The atmospheric dynamics of super-Earth GJ 1214b

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The super-Earth GJ 1214b

gravitational acceleration: 8.93 m s^{-2}

radius: 2.678 R_e

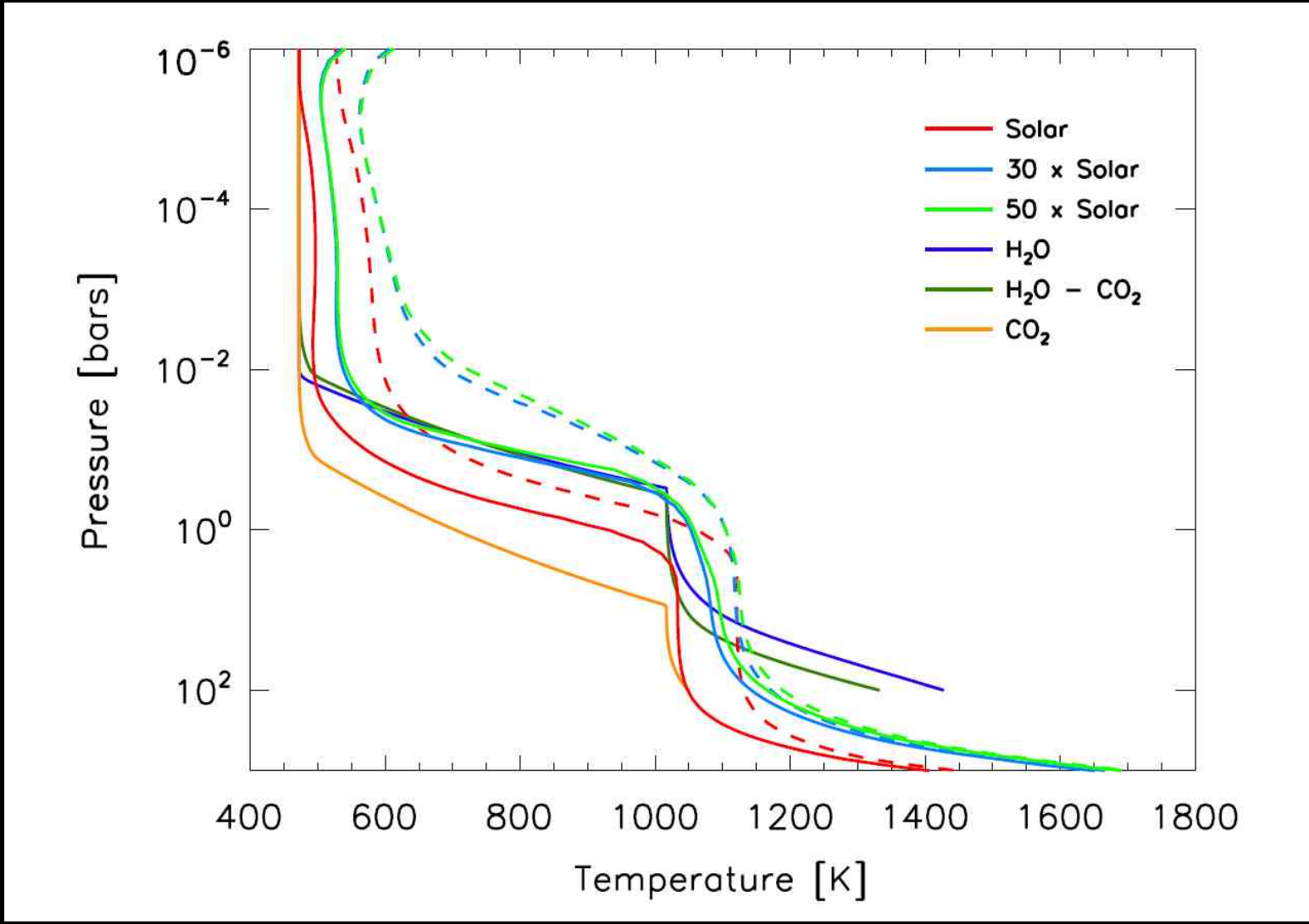
distance from star: 0.01432 AU

stellar flux at planet: 21519 W m^{-2}

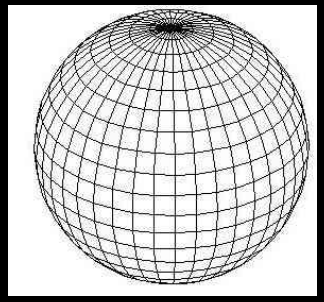
rotation period: 1.5803925 Earth days (synchronous)

(Charbonneau et al. 2009)

Miller-Ricci et al. (2009) radiative-equilibrium models



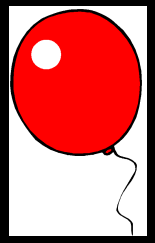
General circulation models (GCMs) are an important tool for investigating planetary atmospheres



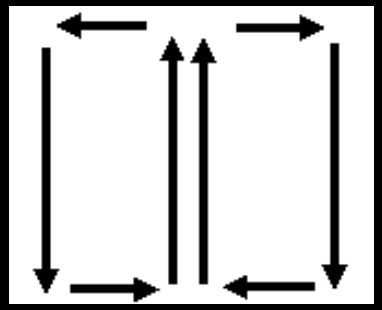
- Provide a global, physically consistent picture of an atmosphere
- Solve for the wind in an atmosphere, for which data is extremely rare even for Solar System planets

?

- Include the effects of wind such as
  - transport of heat by wind (advection)
  - heating/cooling from adiabatic compression/expansion
  - Interactions with solid surface

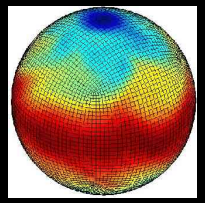


A GCM for GJ 1214b



- Explicit treatment of large-scale atmospheric dynamics (c.f. Miller-Ricci et al. 2009) in 3D
- Includes a solid surface (c.f hot Jupiter, hot Neptune GCMs)
  - No internal heat source
  - Known IR heat source from below (like a hot plate), surface convection?
  - Surface friction

The Massachusetts Institute of Technology (MIT) GCM



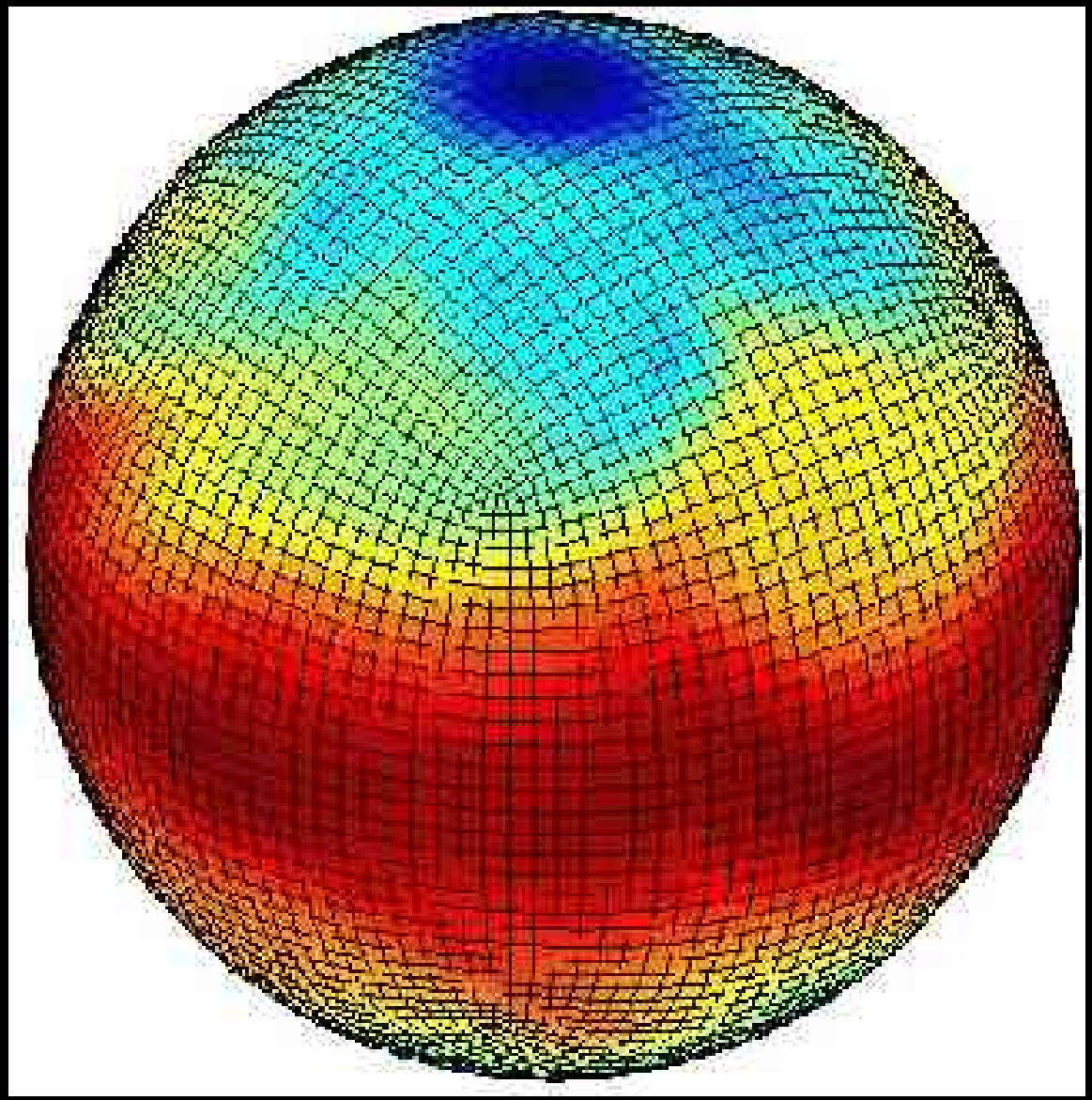
- Began as an Earth ocean model (Marshall et al. 1997)
- Publicly available for download http://mitgcm.org
- Has since been used in a wide range of applications in Earth's atmosphere and ocean, as well as planetary atmospheres (terrestrial and gas giant)
- I have applied it to
  - Mars (Zalucha et al. 2010)
  - Pluto (Zalucha and Gulbis, in review)
  - Super-Earth exoplanet (here)

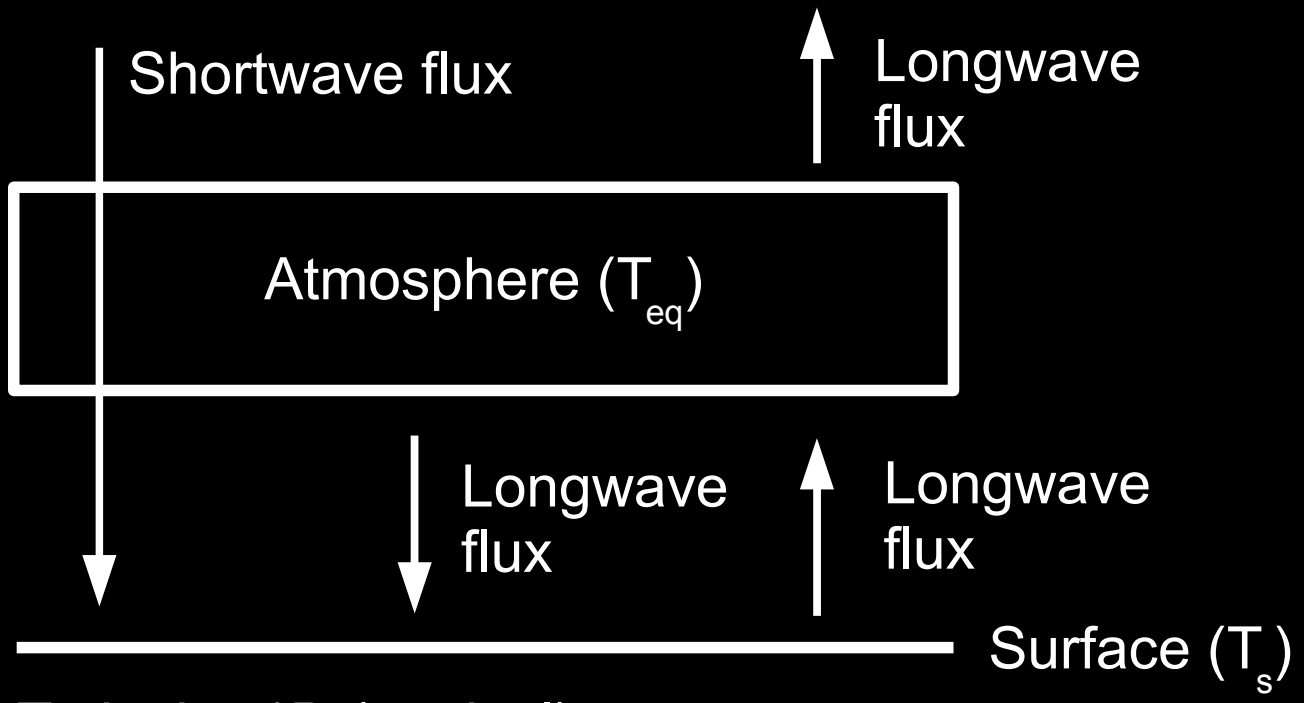
Super-Earth MIT GCM specs

- 32 x 32 x 6 cube-sphere configuration (about 2.8° x 2.8° horizontal resolution)
- 30 vertical levels (eta coordinate)
- Hydrostatic, compressible
- Finite volume method is used to discretize the equations in space
- Temperature below condensation point is snapped back to condensation temperature
- Boundary layer friction given by linear drag law that decays with height
- Model is run for 540 Earth days, time-averaged output every 30 days
- Newtonian relaxation to radiative equilibrium temperature

$$\frac{\partial T}{\partial t} = \boxed{\frac{-(T - T_{eq})}{\tau}} + advection\ of\ T + compressional\ heating$$

Cube-sphere grid



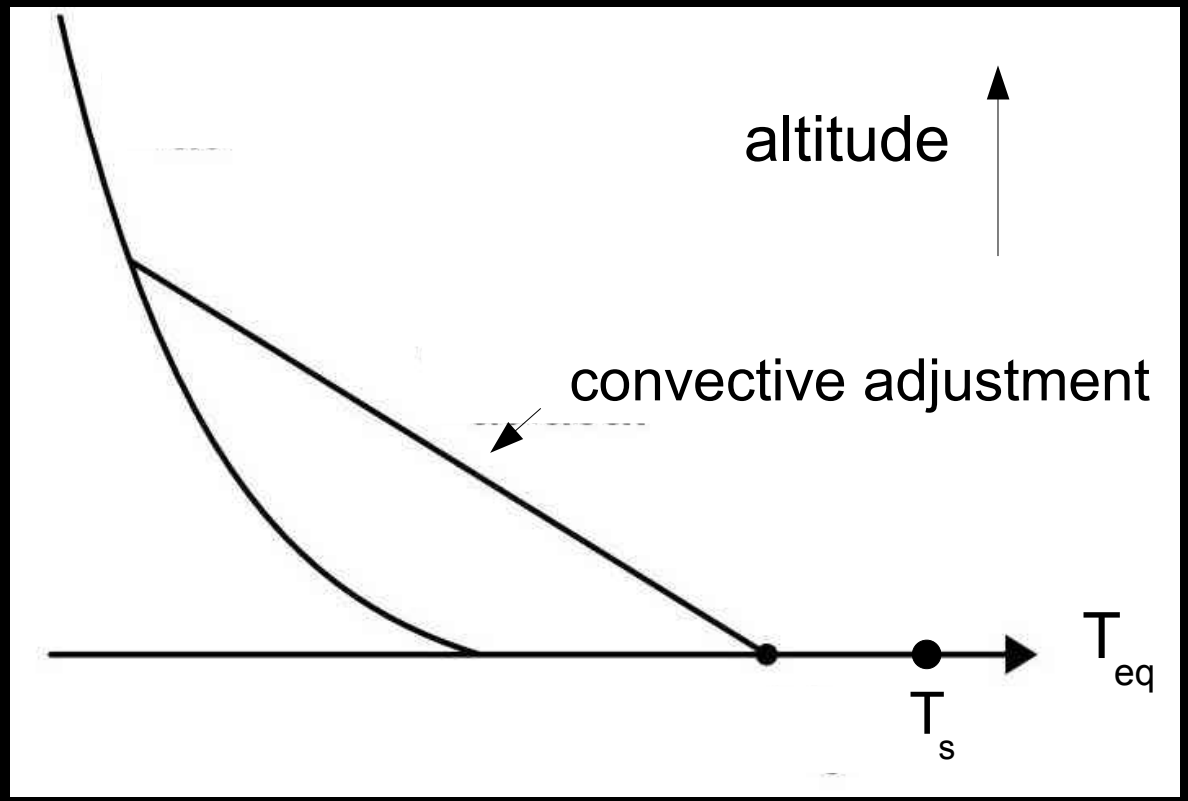


Further assumptions:
- Nonzero shortwave zenith angle
- Eddington approximation
- Infinite layers

T_{eq} is the 1D (vertical) solution to the radiative transfer equation in the absence of atmospheric dynamics.

It is an idealized state that is a proxy for the radiative heating and cooling.

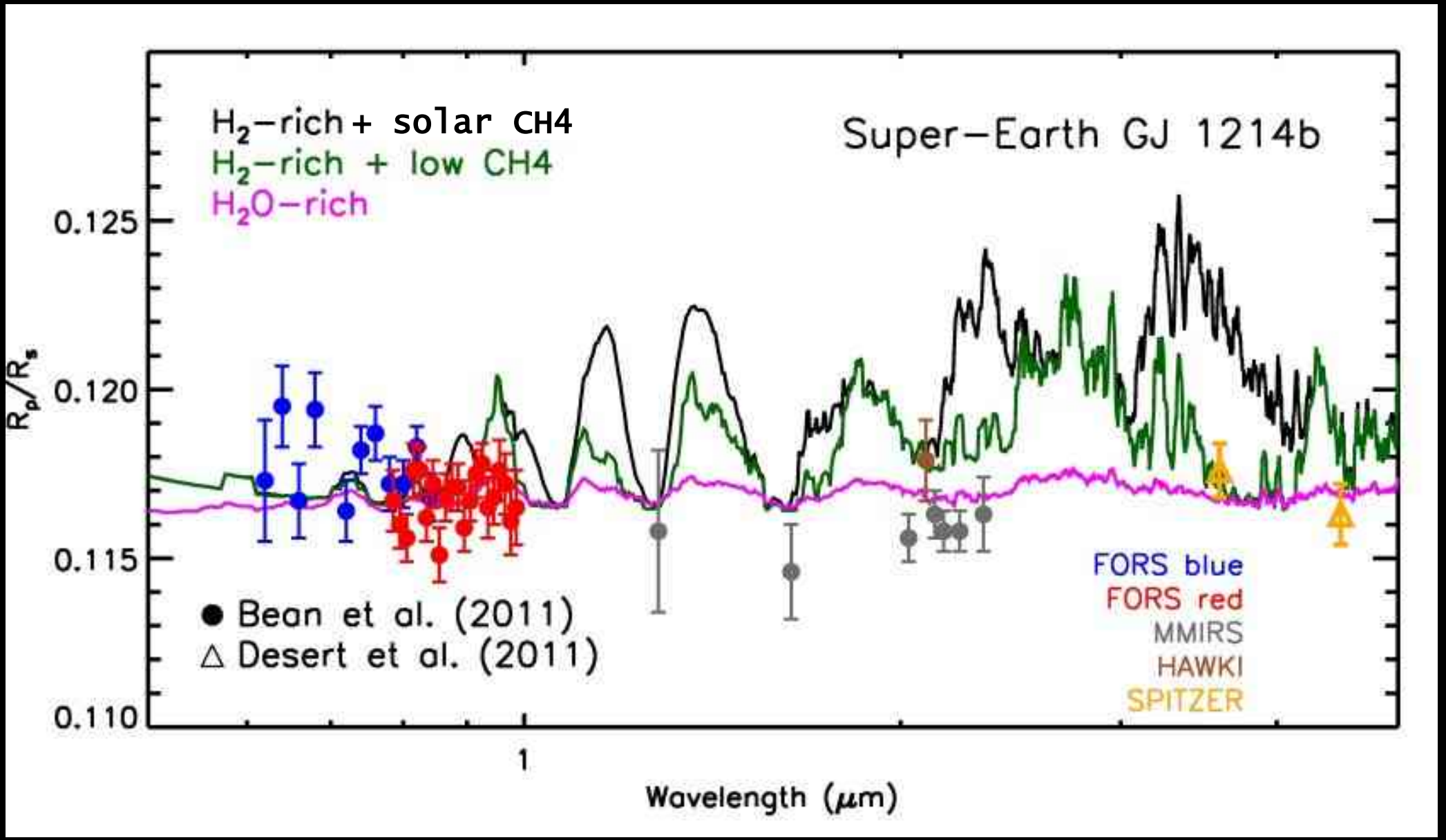
Convective adjustment is performed to eliminate super-adiabatic layers.



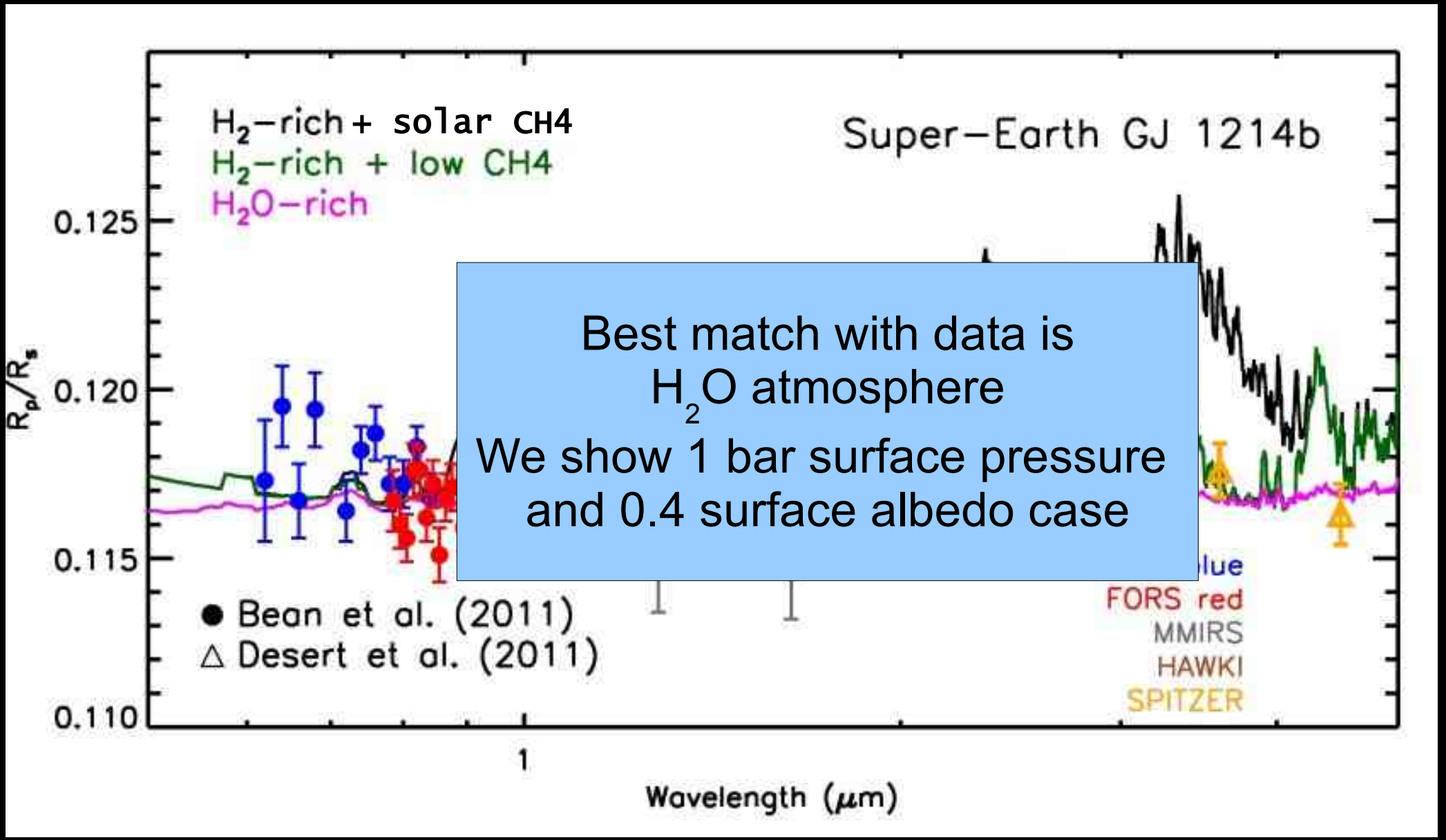
Parameter sweep of GJ 1214b

- Atmospheric pressure: 0.1, 1, 10, 100 bar
- Surface albedo: 0.1, 0.4, 0.7
- Mean molecular weight: H_2, H_2O, CO_2

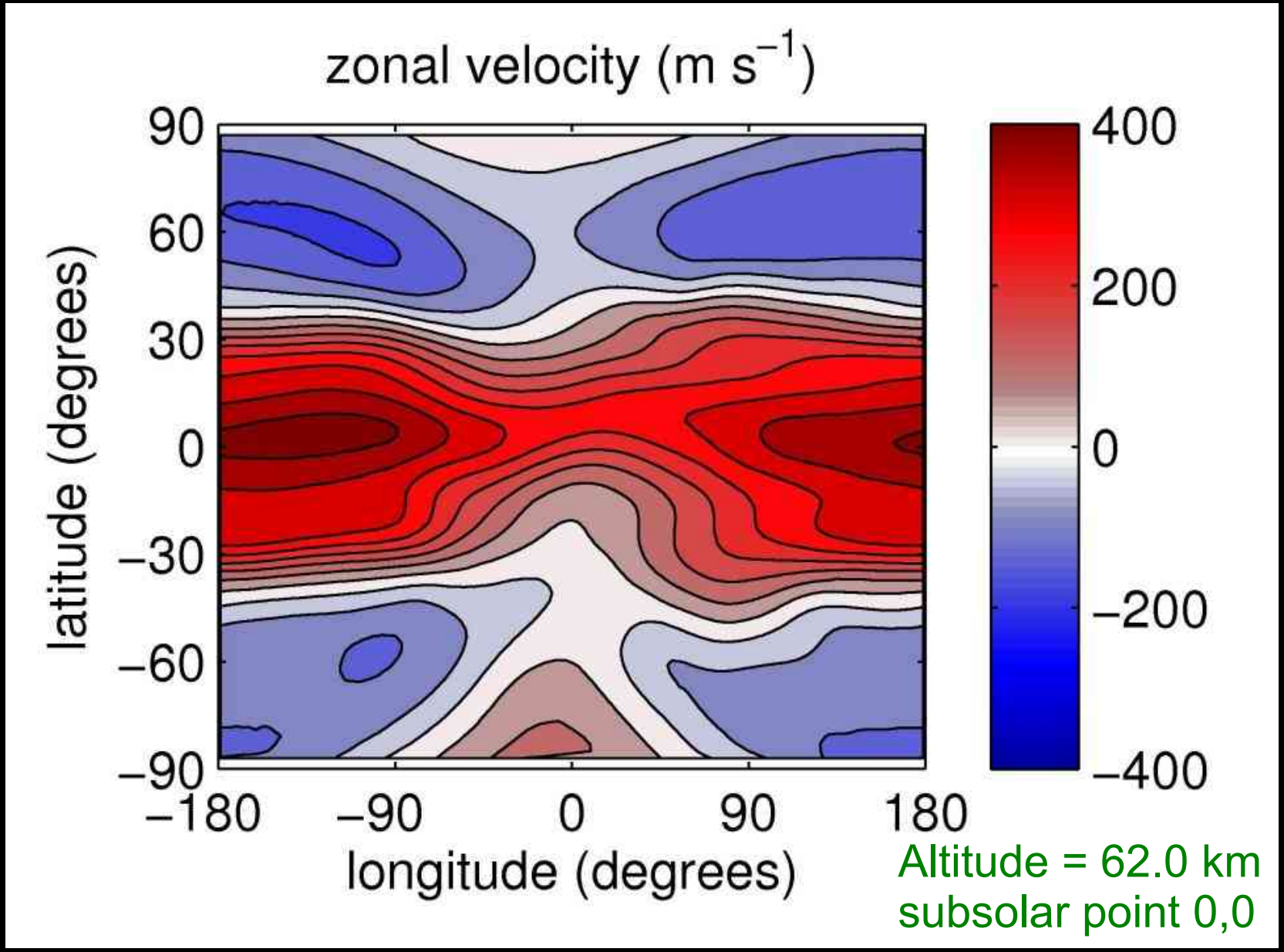
Absorption spectra of GJ 1214b



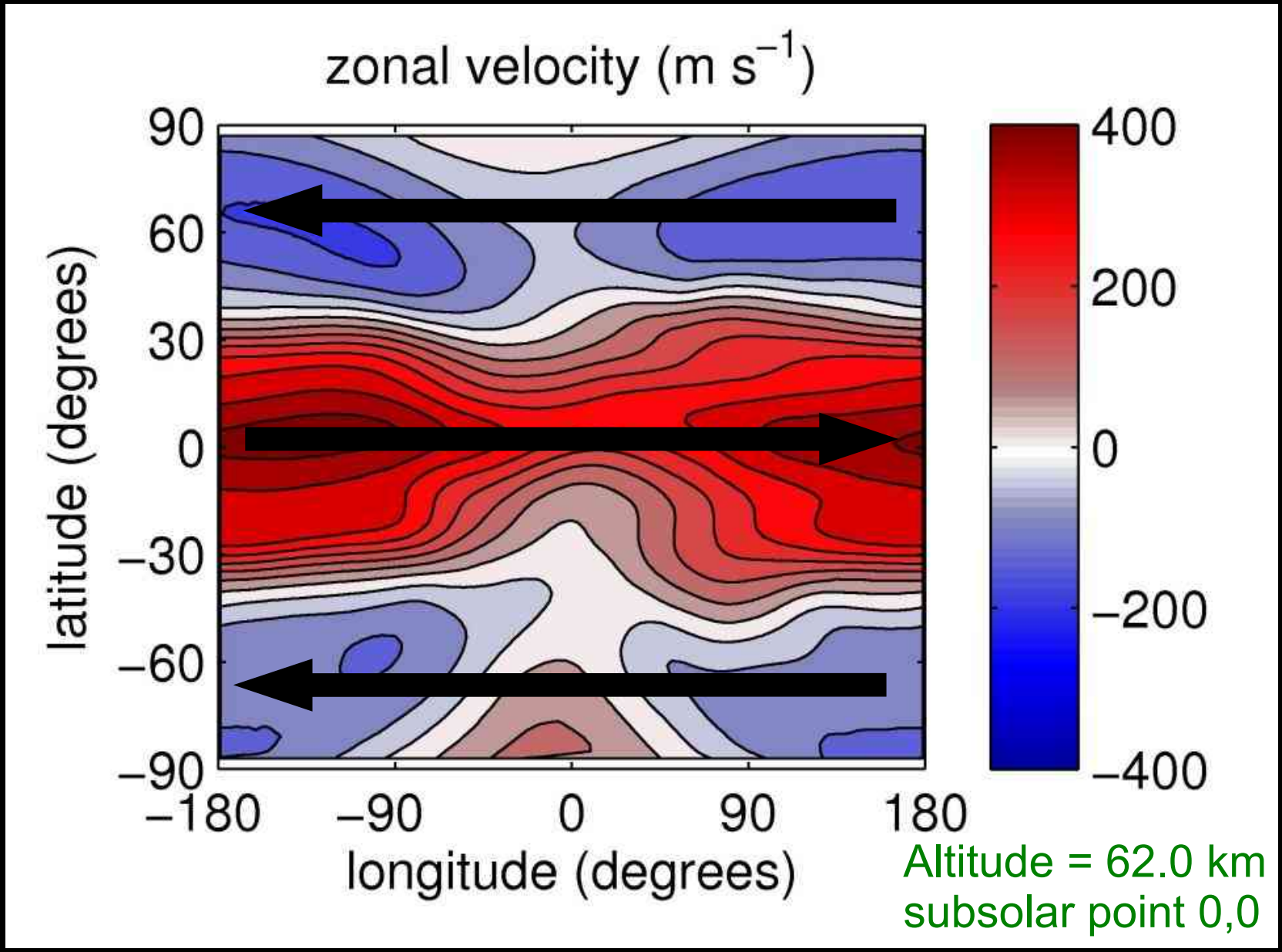
Absorption spectra of GJ 1214b



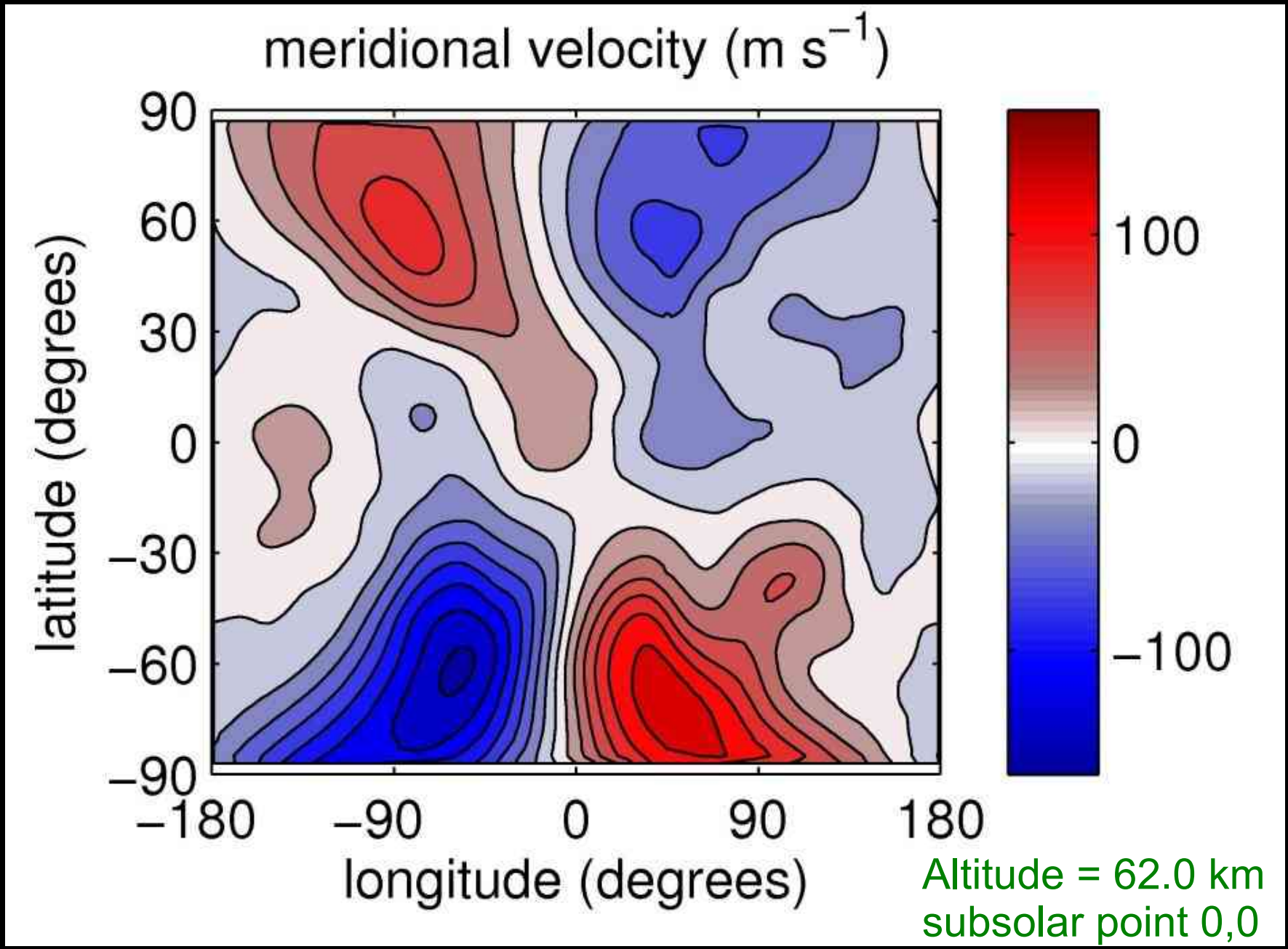
Zonal velocity (eastward positive)



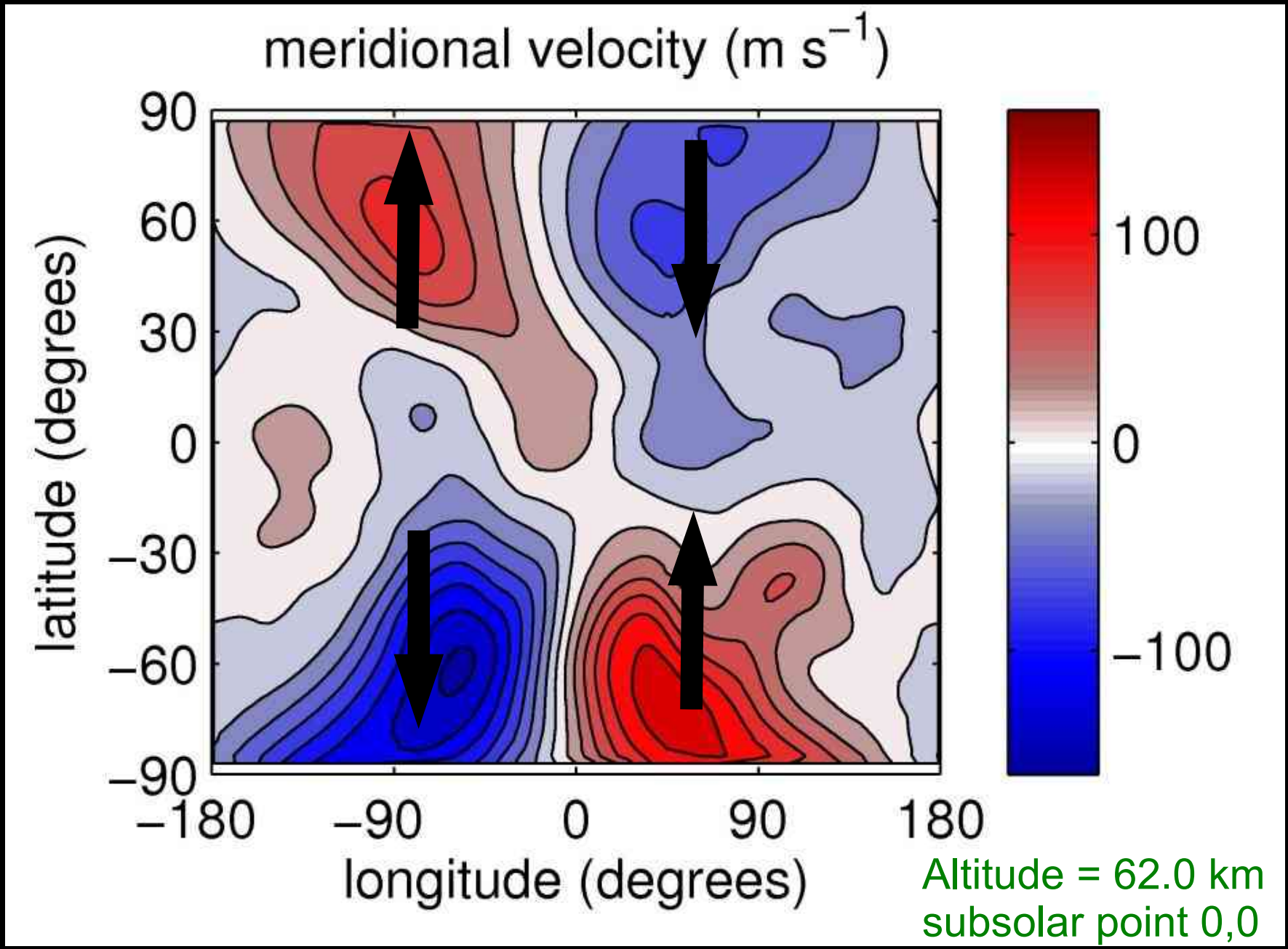
Zonal velocity (eastward positive)



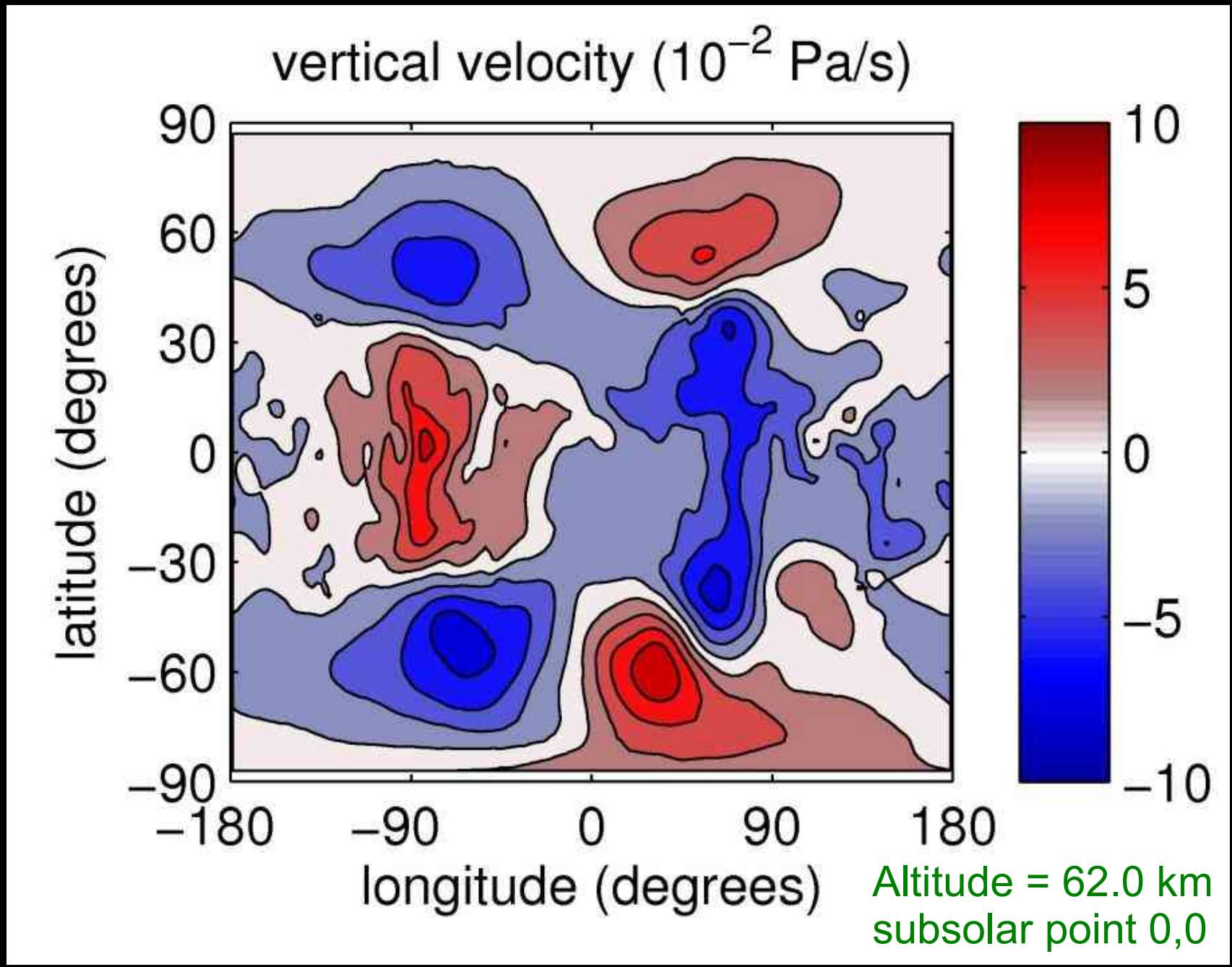
Meridional velocity (northward positive)



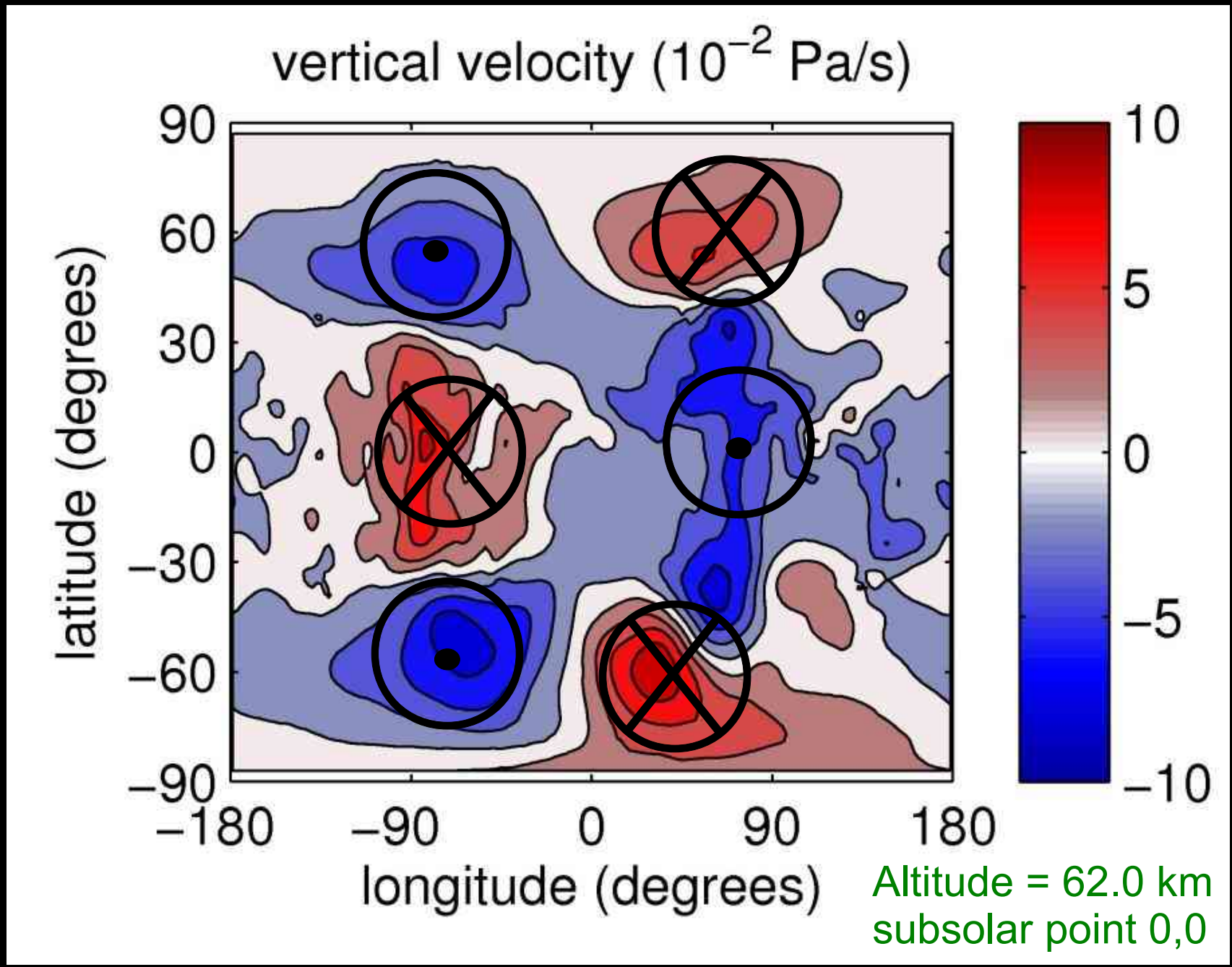
Meridional velocity (northward positive)

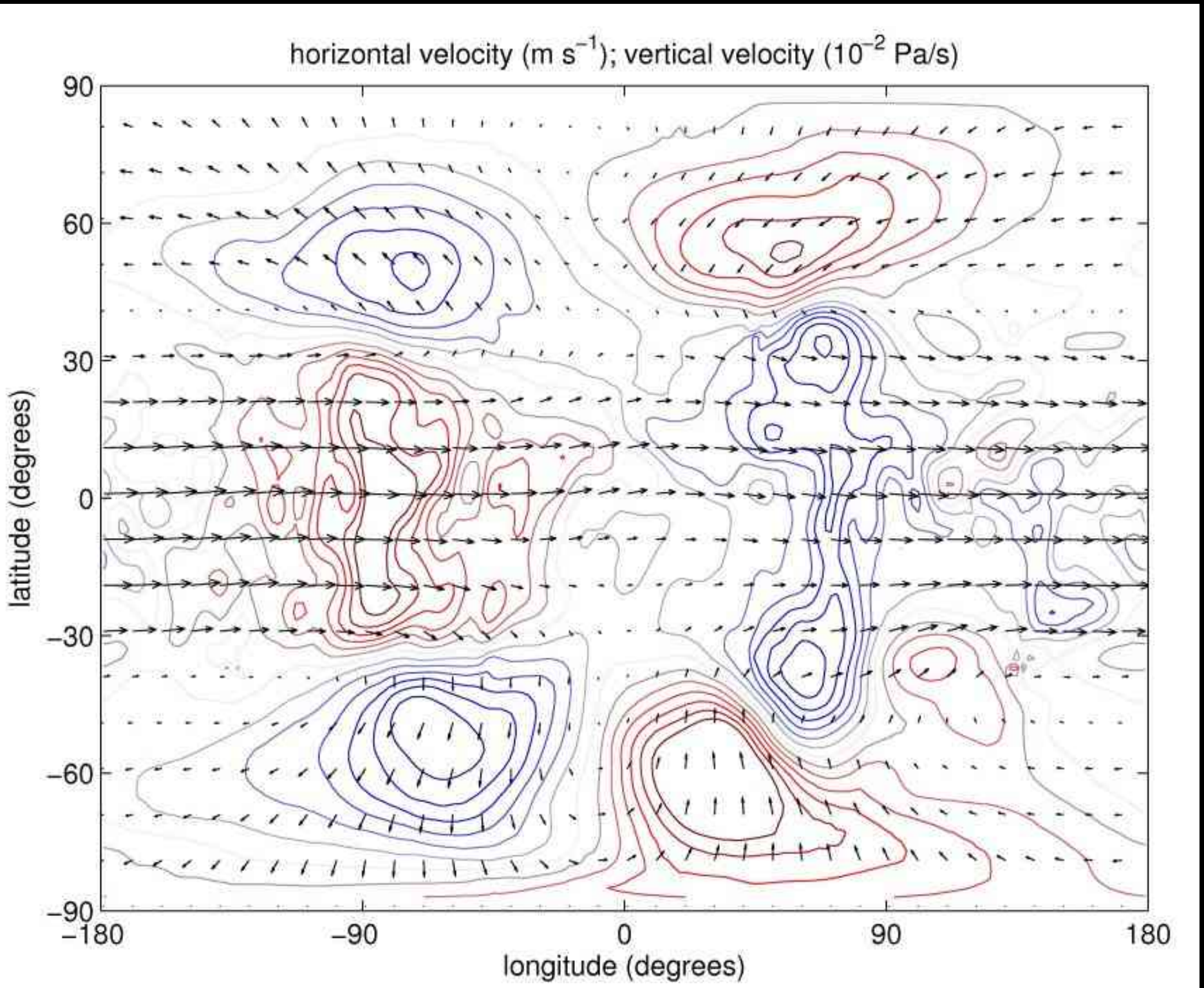


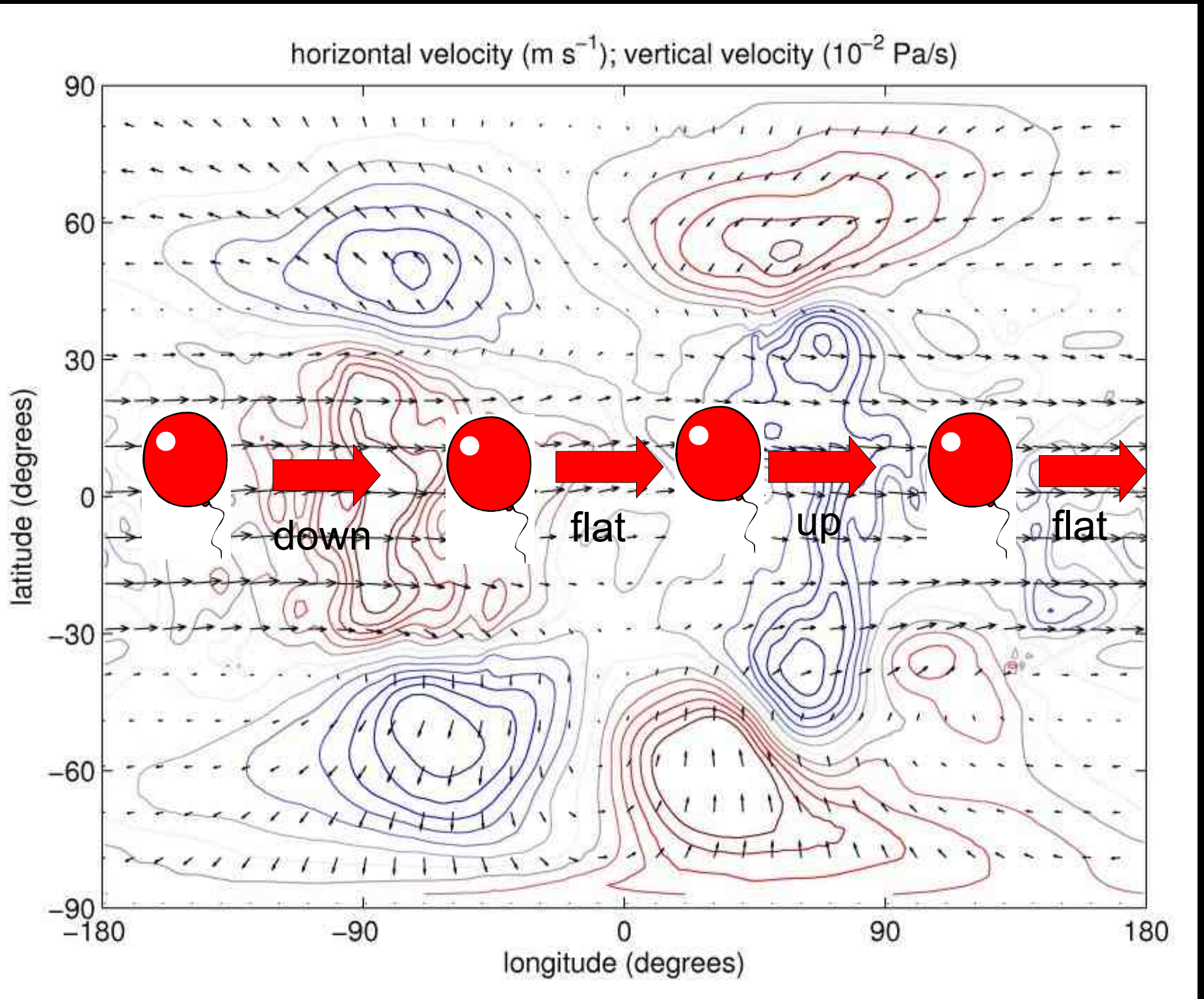
Vertical velocity (downward positive)

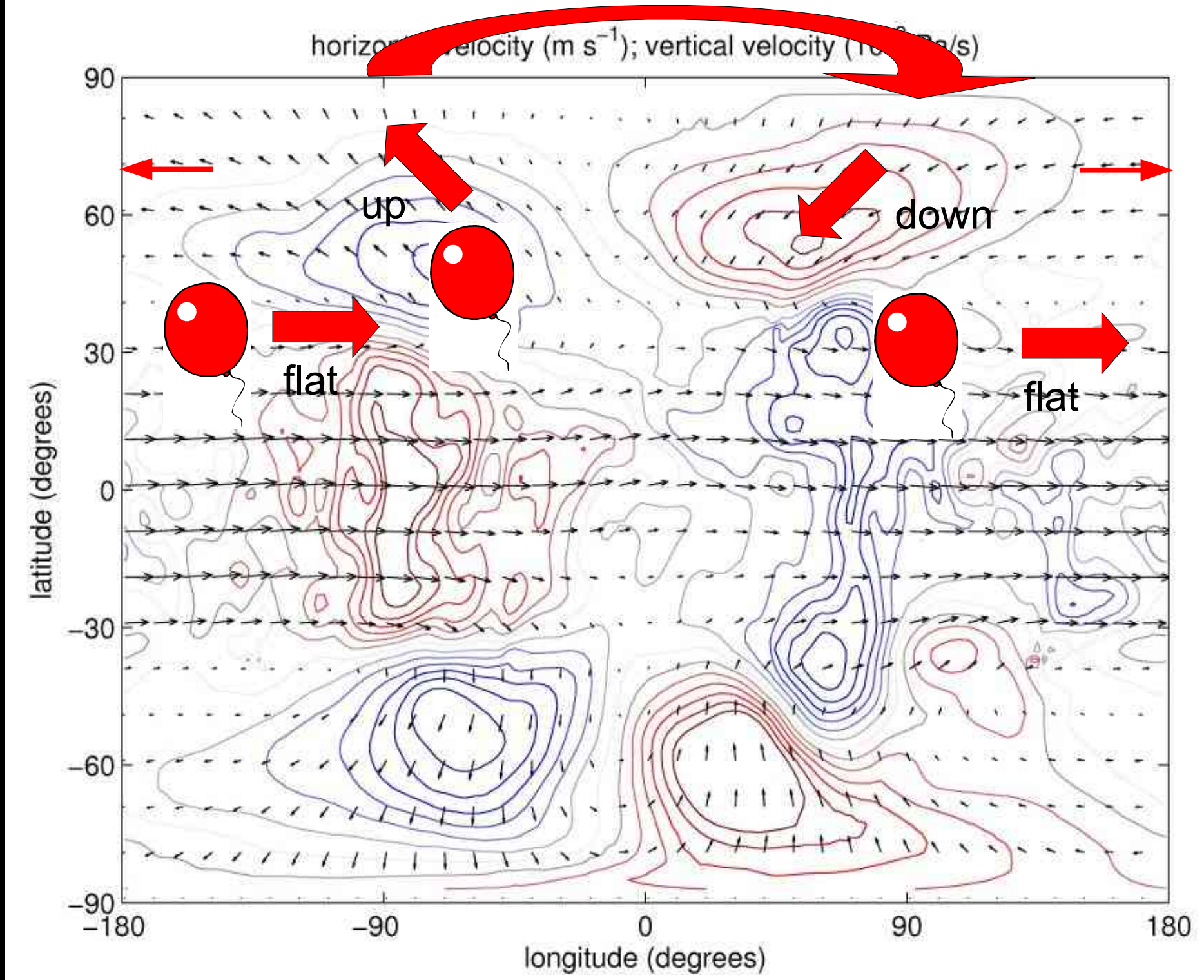


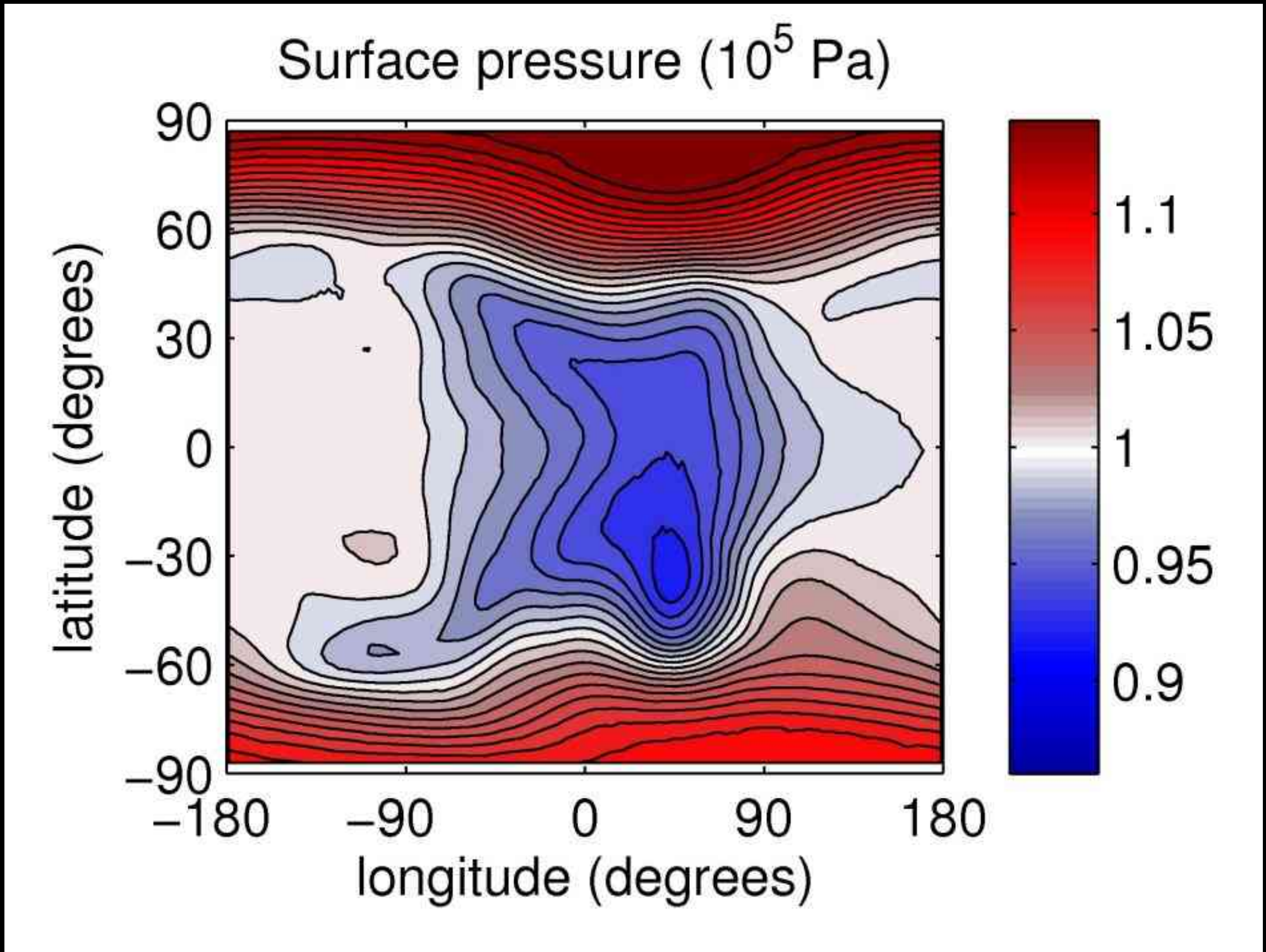
Vertical velocity (downward positive)

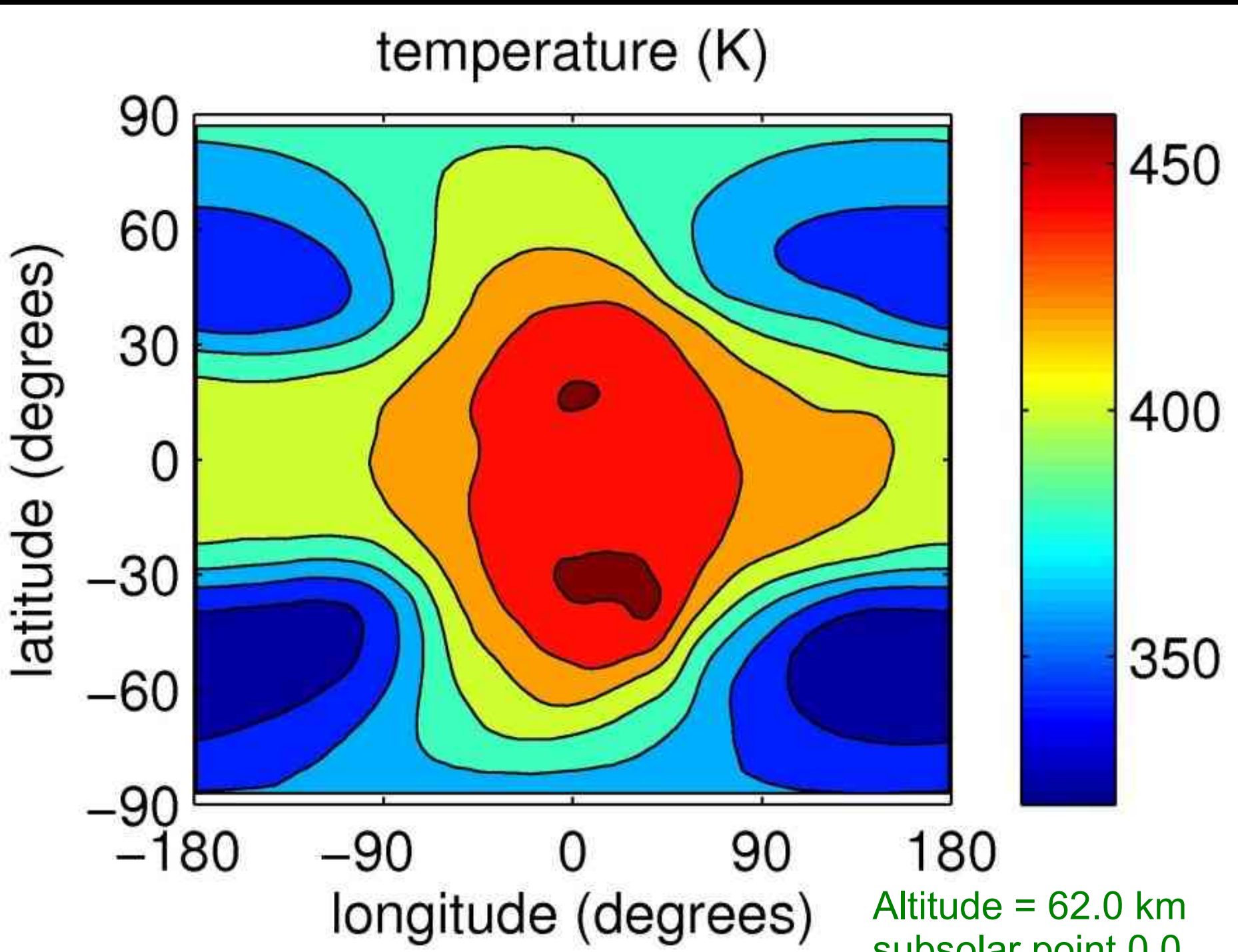



horizontal velocity (m s^{-1}); vertical velocity (10^{-2} Pa/s)
90
60
30
0
−30
−60
−90
latitude (degrees)
−180
−90
0
90
180
longitude (degrees)

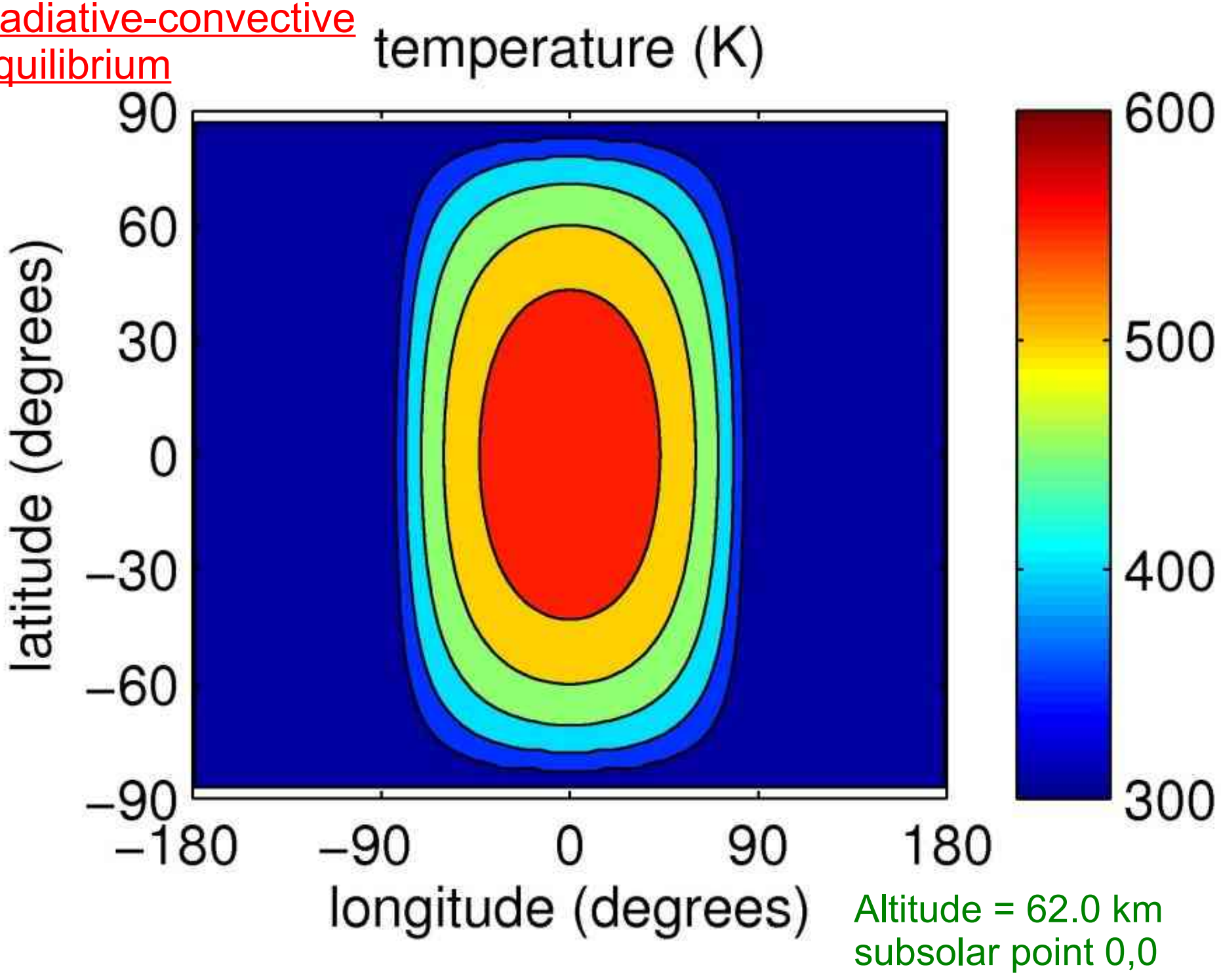

horizontal velocity (m s^{-1}); vertical velocity (10^{-2} Pa/s)
90
60
30
0
−30
−60
−90
latitude (degrees)
−180
−90
0
90
180
longitude (degrees)
down
flat
up
flat

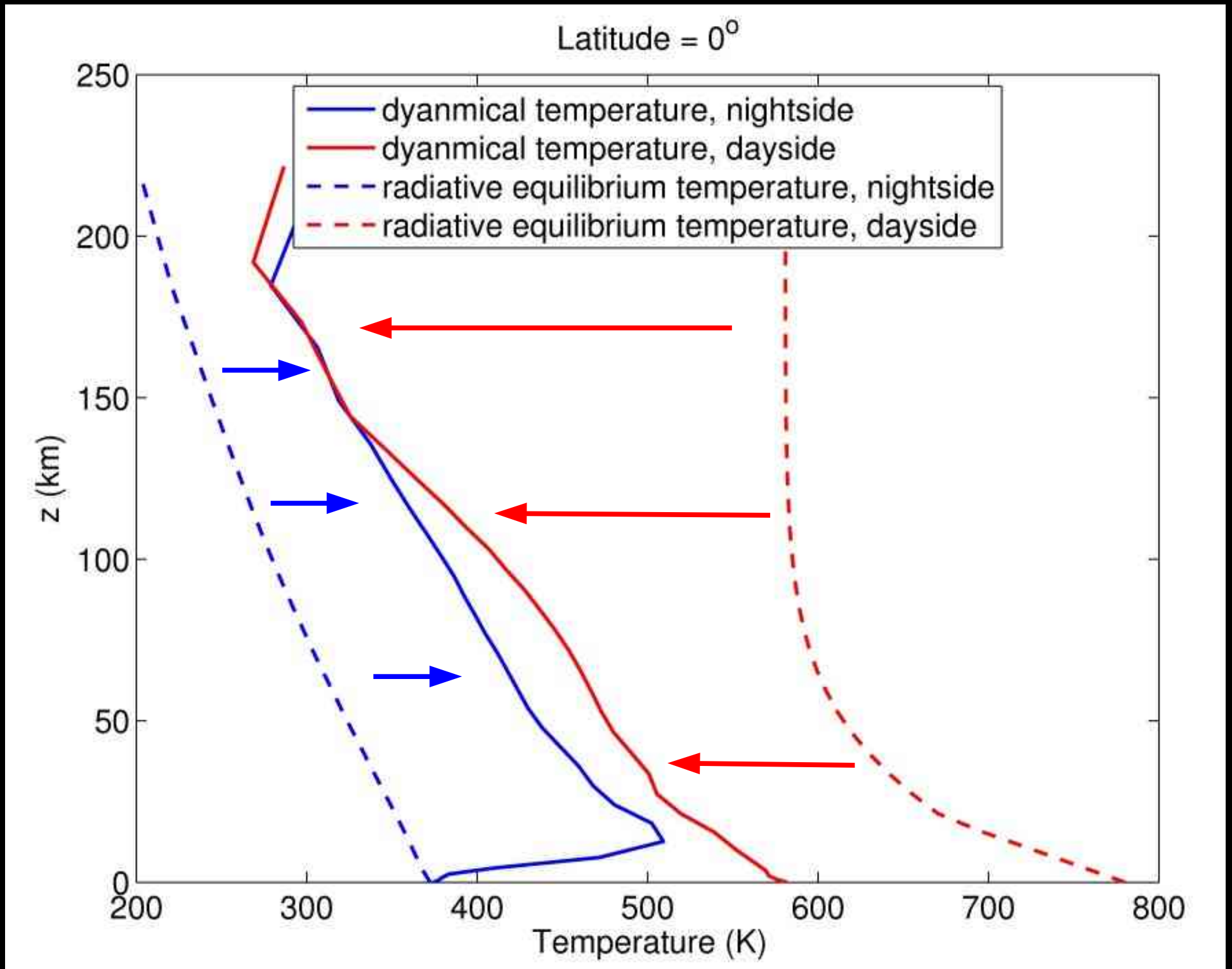

horizo velocity (m s^{-1}); vertical velocity (
/s)
90
60
30
0
−30
−60
−90
−180
−90
0
90
180
latitude (degrees)
longitude (degrees)
up
down
flat
flat

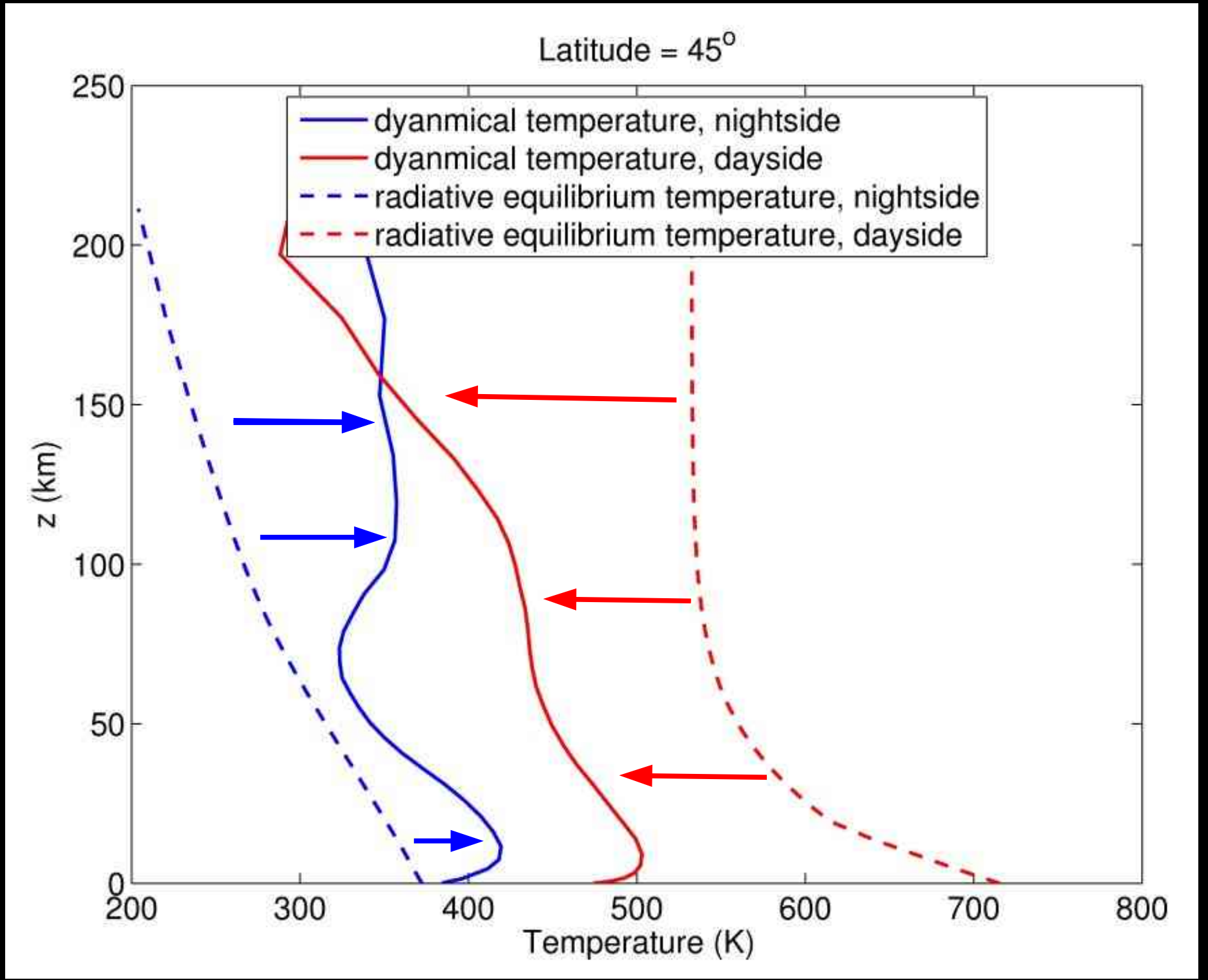

Surface pressure (10^5 Pa)
90
60
30
0
−30
−60
−90
latitude (degrees)
−180
−90
0
90
180
longitude (degrees)
1.1
1.05
1
0.95
0.9


temperature (K)
90
60
30
0
−30
−60
−90
latitude (degrees)
−180
−90
0
90
180
longitude (degrees)
450
400
350
Altitude = 62.0 km
subsolar point 0,0

Radiative-convective equilibrium




Latitude = 0°
dyanmical temperature, nightside
dyanmical temperature, dayside
radiative equilibrium temperature, nightside
radiative equilibrium temperature, dayside
z (km)
Temperature (K)
250
200
150
100
50
0
200
300
400
500
600
700
800


Latitude = 45°
dyanmical temperature, nightside
dyanmical temperature, dayside
radiative equilibrium temperature, nightside
radiative equilibrium temperature, dayside
z (km)
Temperature (K)
250
200
150
100
50
0
200
300
400
500
600
700
800

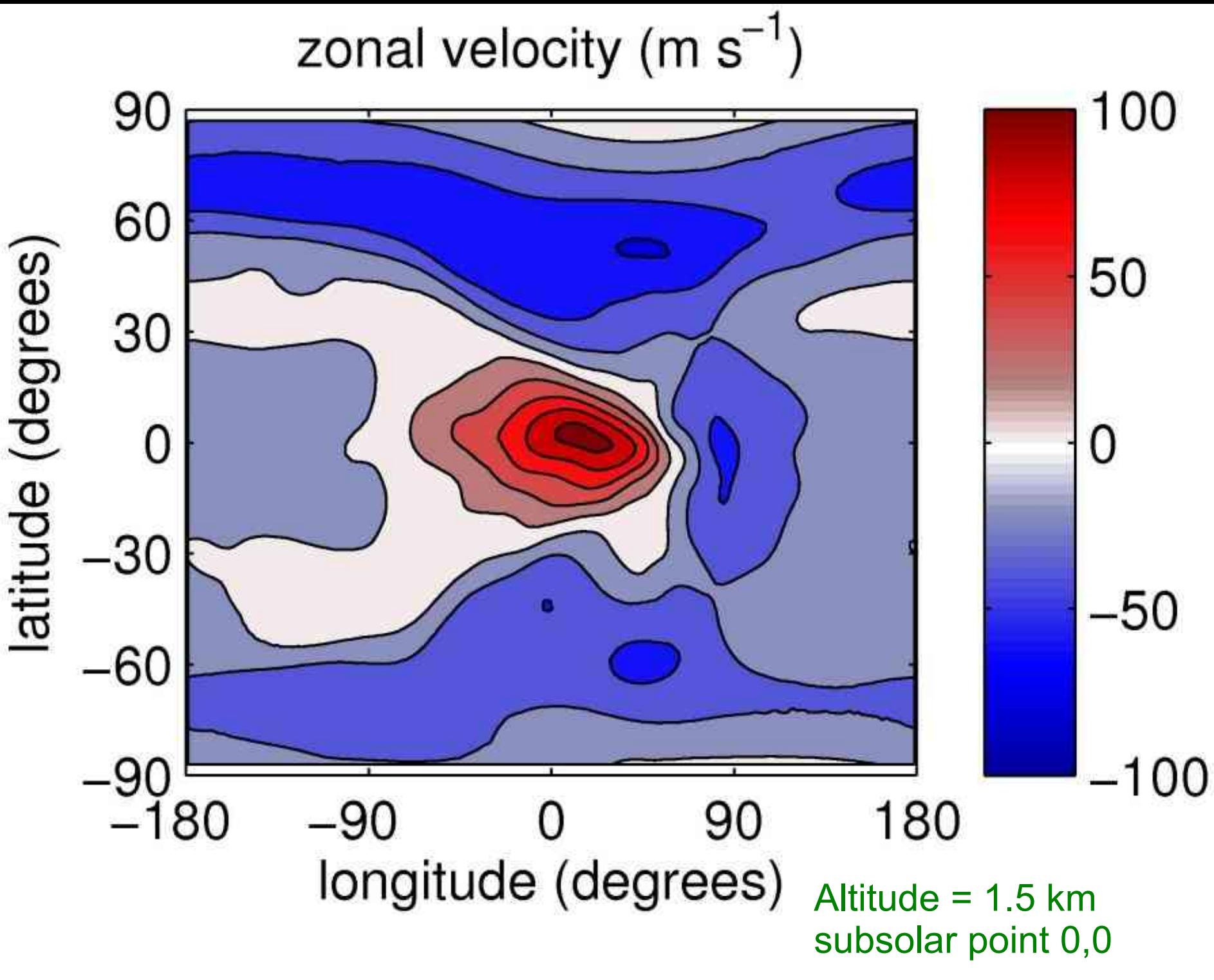
Comparison with previous work

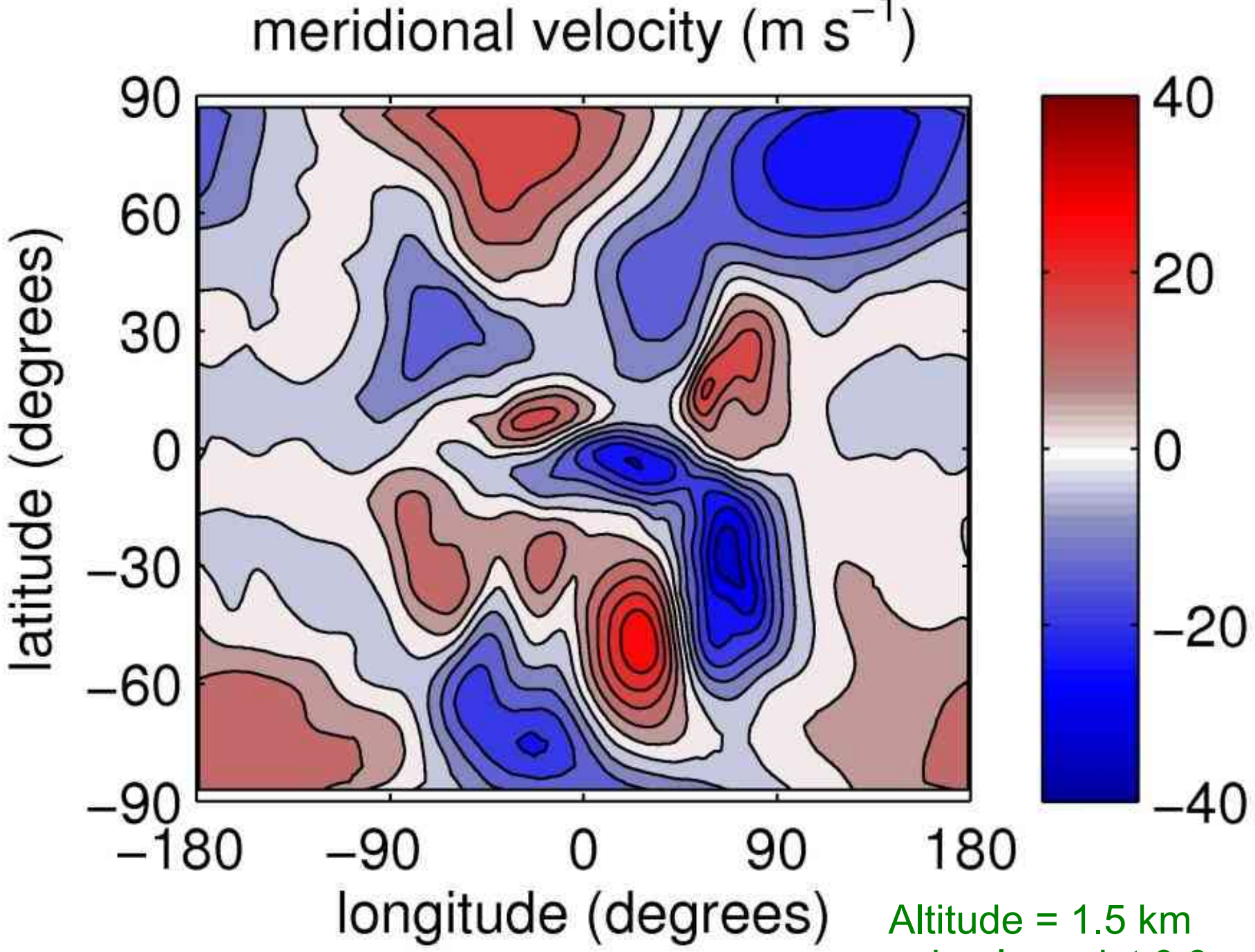
- Unlike any terrestrial-type Solar System planet
- Joshi et al. 1997 (Joshi et al. 2003)
  - “longitudinal, thermally direct cell, which transports heat from the dayside to the nightside. The mass is returned to the dayside through the polar regions at low levels”
  - “Aloft the circulation is fairly longitudinally symmetric, and a superrotating jet is present at the equator”
  - “...the atmosphere being far warmer than radiative-convective calculations, ... especially on the nightside”
- Merlis et al. 2010
  - "Rotational waves and eddies shape the distribution of winds, temperature, and precipitation in the rapidly rotating [1 earth day rotation period] atmosphere"
- Wordsworth et al. 2011
  - Atmospheric stability of Mars-type worlds (GJ 581d)

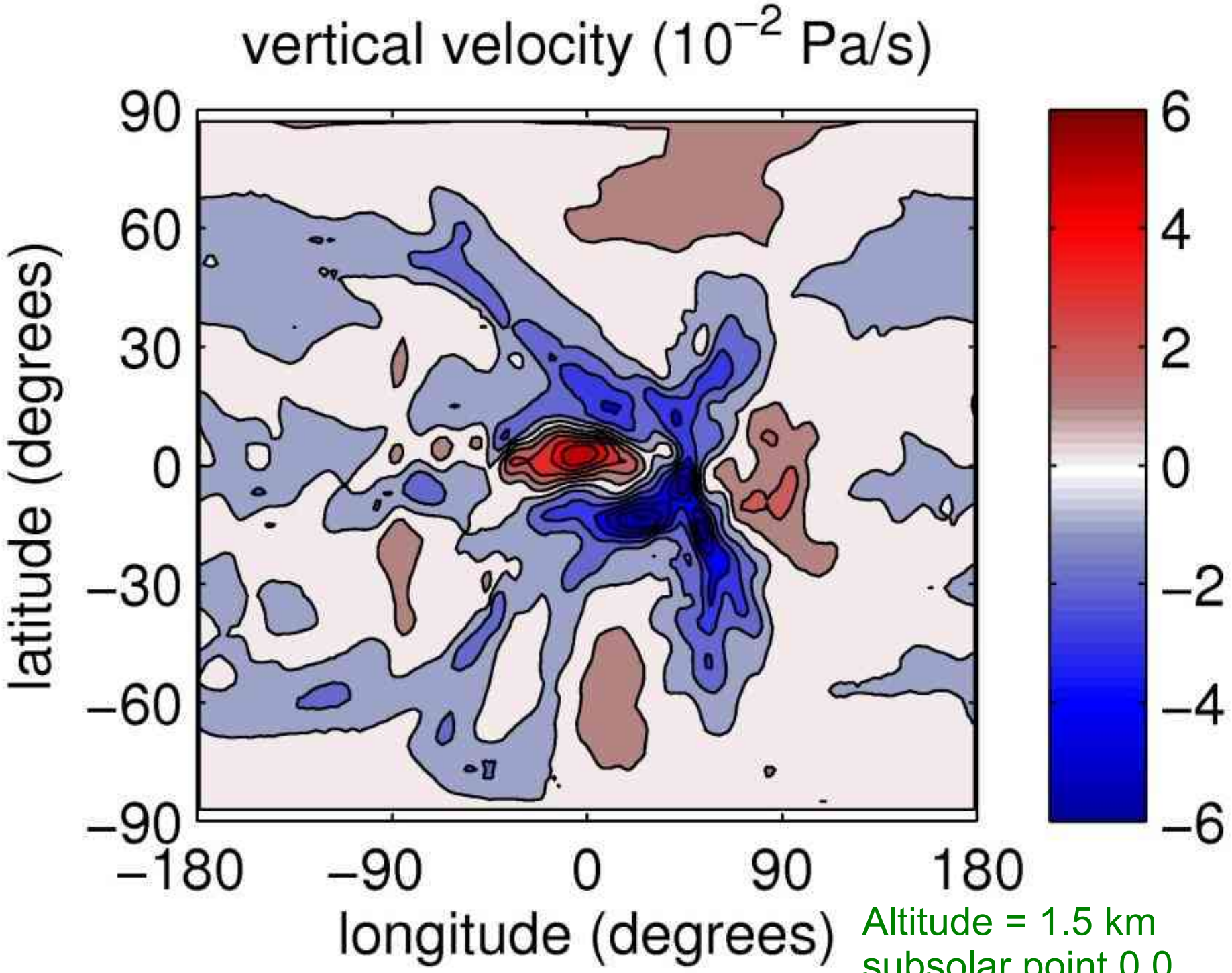
Summary

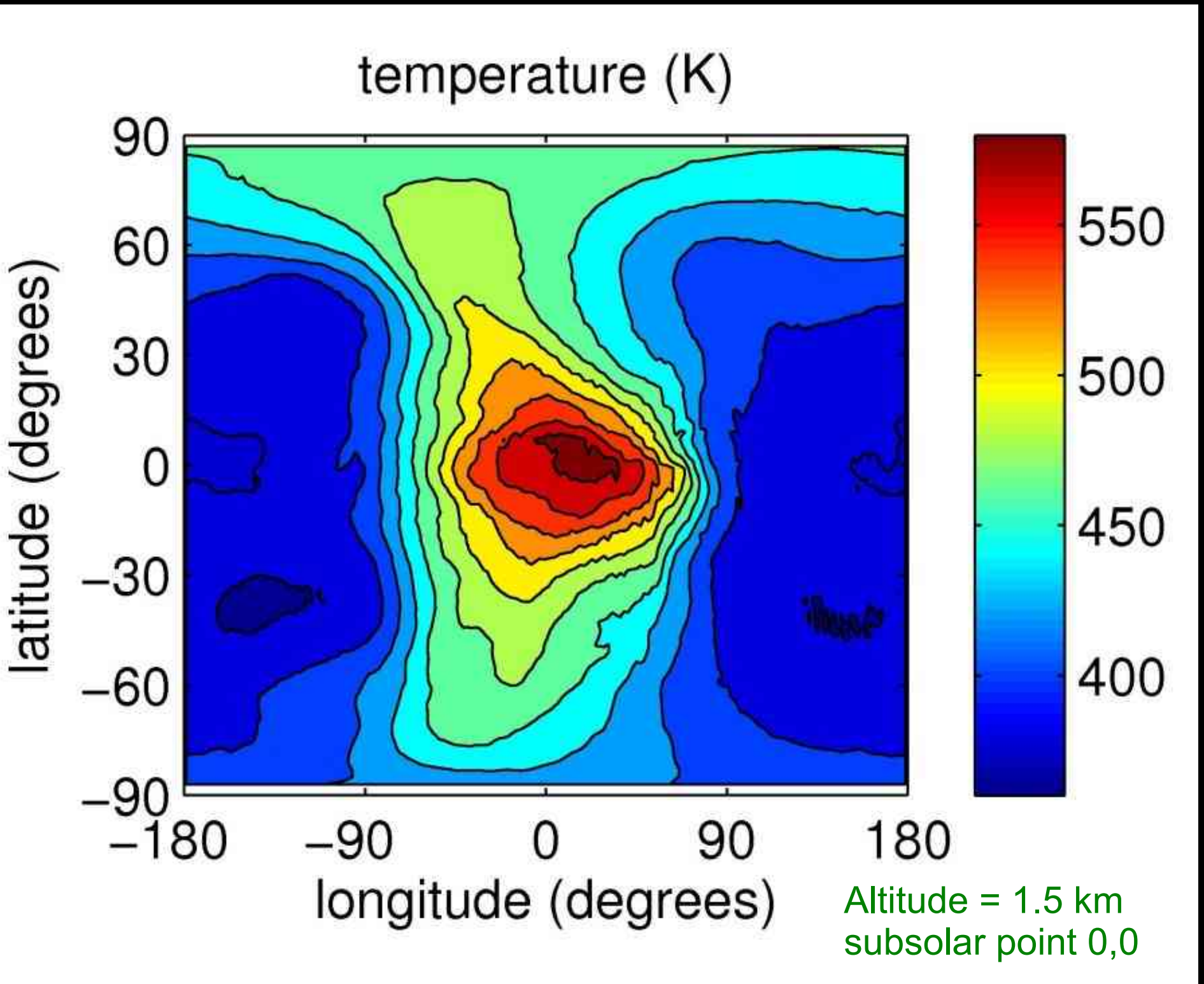
For an H_2O, 1 bar surface pressure, 0.4 surface albedo, GJ 1214b:

- The atmospheric circulation is qualitatively uniform with altitude (except at low levels)
- A strong eastward jet is present at the equator
- Flow at mid- to high latitudes moves over the poles and is slightly deflected westward as it does so
- Surface pressure increases poleward
- Atmospheric circulation mediates the dayside-nightside heating differential
- Future work: add more sophisticated RT (non-gray, clouds); include frost cycle

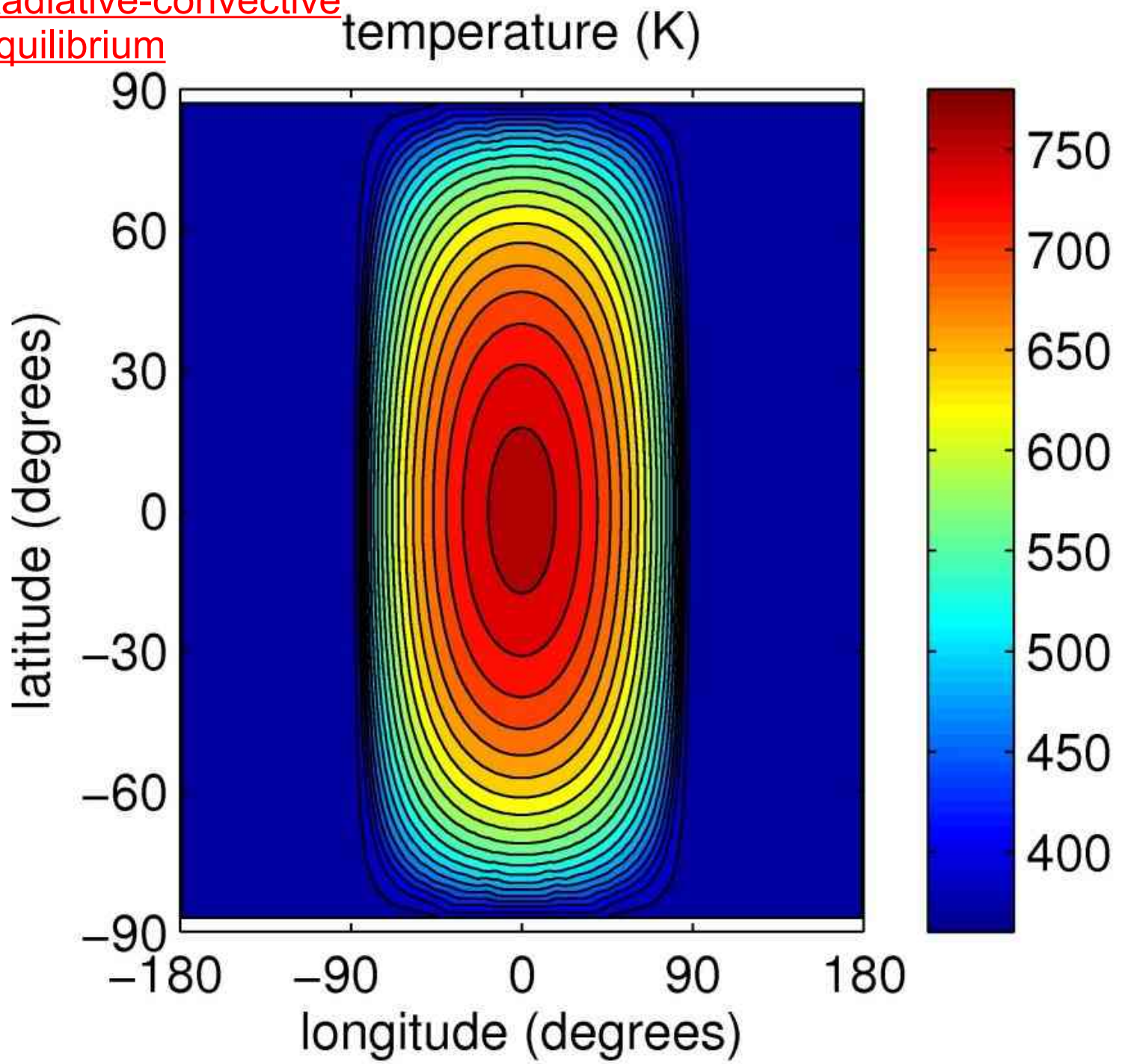

zonal velocity (m s^{-1})
90
60
30
0
−30
−60
−90
latitude (degrees)
−180
−90
0
90
180
longitude (degrees)
100
50
0
−50
−100
Altitude = 1.5 km
subsolar point 0,0


meridional velocity (m s^{-1})
90
60
30
0
−30
−60
−90
latitude (degrees)
−180
−90
0
90
180
longitude (degrees)
40
20
0
−20
−40
Altitude = 1.5 km
subsolar point 0,0

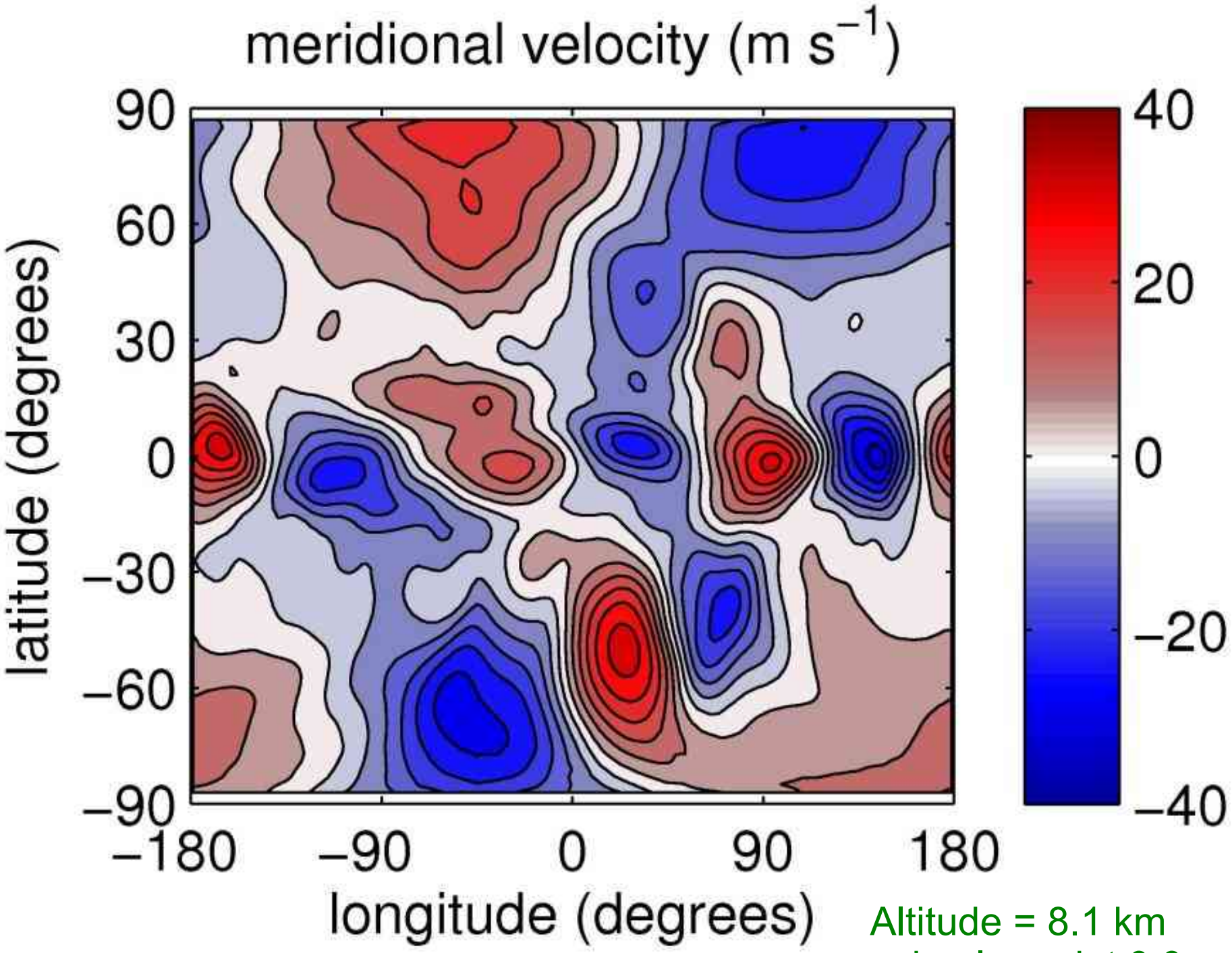

vertical velocity (10^{-2} Pa/s)
90
60
30
0
−30
−60
−90
latitude (degrees)
−180
−90
0
90
180
longitude (degrees)
6
4
2
0
−2
−4
−6
Altitude = 1.5 km
subsolar point 0,0


temperature (K)
90
60
30
0
−30
−60
−90
latitude (degrees)
−180
−90
0
90
180
longitude (degrees)
550
500
450
400
Altitude = 1.5 km
subsolar point 0,0

Radiative-convective equilibrium



Altitude = 1.5 km
subsolar point 0,0


meridional velocity (m s^{-1})
90
60
30
0
−30
−60
−90
latitude (degrees)
−180
−90
0
90
180
longitude (degrees)
40
20
0
−20
−40
Altitude = 8.1 km
subsolar point 0,0