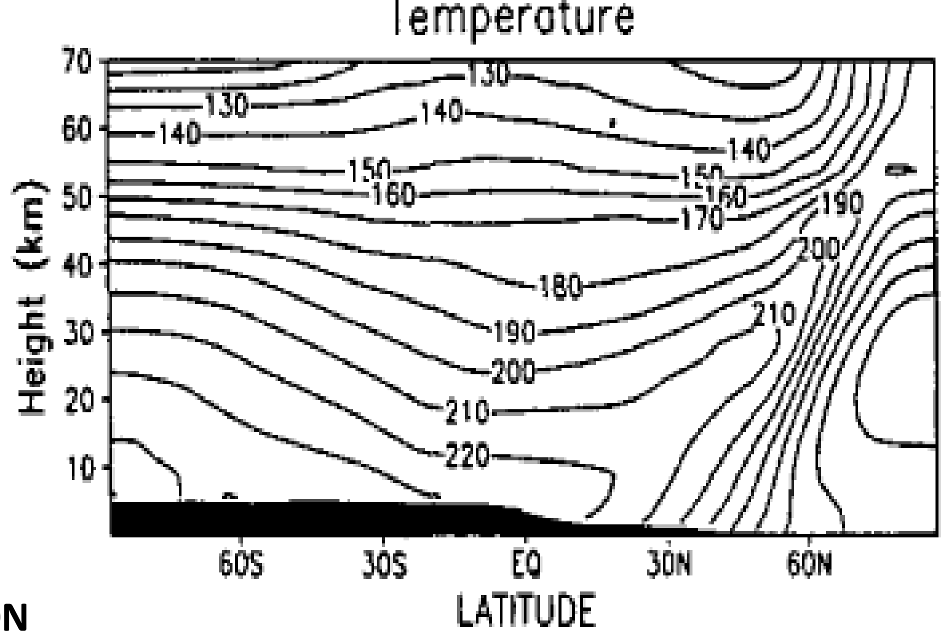

APPROXIMATE HEIGHT (km)
90
80
70
60
50
40
30
20
10
0
COOLING
L40 FRICTION
0.001
0.003
0.01
0.03
0.1
0.3
1.0
2.0
6.1
PRESSURE (mb)
0
2
4
6
DAMPING RATE (day⁻¹)
NASA
AMES
NOAA
GFDL

Sponge Layer

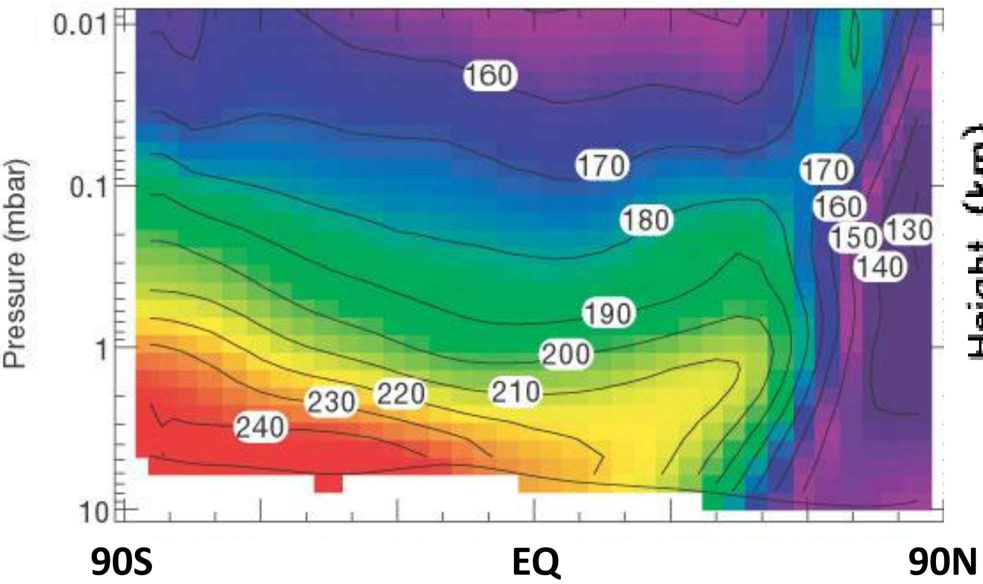




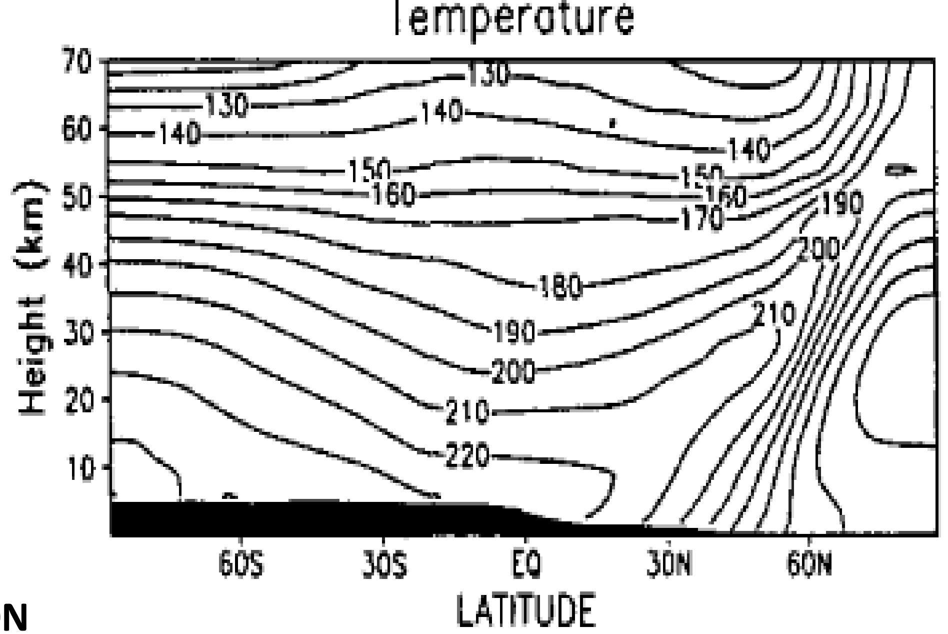
Mars Global Surveyer – Thermal Emission Spectrometer Data



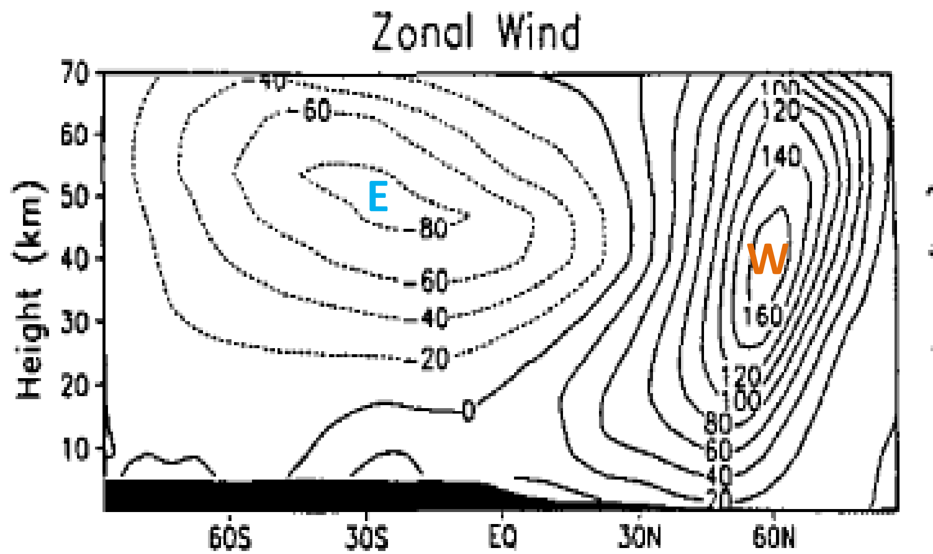
GFDL General Circulation Model



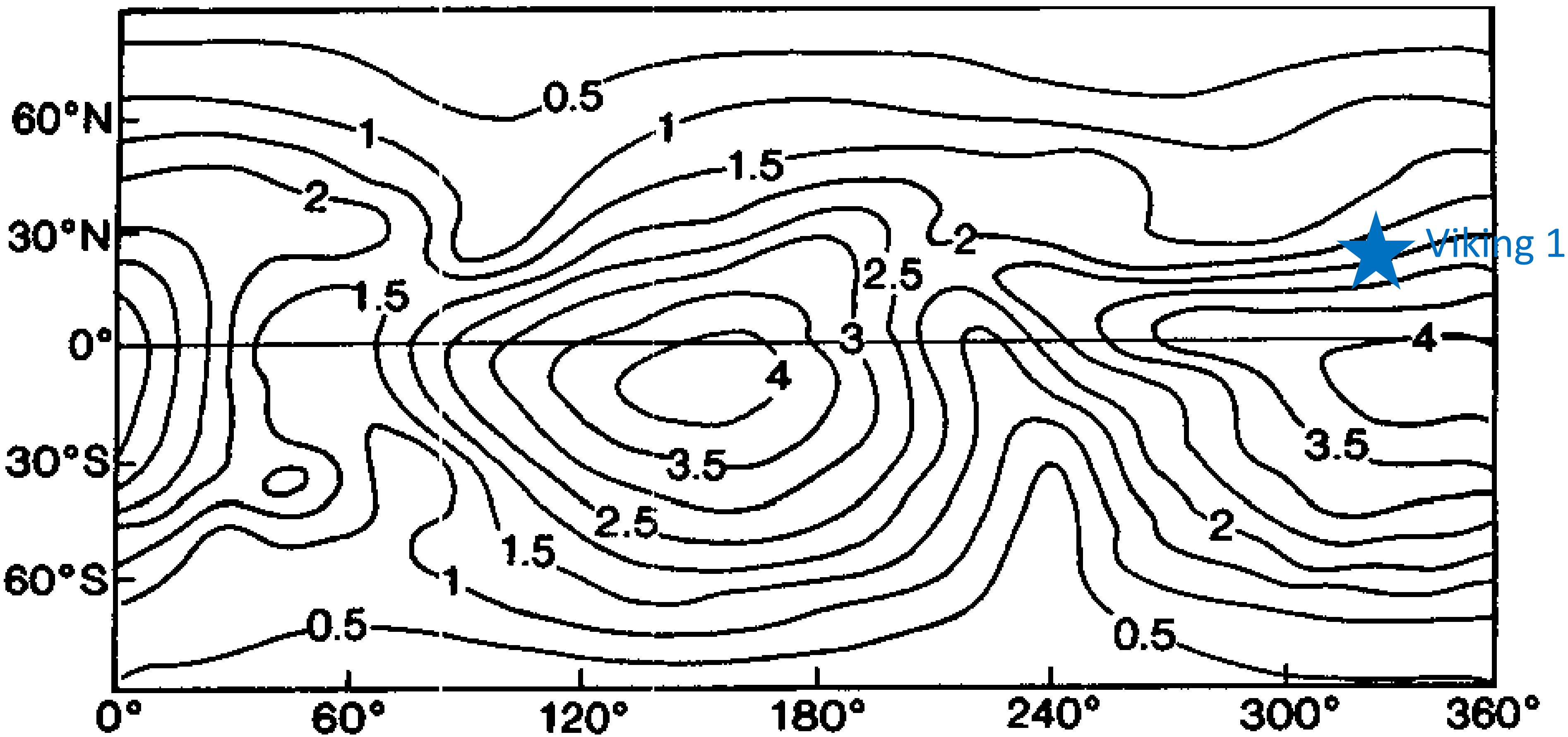
Mars Global Surveyer – Thermal Emission Spectrometer Data



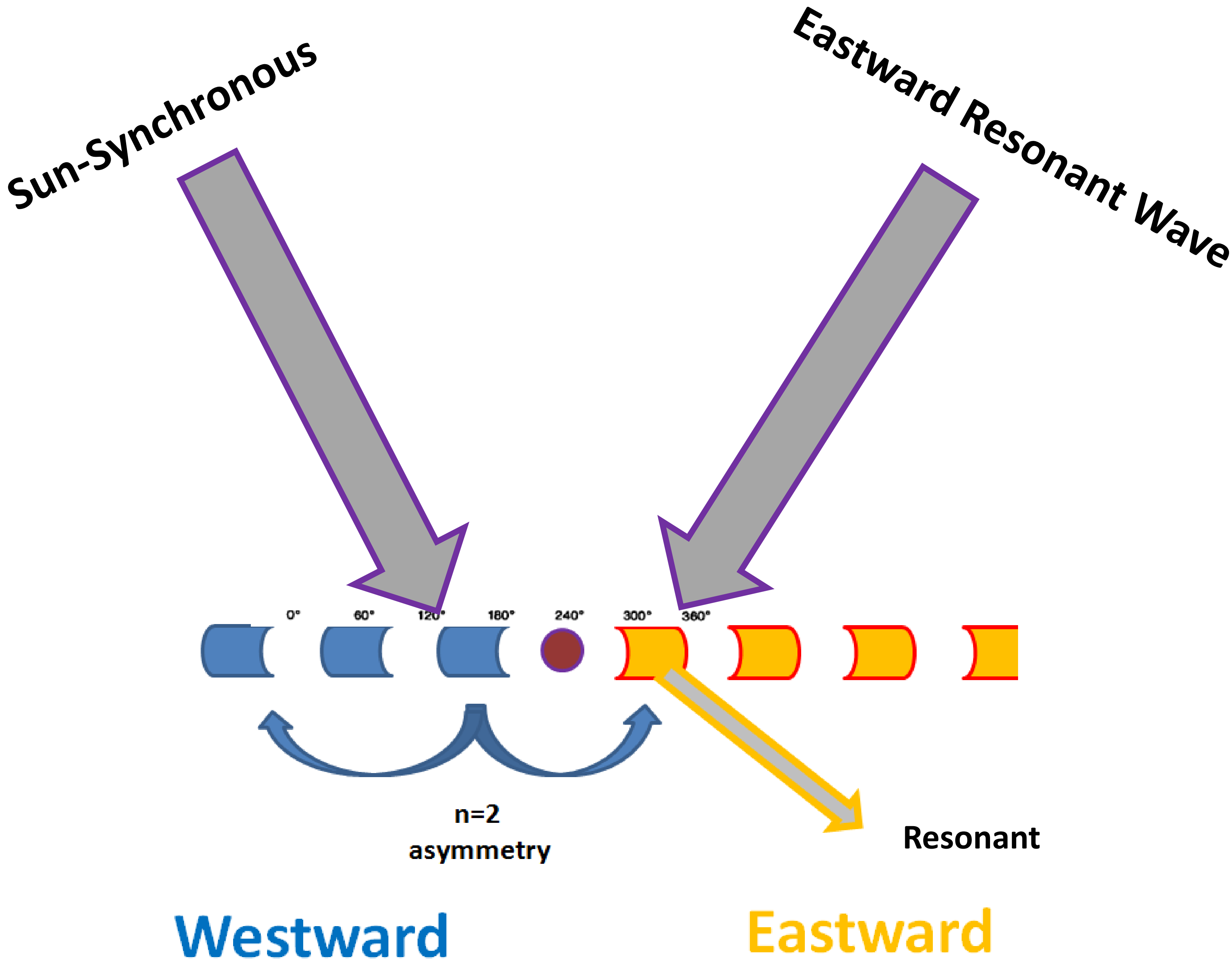
GFDL General Circulation Model



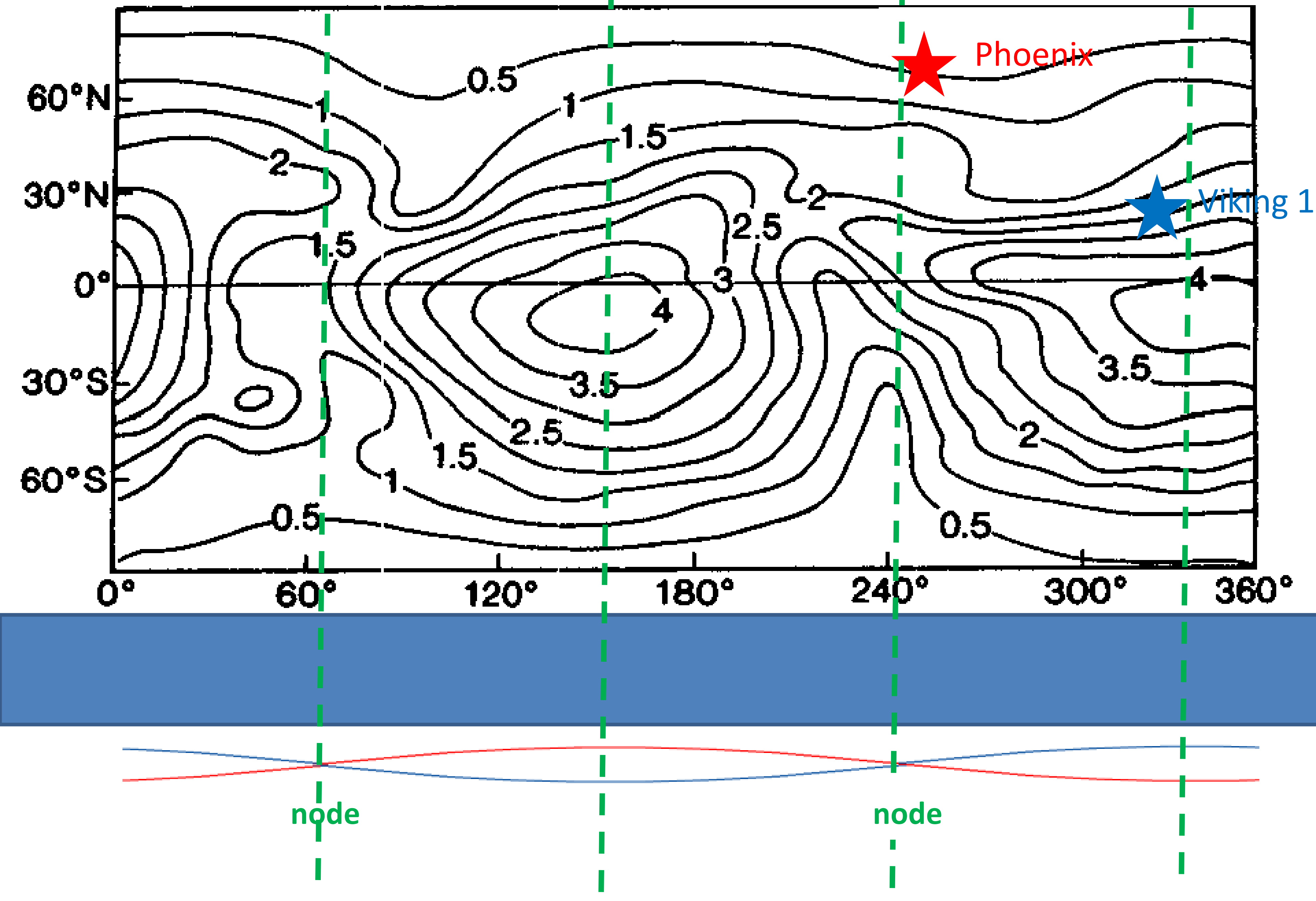
$S_1(p)$ amplitude (%of mean pressure) Boreal summer



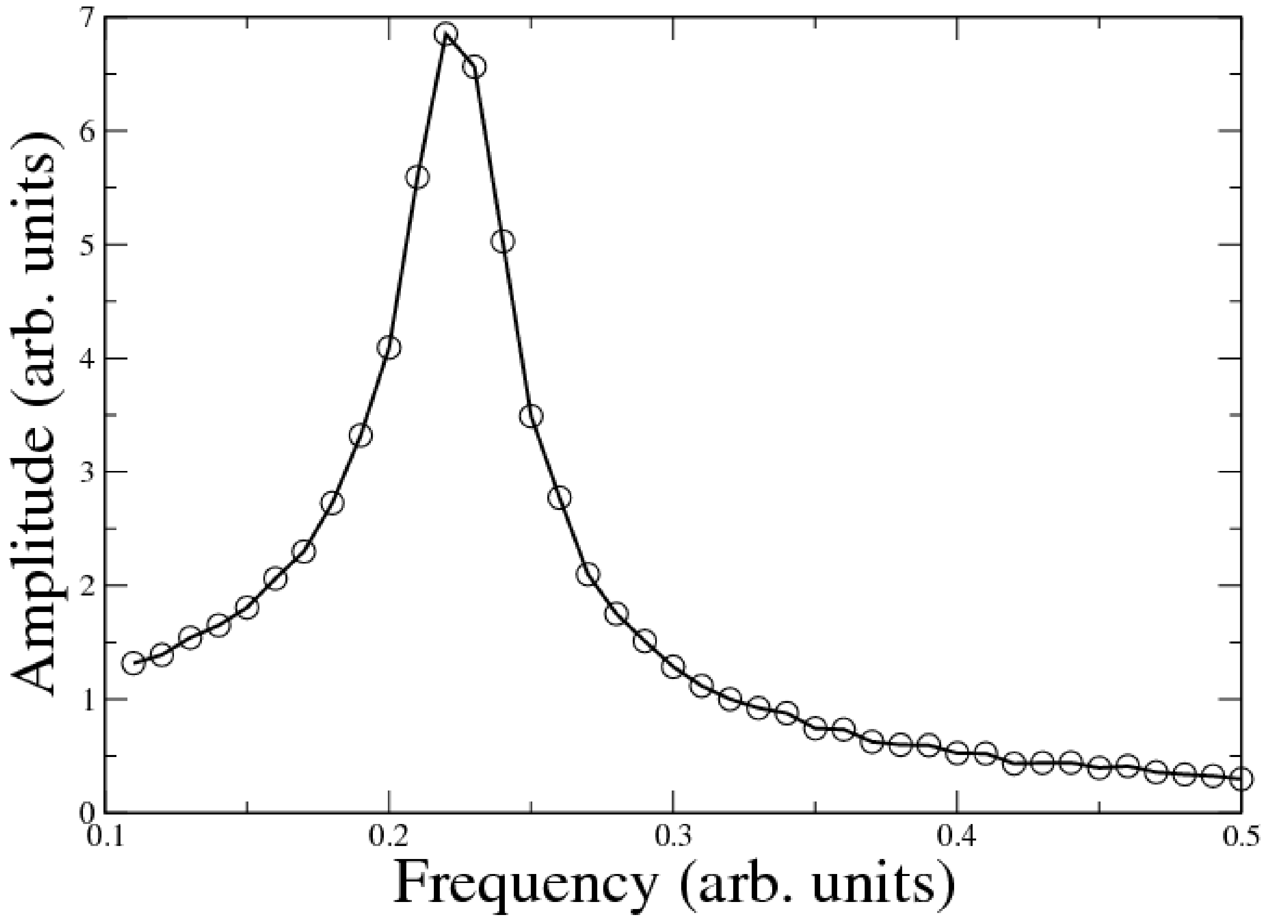
"clear conditions"

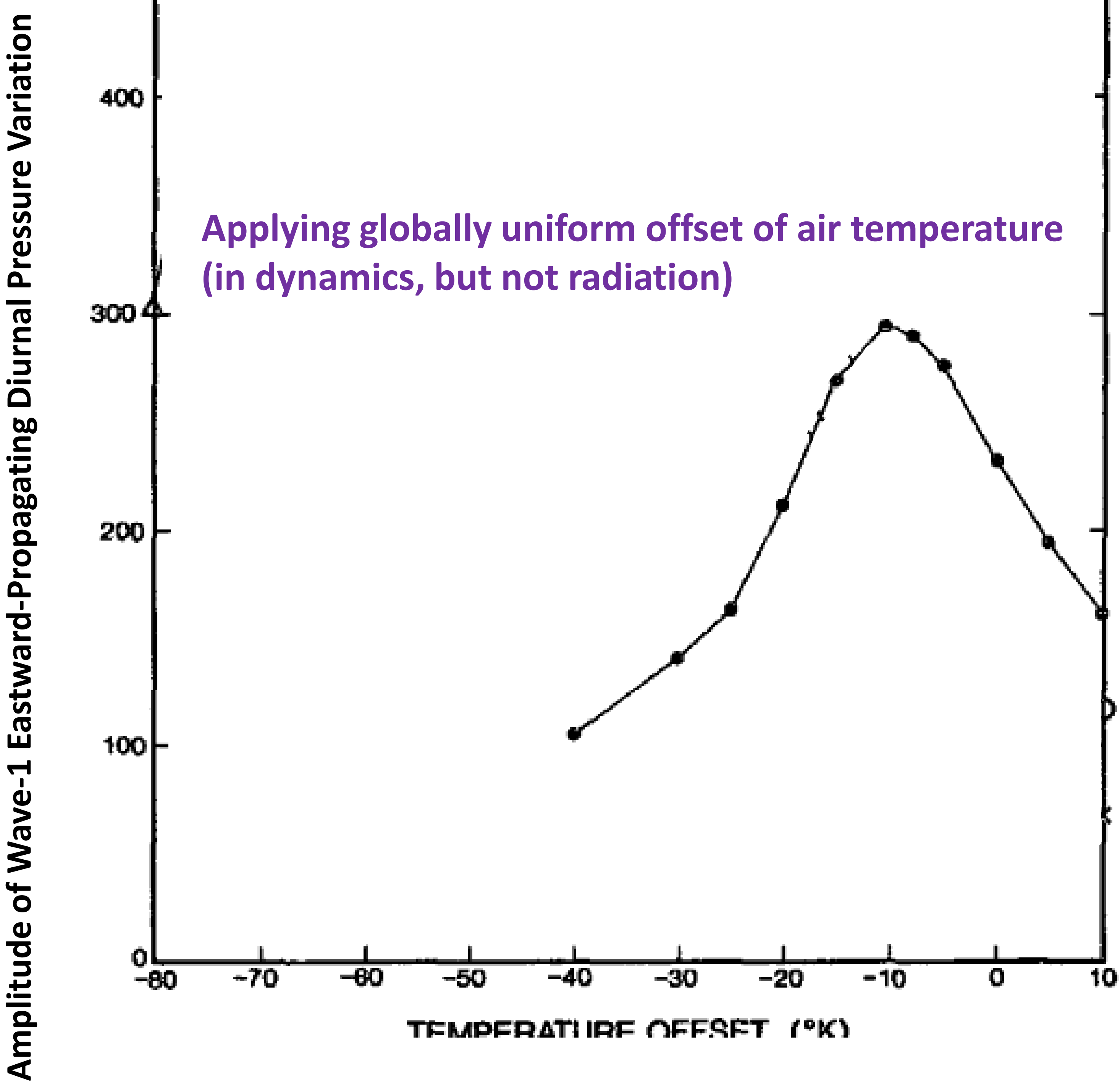

Sun-Synchronous
Eastward Resonant Wave
0°
60°
120°
180°
240°
300°
360°
n=2
asymmetry
Resonant
Westward
Eastward

$S_1(p)$ amplitude (%of mean pressure) Boreal summer



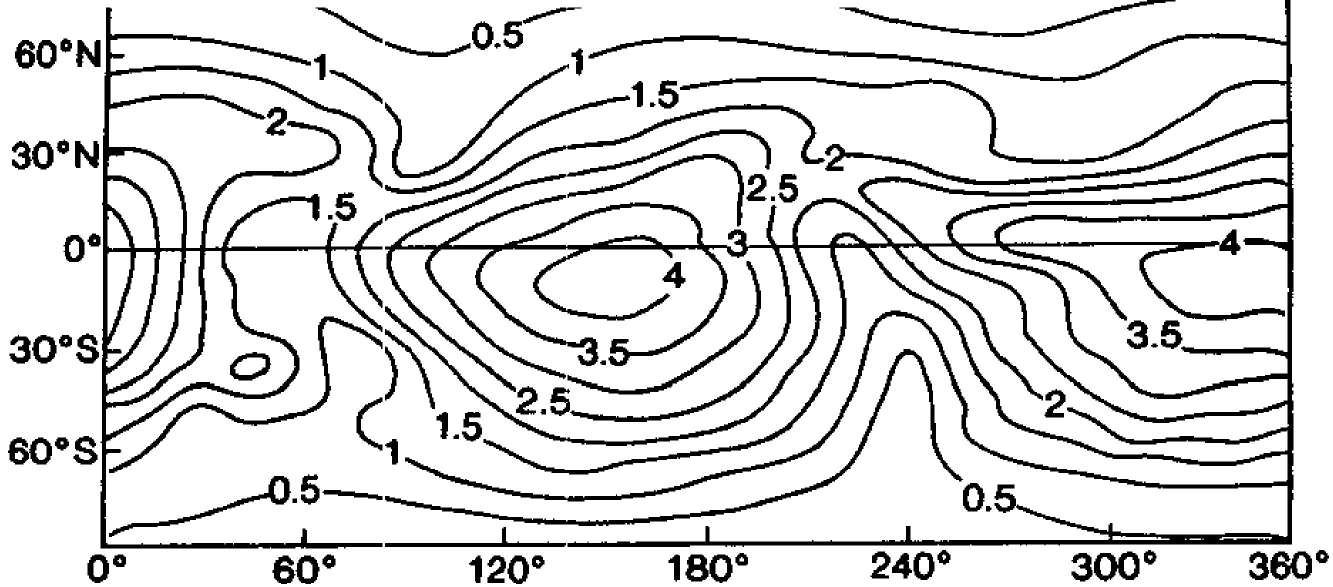
Generic Resonance Curve for An Oscillatory System with Monochromatic Forcing



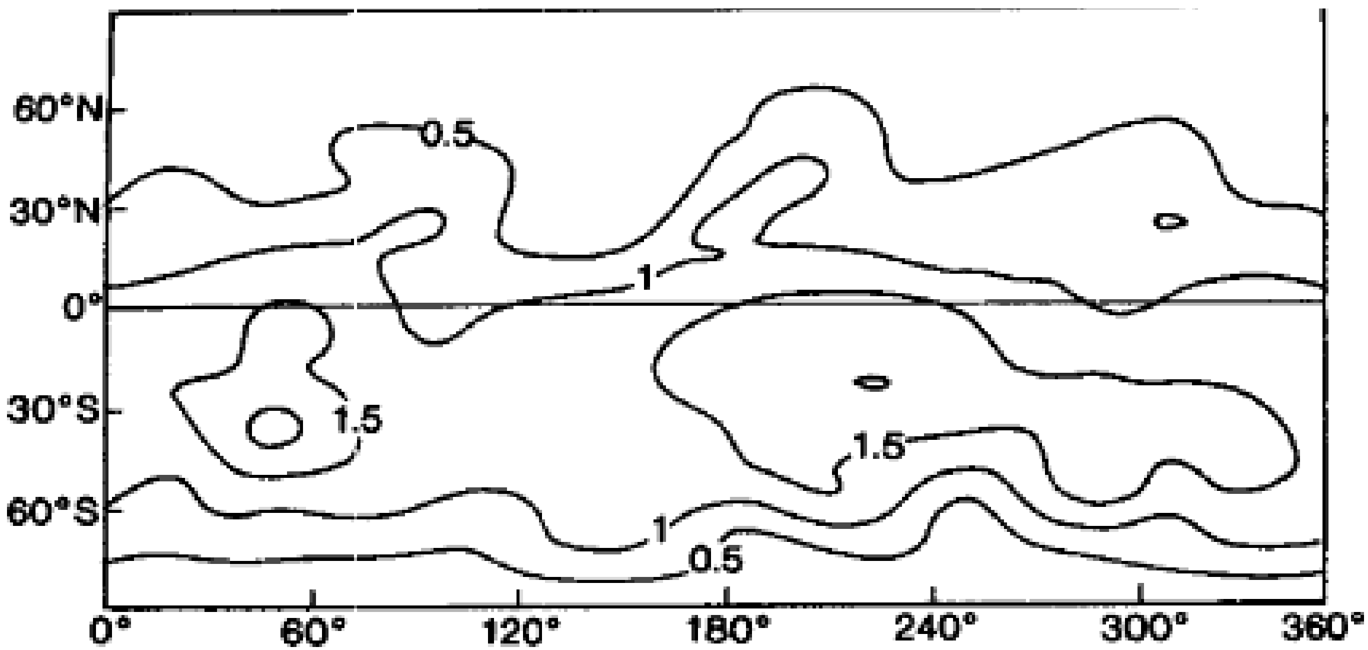


Applying globally uniform offset of air temperature
(in dynamics, but not radiation)
Amplitude of Wave-1 Eastward-Propagating Diurnal Pressure Variation
400
300
200
100
0
-80
-70
-60
-50
-40
-30
-20
-10
0
10

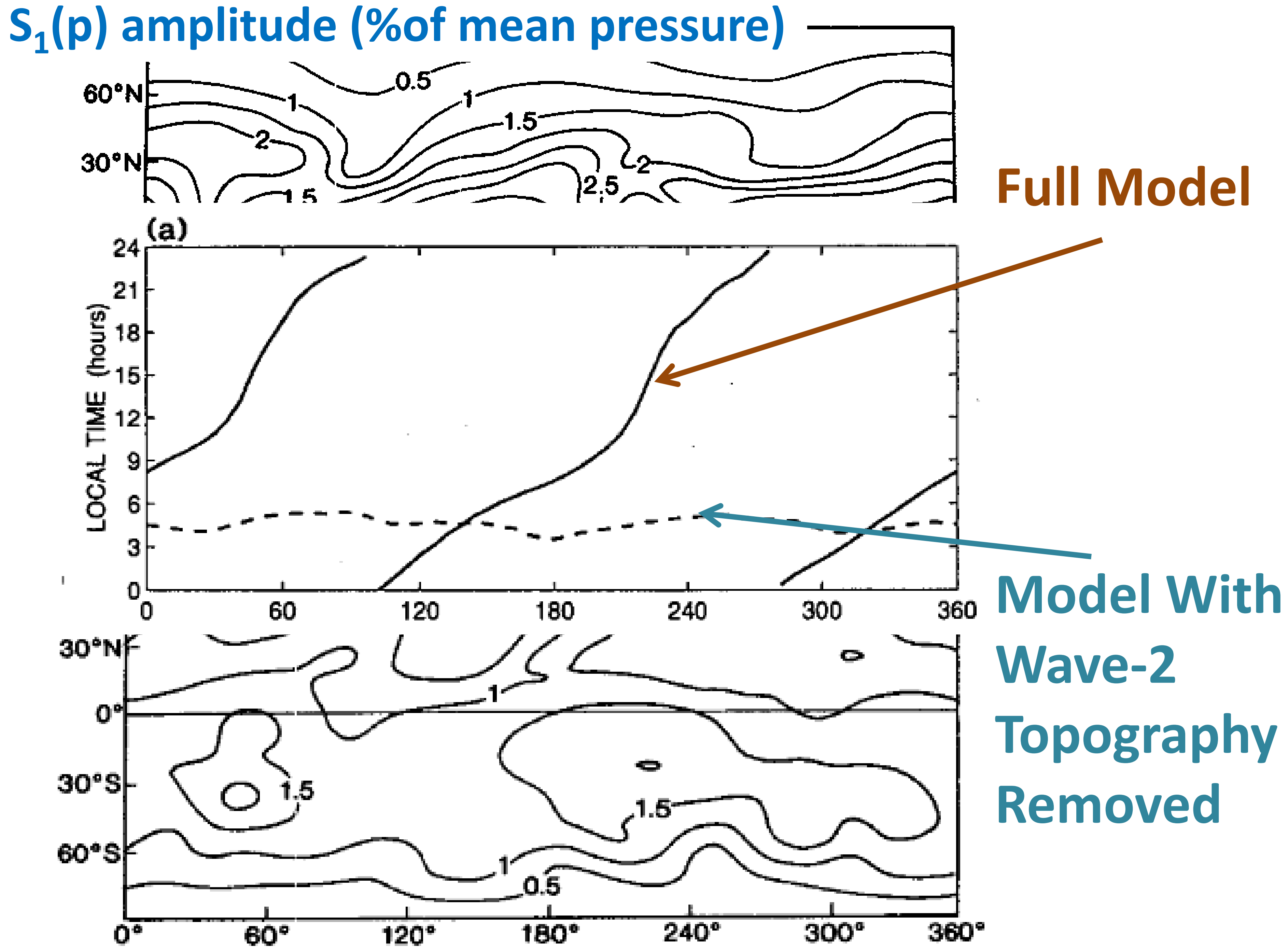
$S_1(p)$ amplitude (%of mean pressure)



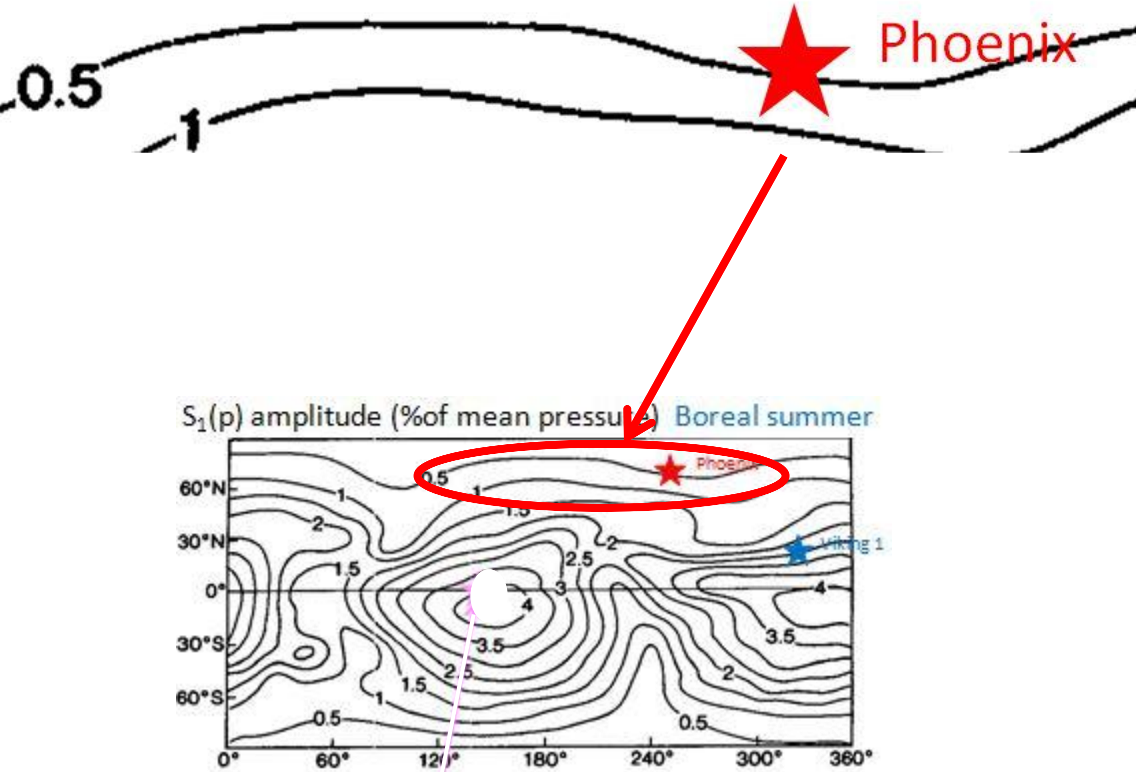
Full Model

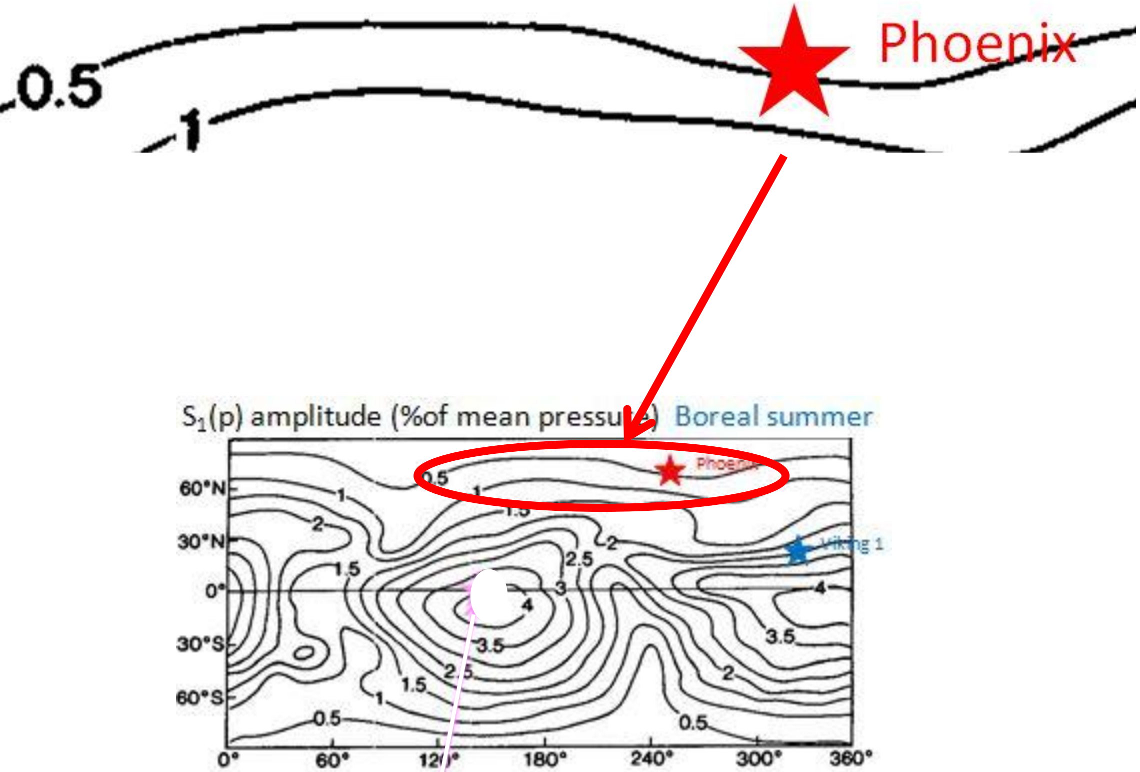


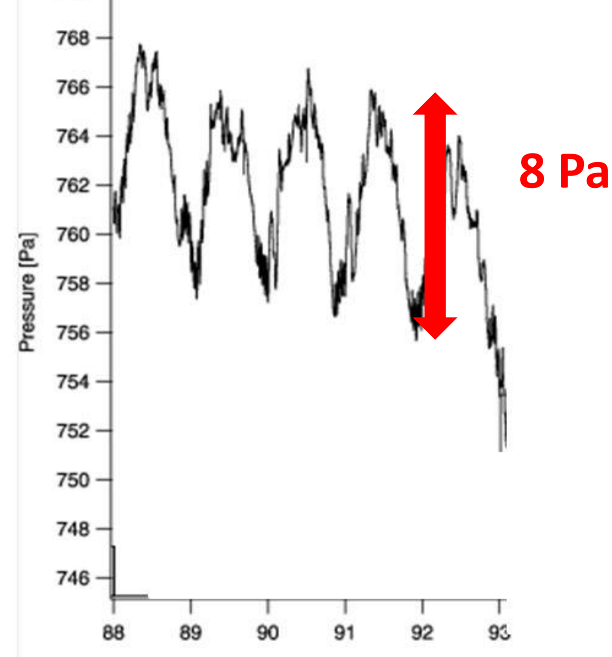
Model With Wave-2 Topography Removed



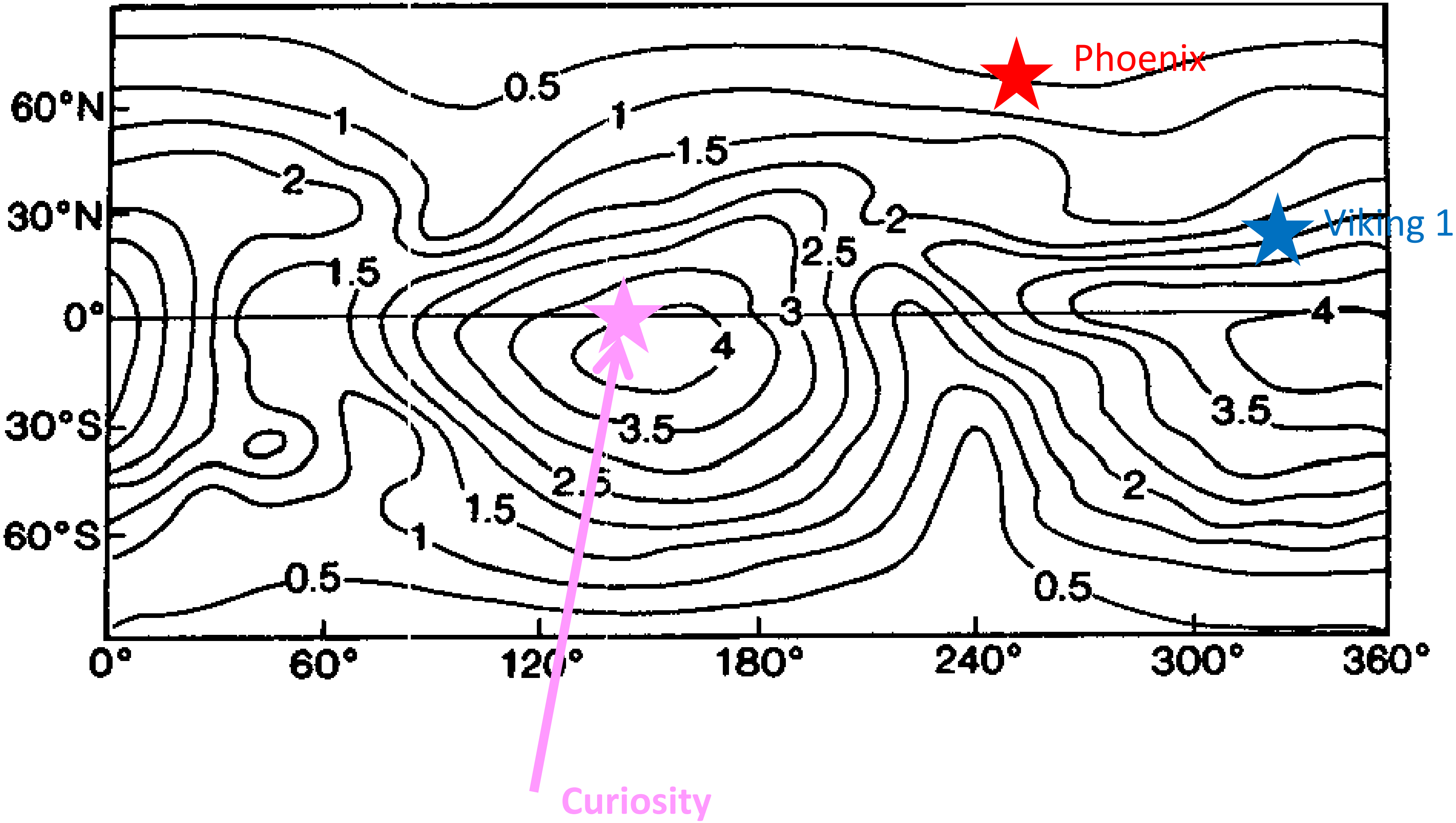
S_1(p) amplitude (%of mean pressure)
60°N
30°N
0.5
1
1.5
2
2.5
(a)
LOCAL TIME (hours)
24
21
18
15
12
9
6
3
0
60
120
180
240
300
360
Full Model
Model With Wave-2 Topography Removed
30°N
0°
30°S
60°S
0°
60°
120°
180°
240°
300°
360°

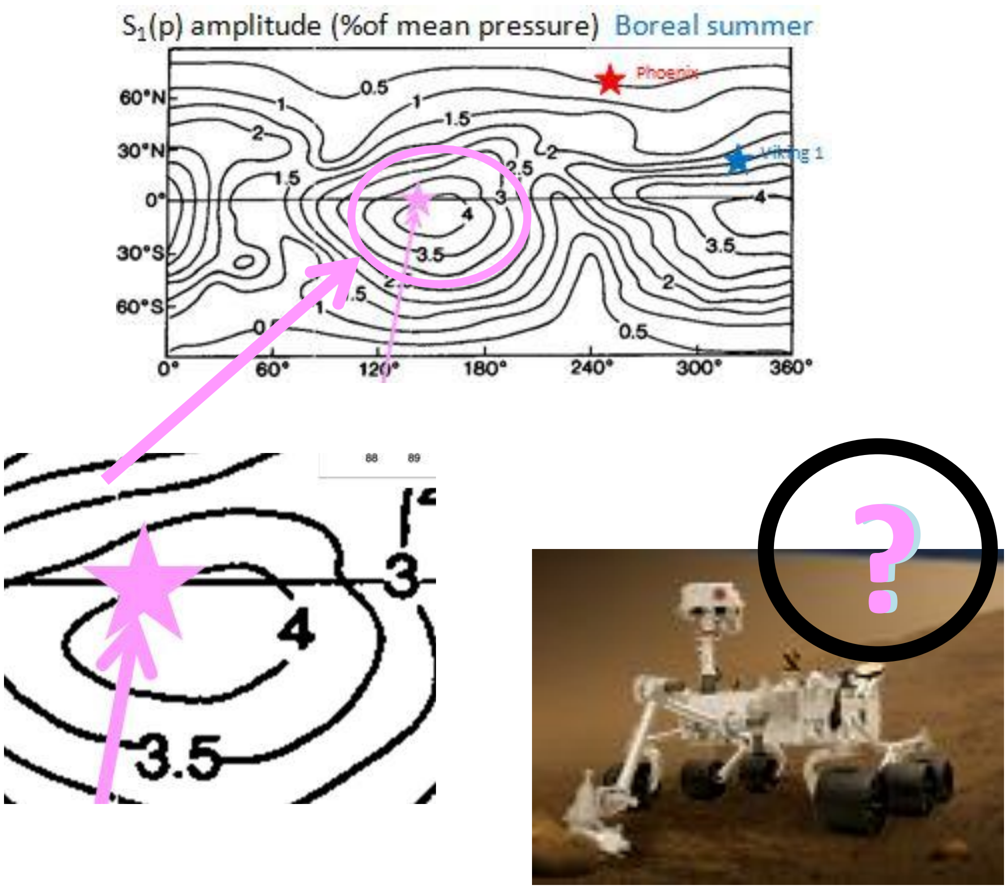

0.5
1
Phoenix
S1(p) amplitude (%of mean pressure) Boreal summer
60°N
30°N
0°
30°S
60°S
0°
60°
120°
180°
240°
300°
360°
Phoenix
Viking 1


0.5
1
Phoenix
S1(p) amplitude (%of mean pressu
Boreal summer
Phoenix
Viking 1
60°N
30°N
0°
30°S
60°S
0°
60°
120°
180°
240°
300°
360°


Pressure [Pa]
8 Pa
768
766
764
762
760
758
756
754
752
750
748
746
88
89
90
91
92
93

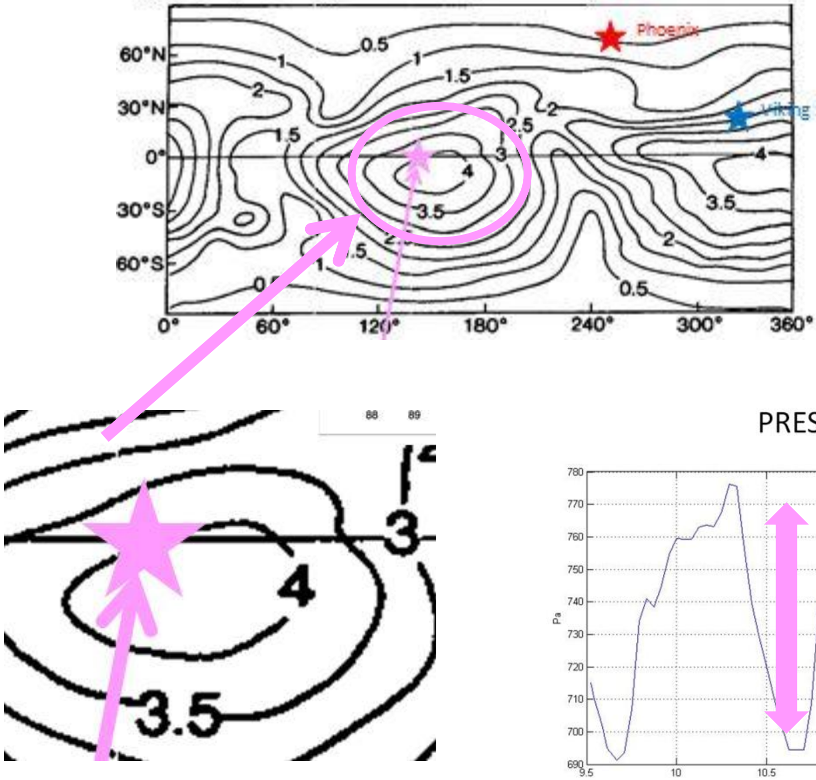
$S_1(p)$ amplitude (%of mean pressure) Boreal summer



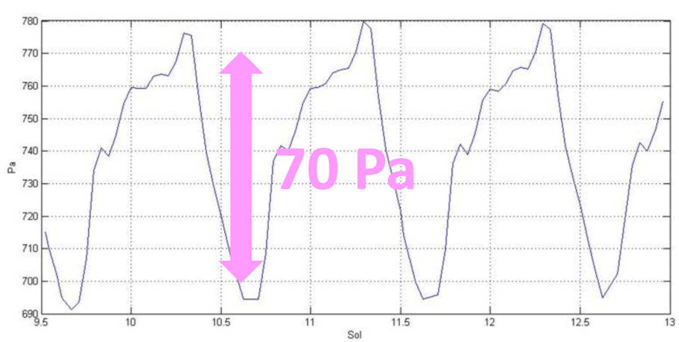


S$_1$(p) amplitude (%of mean pressure) Boreal summer
Phoenix
Viking 1
60°N
30°N
0°
30°S
60°S
0°
60°
120°
180°
240°
300°
360°
0.5
1
1.5
2
2.5
3
3.5
4
?

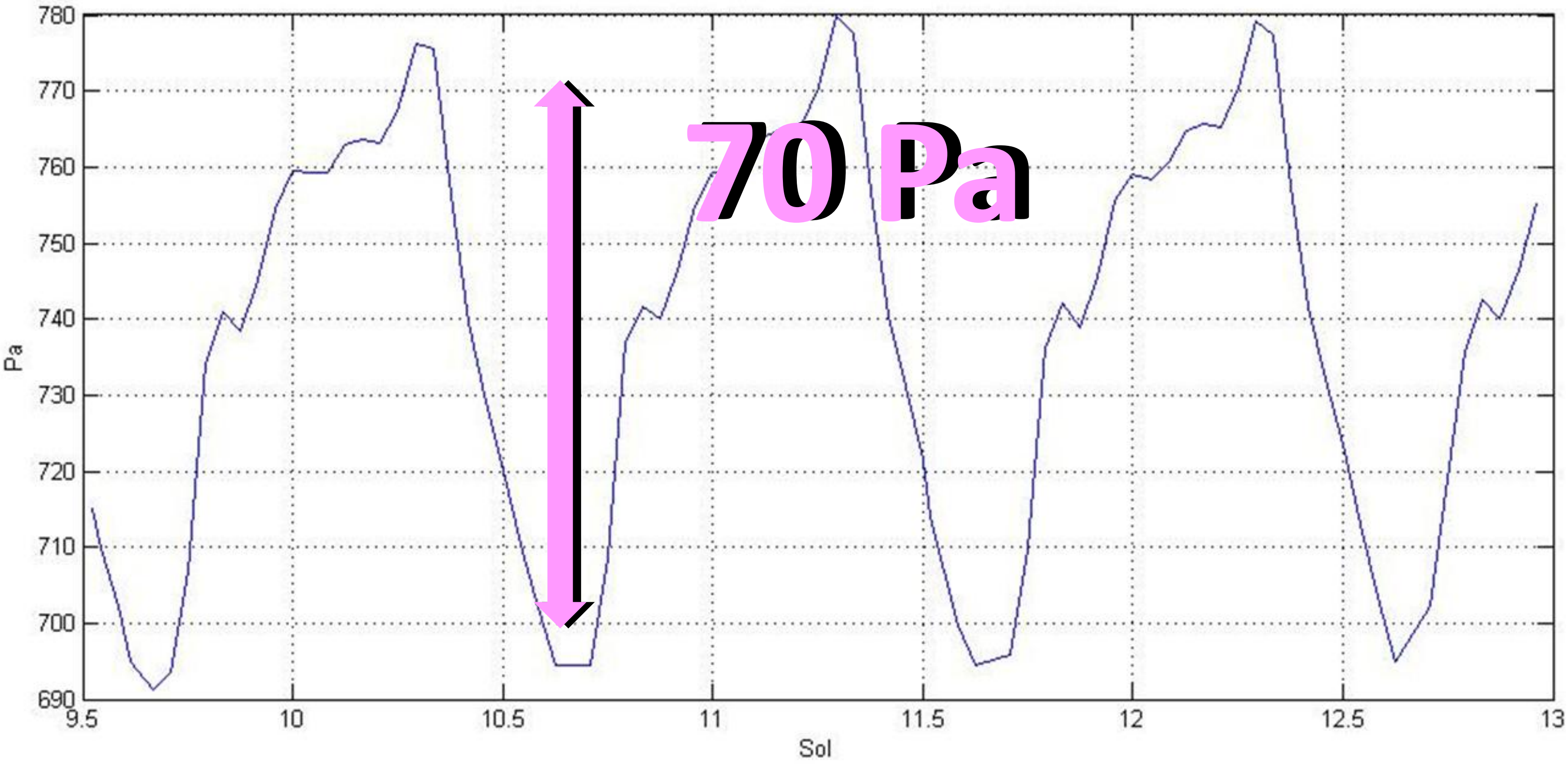
$S_1(p)$ amplitude (%of mean pressure) Boreal summer



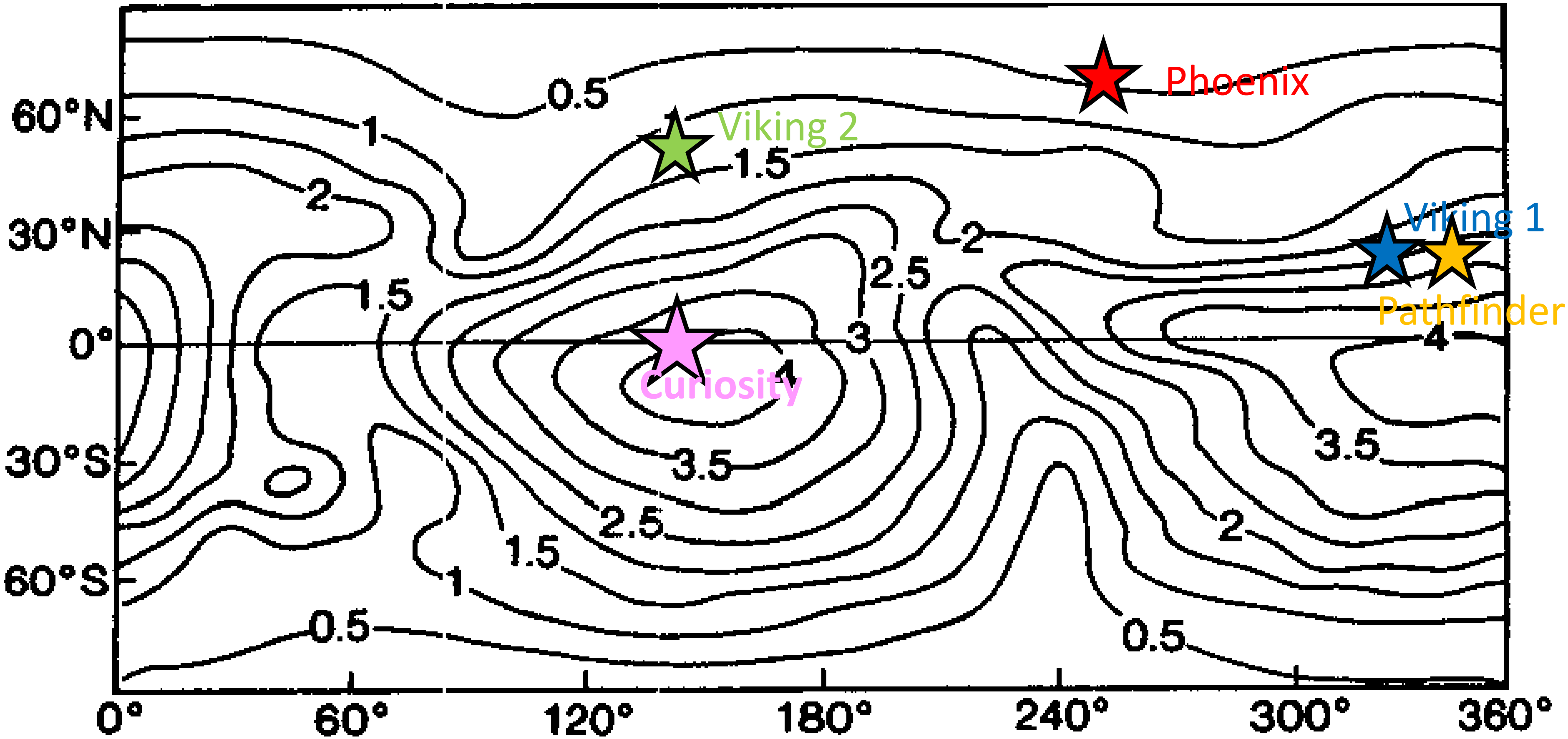
PRESSURE SENSOR

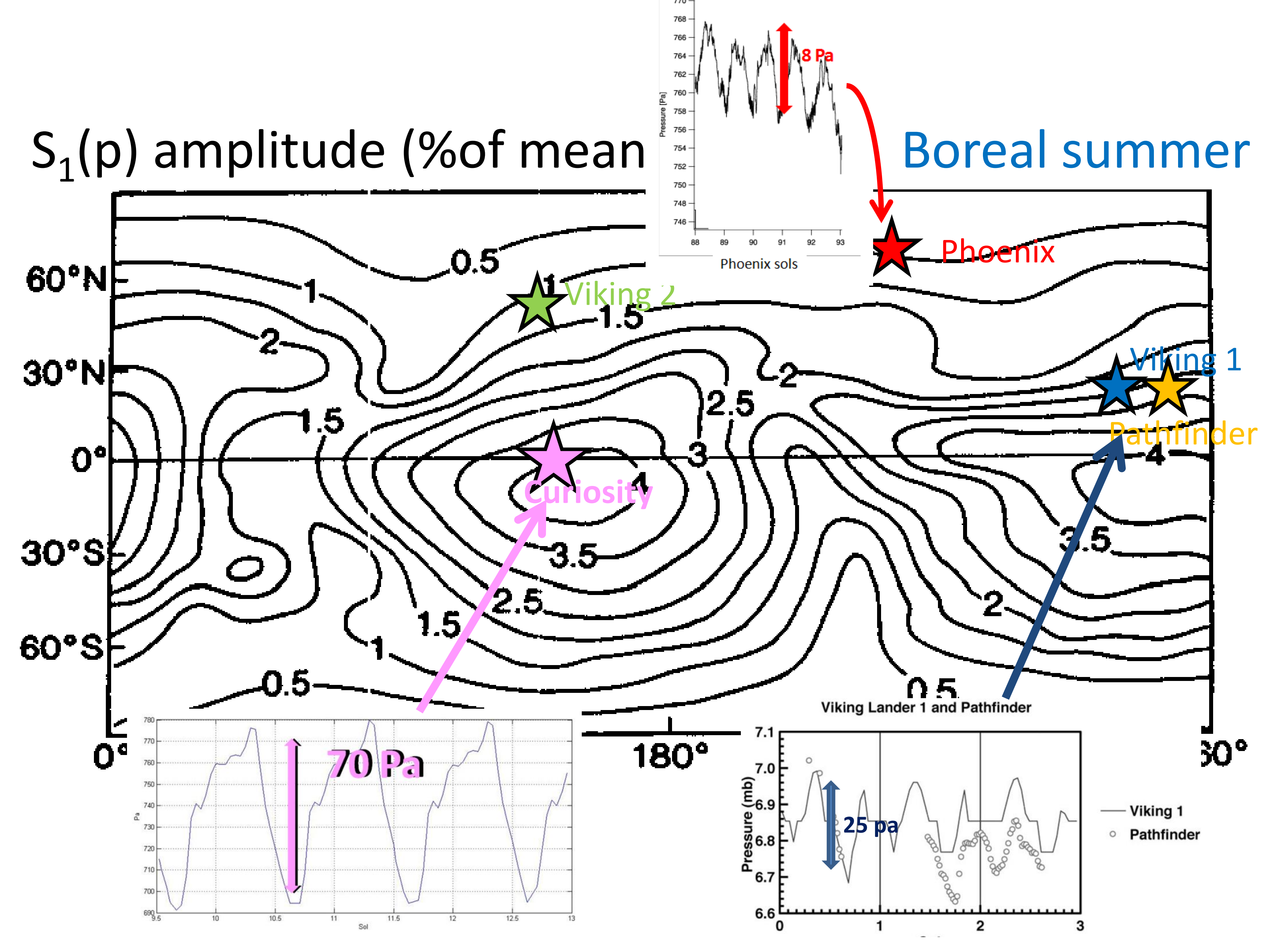


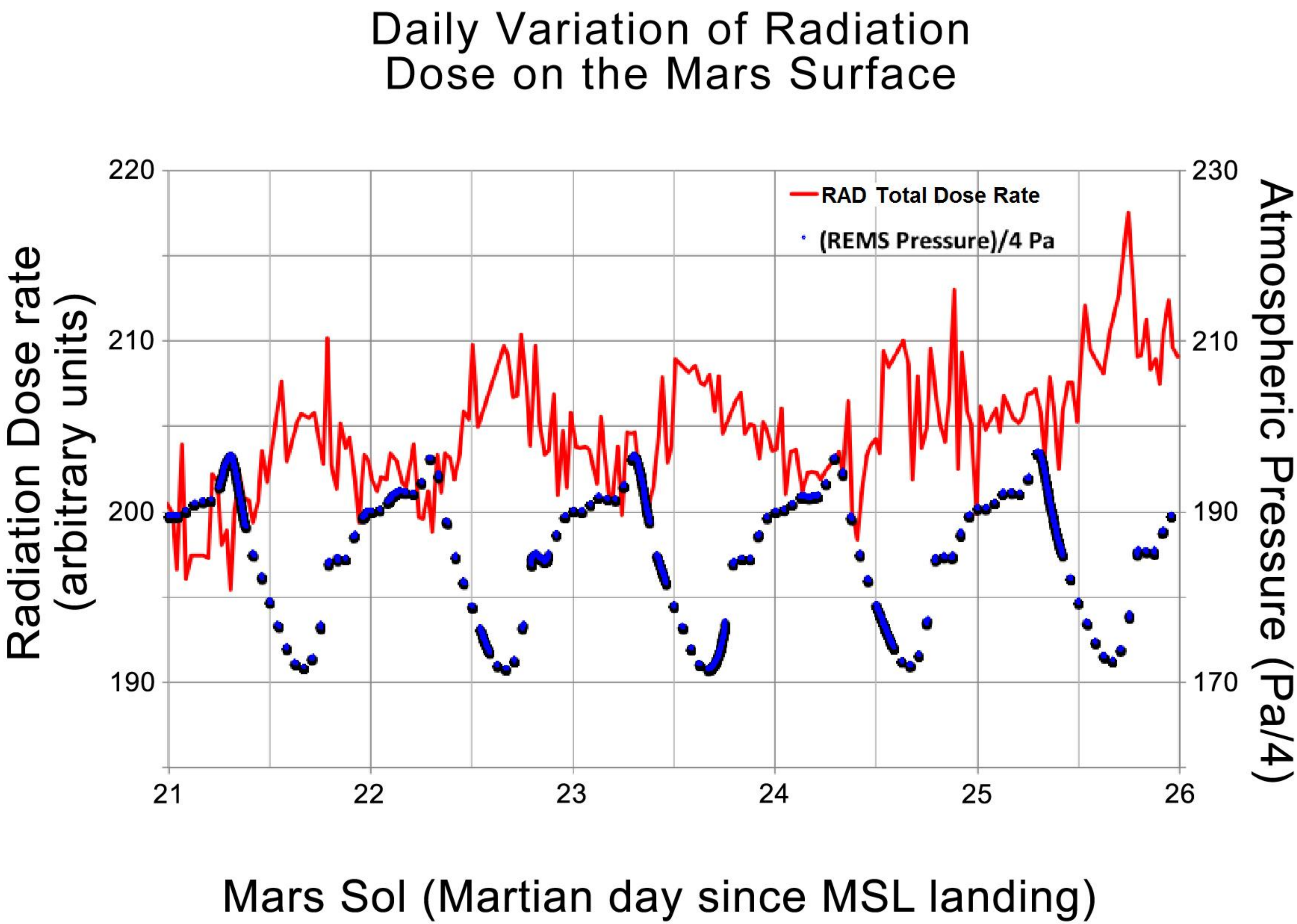
PRESSURE SENSOR

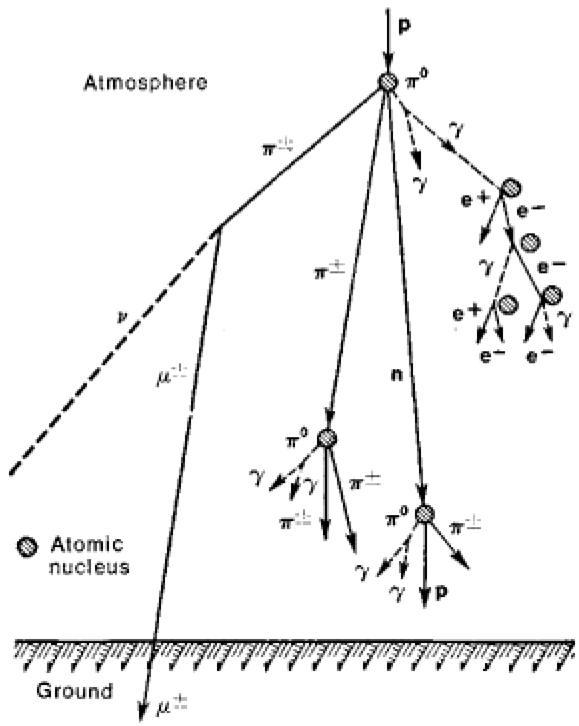


$S_1(p)$ amplitude (%of mean pressure) Boreal summer




S1(p) amplitude (%of mean
Boreal summer
Phoenix
Viking 2
Viking 1
Pathfinder
Curiosity
8 Pa
Phoenix sols
Pressure [Pa]
70 Pa
Sol
Pa
Viking Lander 1 and Pathfinder
25 pa
Pressure (mb)
Viking 1
Pathfinder
60°N
30°N
0°
30°S
60°S
180°


Daily Variation of Radiation
Dose on the Mars Surface
RAD Total Dose Rate
(REMS Pressure)/4 Pa
Radiation Dose rate
(arbitrary units)
Atmospheric Pressure (Pa/4)
220
210
200
190
230
210
190
170
21
22
23
24
25
26
Mars Sol (Martian day since MSL landing)


p
Atmosphere
π⁰
π±
γ
γ
e+
e−
e−
γ
e+
γ
e−
e−
ν
μ±
π±
n
π⁰
γ
γ
π±
π±
π⁰
π±
Atomic
nucleus
γ
γ
p
Ground
μ±

Thank you!

(and thank the NASA engineers and the American taxpayers for the great Martian data!)