

Energy budget and surface temperature of rocky planets

Bibliographic material:

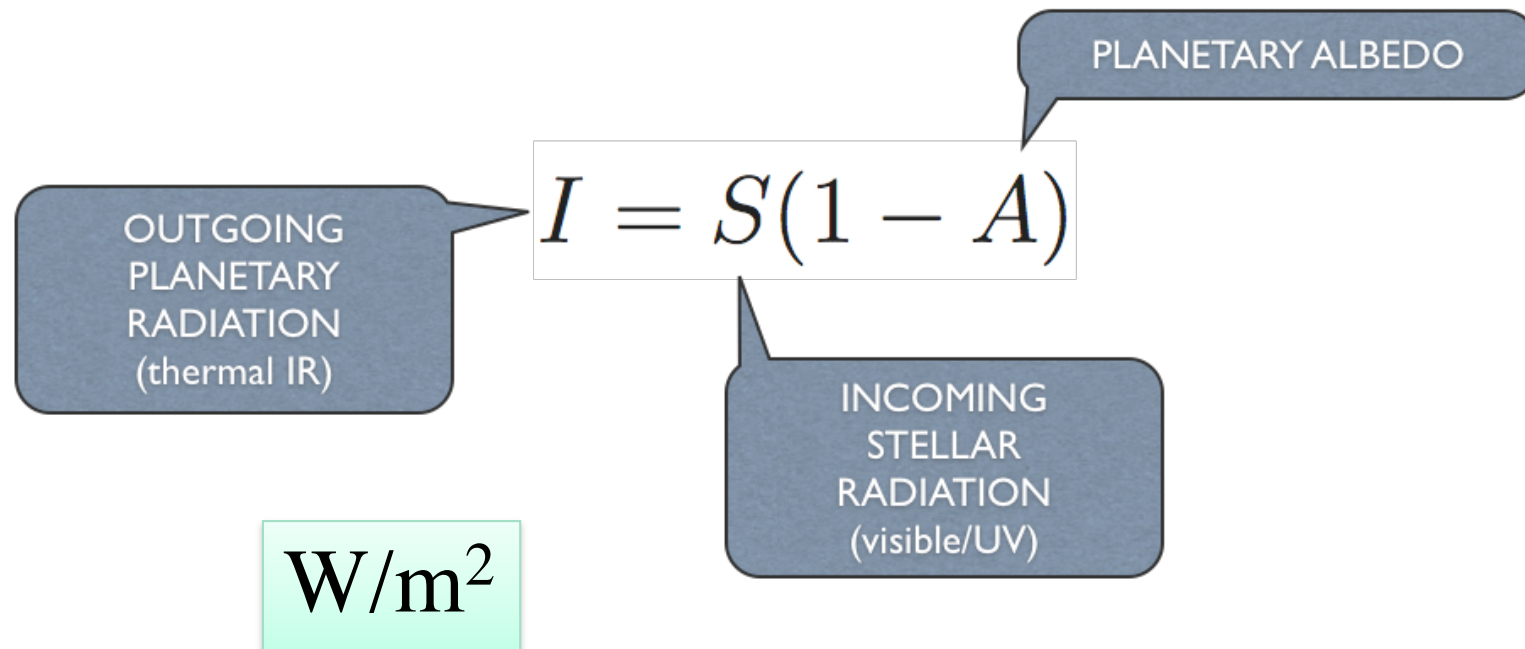
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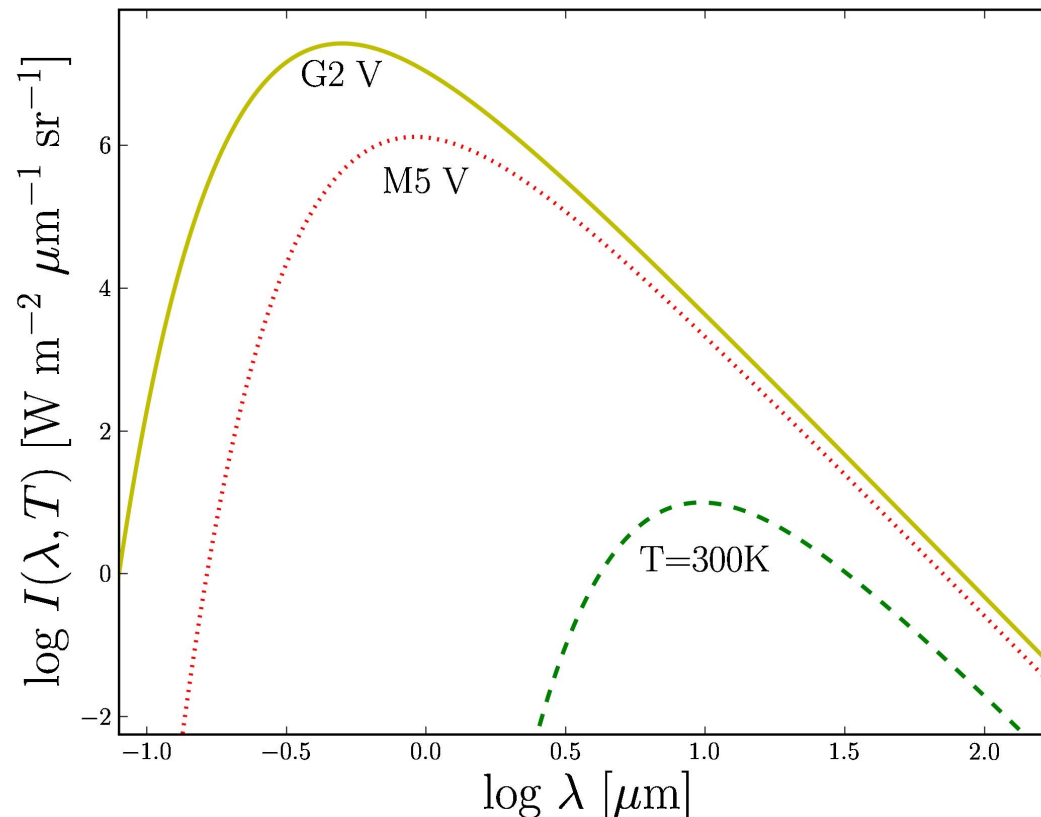
G. Vladilo

zero-order, global planetary Energy Balance



Spectral distributions of the incoming stellar radiation, S ,
and of the outgoing planetary radiation, I

Given the different location of the maximum of the spectral distributions, these two terms of the planetary energy balance can be treated separately



Planet effective temperature

Zero-order energy balance calculation

Provides an estimate of the black-body temperature of the planet

From the energy equilibrium equation, assuming black body emission

$$4 \pi R^2 \sigma T_{eff}^4 = \pi R^2 S (1-A)$$

Where

S : insolation

stellar flux (W/m^2) received by the planet

A : planetary albedo

fraction of stellar radiation reflected back into space

Energy balance

$$\sigma T_{eff}^4 = \frac{1}{4} S (1-A)$$

Insolation

The insolation of a planet located at a distance d from its central star is

$$S = L_*/(4\pi d^2)$$

where L_* is the stellar luminosity
and the insolation is measured on a surface
perpendicular to the star-planet direction

In the case of the Earth,
 S is called the “solar constant”

$$S = 1361 \text{ W/m}^2$$
$$d = a = 1 \text{ AU} = 1.495 \times 10^{11} \text{ m}$$

Planetary albedo

Albedo

- Fraction of stellar photons reflected back to space without heating the planet
 - *Surface albedo*, depends on the type of surface
 - Examples:
 $A(\text{ice}) \sim 0.5/0.6$ $A(\text{snow}) \sim 0.8/0.9$ $A(\text{sand}) \sim 0.25$
 - *Atmospheric albedo*, depends on the radiative transfer of stellar photons through the planetary atmosphere and on the presence of clouds
 - **Top-of-atmosphere (TOA) albedo**
 - Takes into account both surface and atmospheric contributions to the albedo
 - **All albedo contributions are wavelength-dependent**
 - *The albedo also depends on the spectral distribution of the stellar emission*
 - *Mostly because of Rayleigh scattering, which is more effective at shorter wavelengths*
 - *Hotter stars have a larger fraction of short-wavelength photons, which are more scattered by the planetary atmosphere (higher albedo)*

Planetary albedo

Planet	Albedo in the <u>visible</u>
Mercury	0.11
Venus	0.65
Earth	0.38
Mars	0.15
Jupiter	0.52
Moon	0.12

Allen (2000)

Insolation and planet temperature

$$\sigma T_{eff}^4 = \frac{1}{4} S (1-A)$$

$$S = L_* / (4\pi d^2)$$

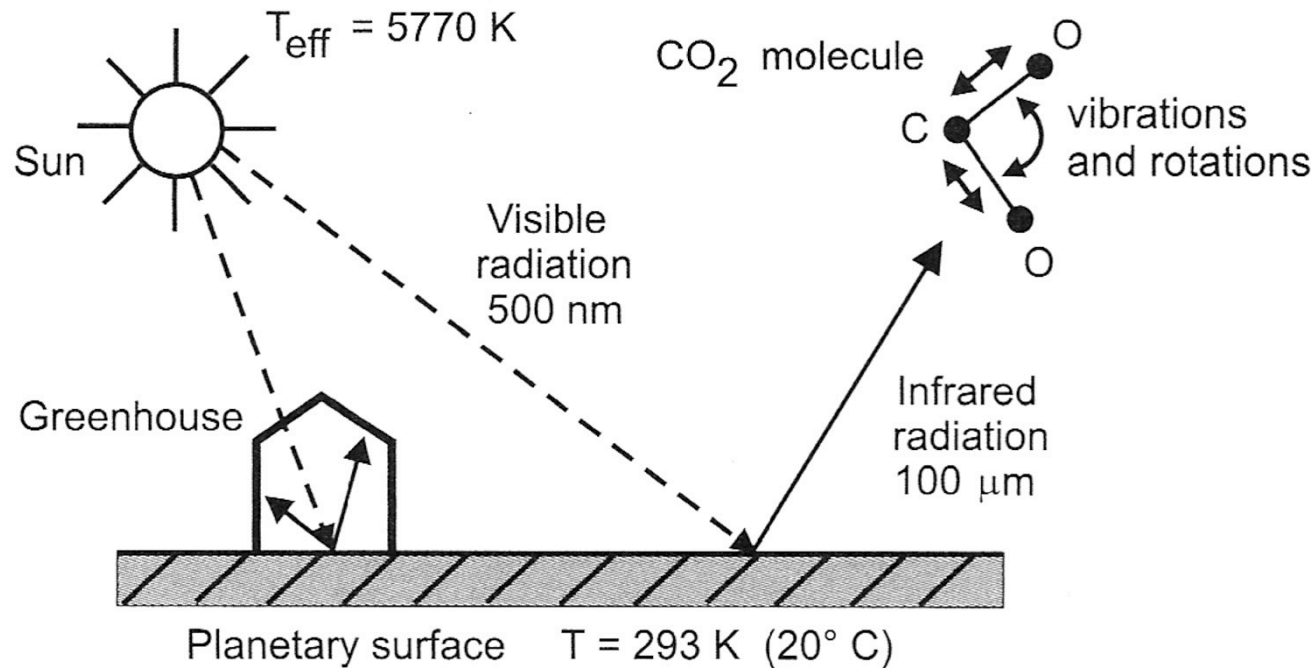
For a given value of planetary albedo, the effective temperature of the planet is determined by the insolation and therefore by the planet-star distance, d

In this idealized situation,

a ring of distances will yield an interval of effective temperatures

The concept of “circumstellar habitable zone”, that will be specified later in this course, originates from this simple concept

However, the real planet temperature is determined not only by the insolation and albedo, but also by a variety planetary factors, such as the greenhouse effect and many other factors that alter the planetary energy budget



Greenhouse effect

The visible radiation is almost unabsorbed by the atmosphere, whereas the thermal radiation is trapped by molecular absorption

As a result, the surface temperature rises

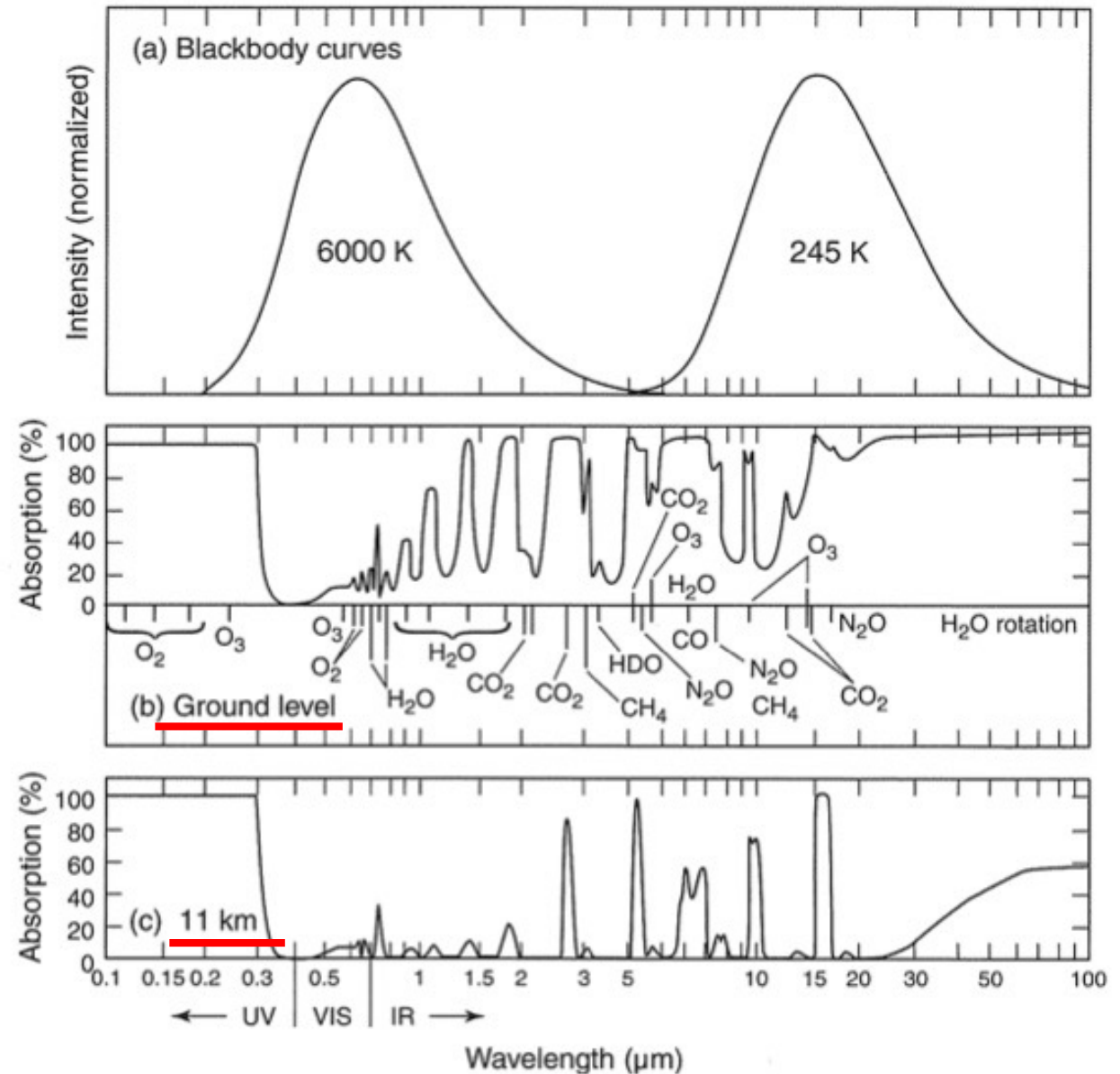
Greenhouse effect

Wavelength dependence of the stellar and planetary radiation.

Wavelength dependence of the absorption of the Earth's atmosphere

Molecules absorbing in the thermal infrared are effective greenhouse contributors

The most effective and abundant greenhouse molecules are H_2O , CO_2 and CH_4



Effective temperature versus surface temperature

Planet	Mean surface temperature T_s [K]	T_{eff} [K]
Venus	730	230
Earth	288	255
Mars	210	212

Differences are mostly due to the greenhouse effect, which is not accounted for in the calculation of T_{eff}

$$T_s = T_{\text{eff}} + \Delta T(\text{greenhouse})$$

Earth: $\Delta T = +33$ K

the Earth would be completely frozen without greenhouse effect

Venus: strong difference is due to the presence of a thick CO_2 atmosphere

Mars: good agreement due to its very tenuous atmosphere

Atmospheres and climate of rocky planets

- Atmospheres influence the climate in two ways
 - The atmosphere governs the *vertical transport*, a key factor of the planet energy budget

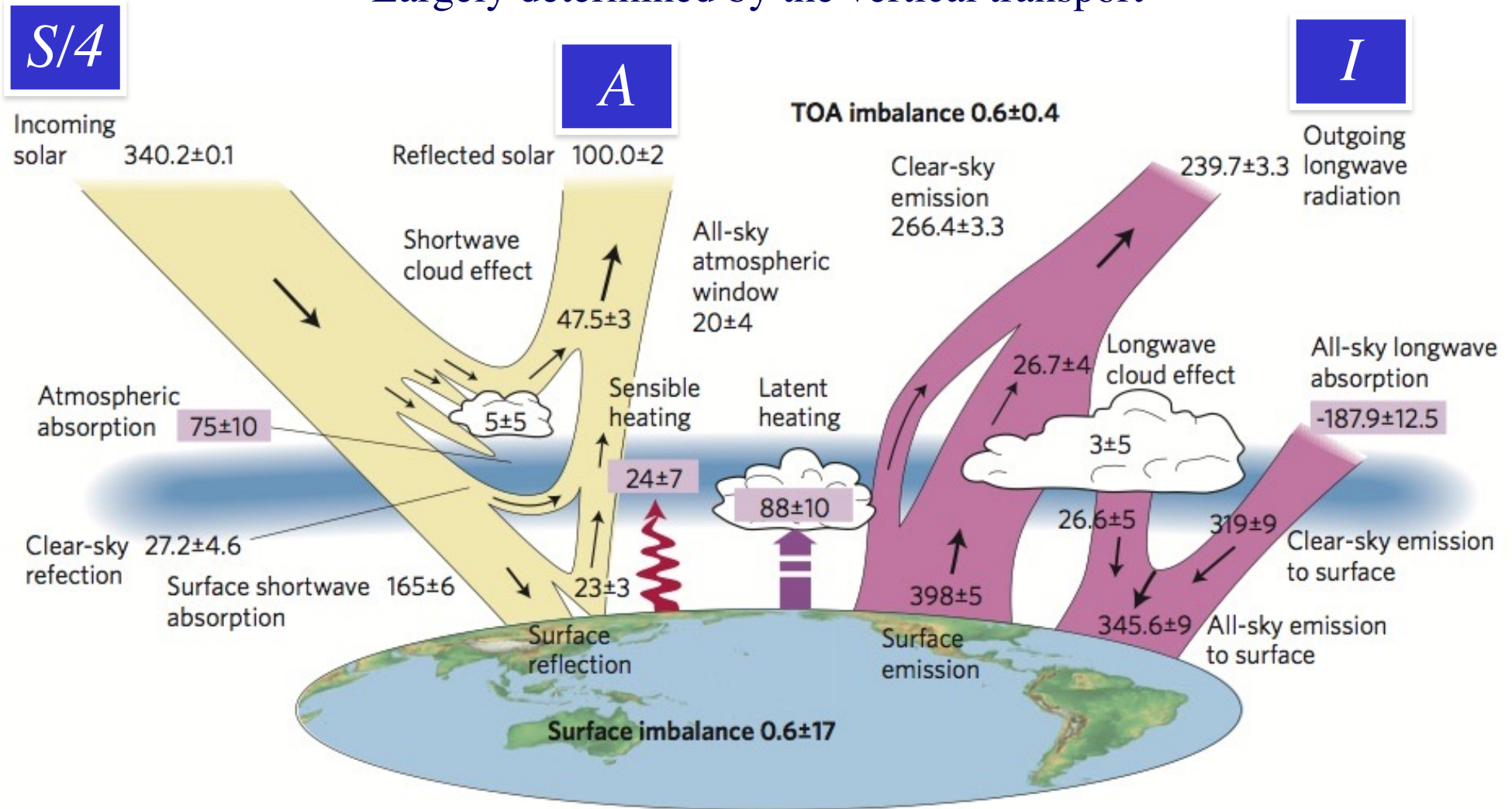
The vertical transport is largely determined by the radiative transfer of incoming stellar radiation and outgoing planetary radiation

Also convection plays an important role in the troposphere
 - The fluidodynamics of the atmosphere plays a fundamental role in the *horizontal transport*, i.e. the energy transport along the planet surface

The circulation of the atmosphere is driven by temperature gradients and influenced by planetary rotation

Earth's energy budget

Largely determined by the vertical transport

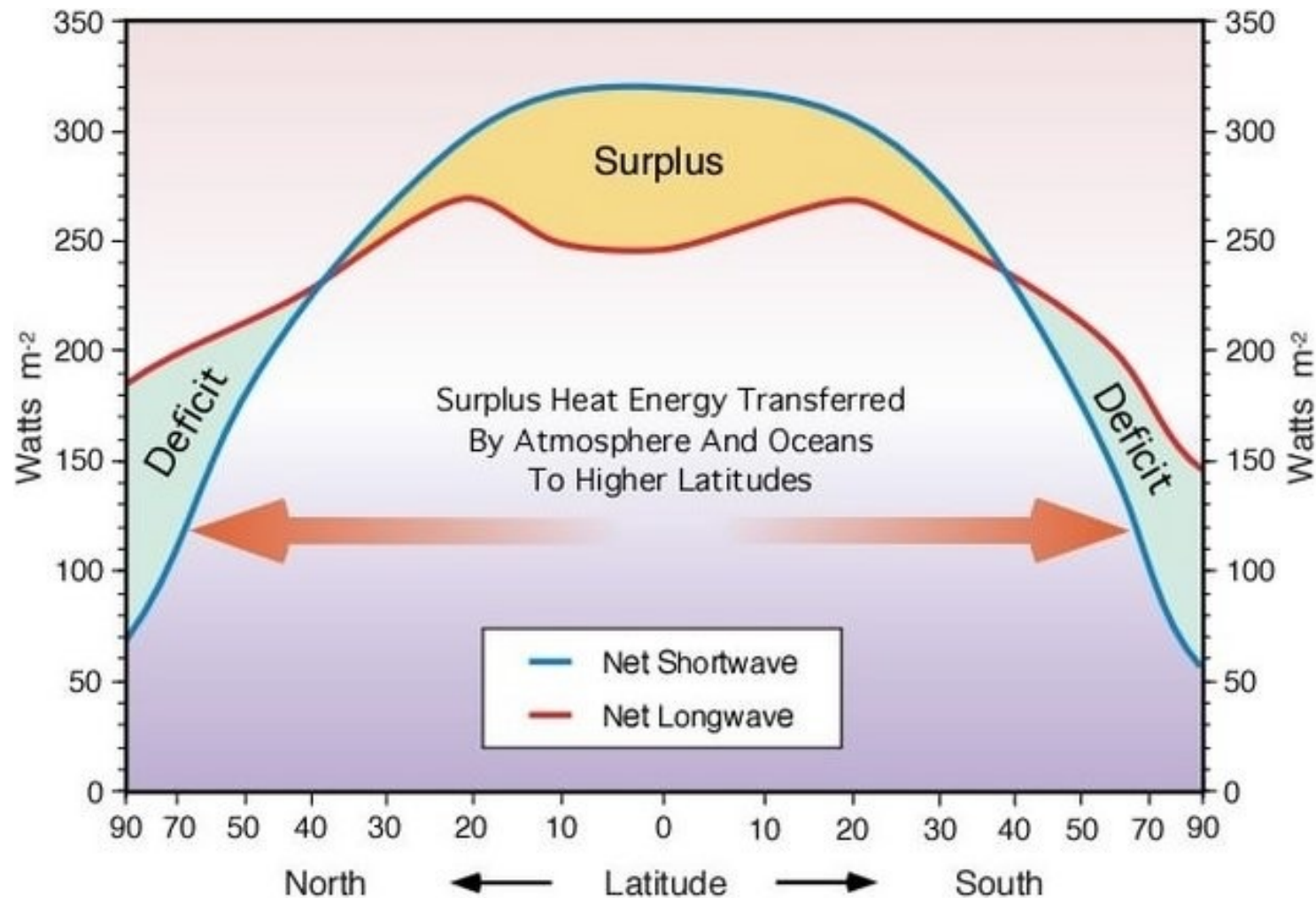


Stephens et al. (2012)

Radiation balance at different latitudes

-- Incoming stellar radiation

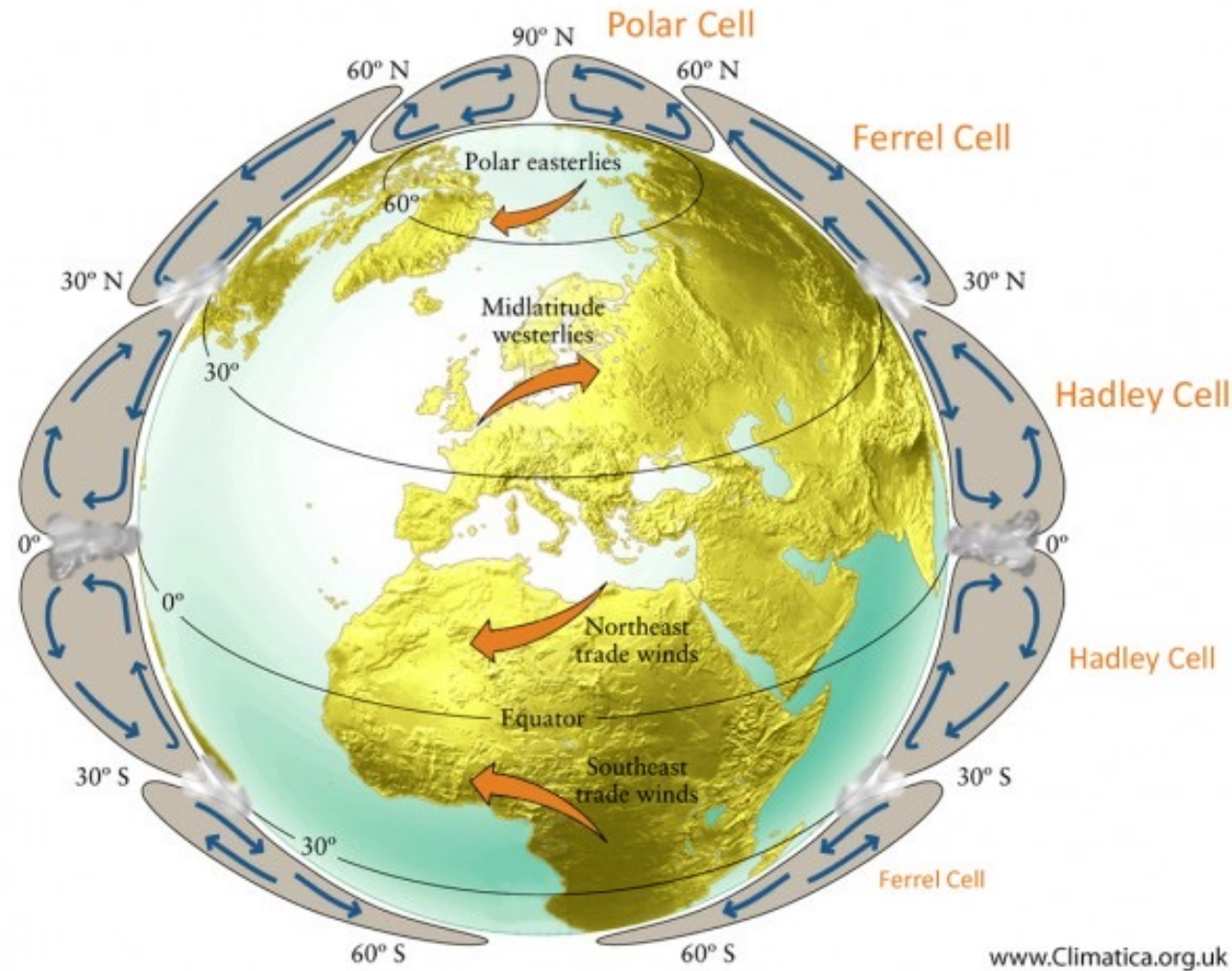
-- OLR (Outgoing Long-wavelength Radiation)



Atmospheric circulation and horizontal transport

- The horizontal structure of the atmosphere is determined by the atmospheric circulation
- The circulation is driven by the latitudinal temperature gradient and by the planet rotation
 - If the planet rotates the circulation is affected by Coriolis forces
 - Coriolis forces act for bodies moving relative to a rotating system of reference and are proportional to the velocity of the moving body
 - The air that flows polewards preserves its angular momentum and at high latitudes rotates faster than the surface, developing east-west streams

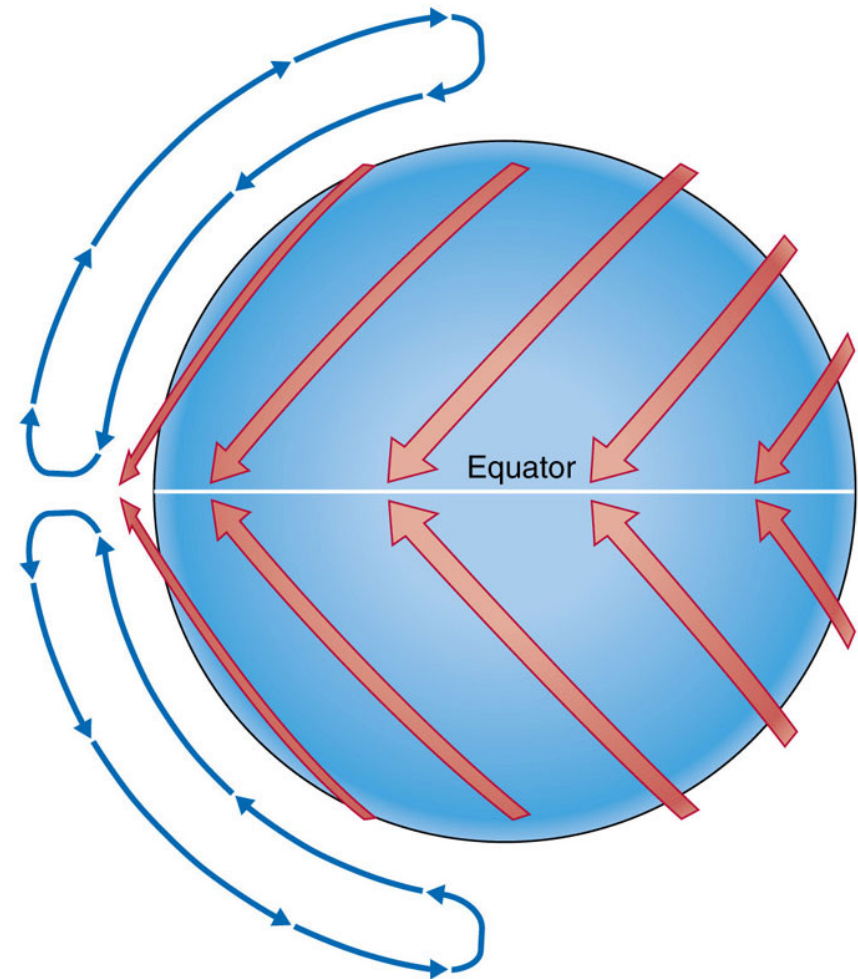
Earth's atmospheric transport



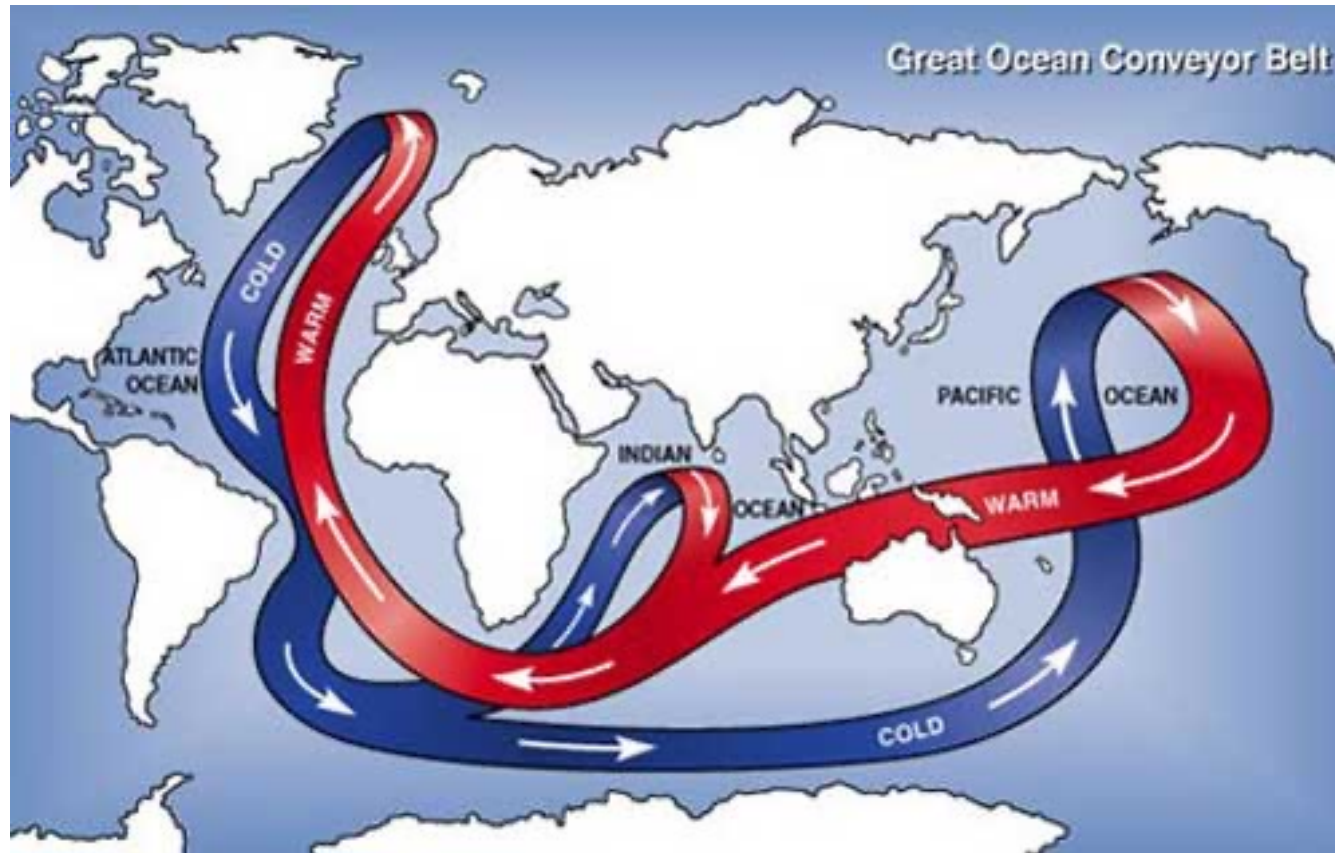
Coriolis forces prevent the direct transport from the equator to the poles
The transport takes place via convection cells created in each hemisphere

Meridional transport for slowly-rotating planets

- When the rotation rate is negligible, the meridional transport takes place along a single convective cell
 - Each hemisphere has its own convective cell driven by the equator-pole temperature gradient
 - The meridional transport is extremely efficient in this case
- *Venus provides an example of this type of meridional transport*



Earth's ocean transport



Ocean currents provide a form of energy transport that redistributes heat on the Earth surface on relatively long time scales (many years)
Due to the high thermal capacity of water, oceans stabilize the climate

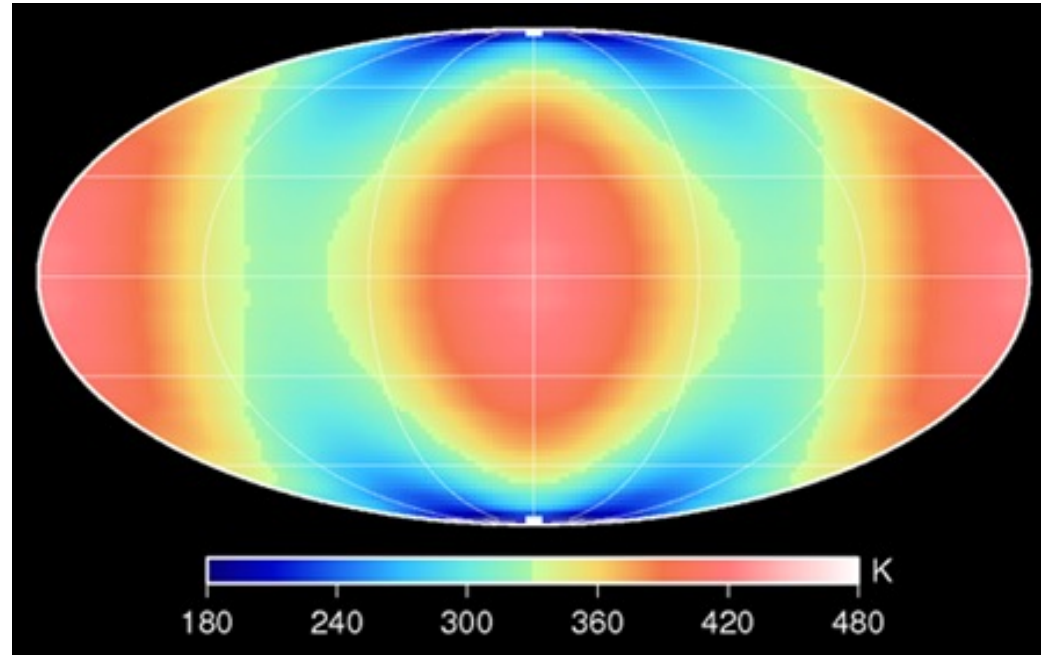
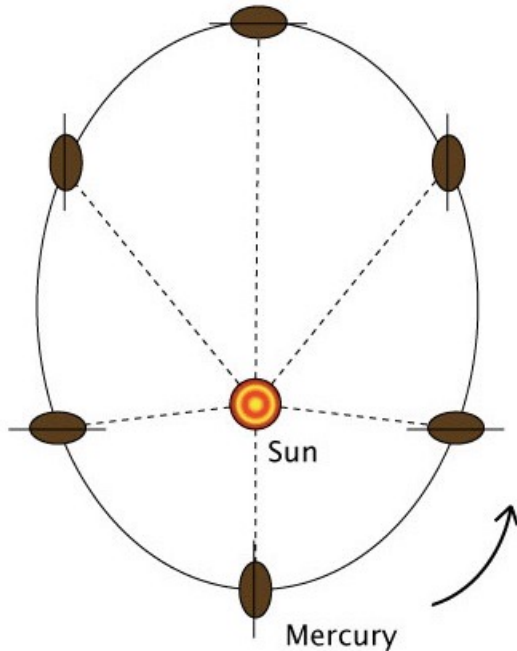
The surface temperature of rocky planets

The surface temperature of rocky planets is determined by the energy balance between incoming and outgoing radiation and by the horizontal energy transport

- Astronomical parameters (stellar luminosity, orbital parameters, rotation spin) and planetary parameters (atmosphere, hydrosphere, distribution of continents) affect the seasonal and latitudinal excursions of surface temperature
- The rocky planets of the Solar System provide a variety of examples of the impact of astronomical and planetary parameters on the surface temperature

Mercury surface temperature

extremely large excursions in latitude and longitude

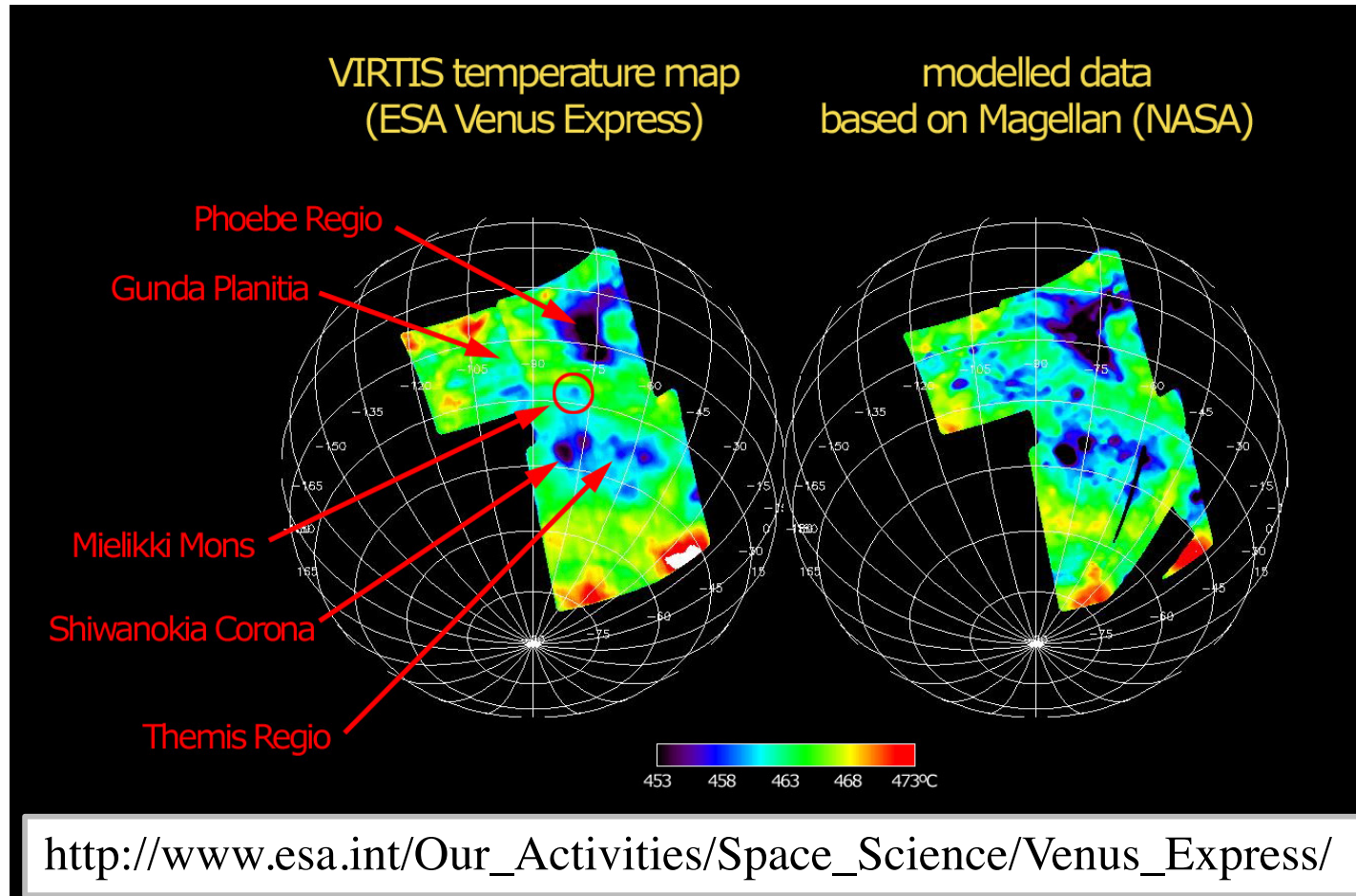


<http://diviner.ucla.edu/mercury/posters/Poster-03/poster-03.html>

Mercury's orbit locked in a 3:2 spin-orbit resonance. As a result, longitudes 0° and 180° always experience noon at perihelion, and longitudes 90° and 270° noon at aphelion. Because of its relatively high eccentricity ($e=0.21$), the insolation varies from $14,464 \text{ W m}^{-2}$ to 6279 W m^{-2} . Mercury also experiences a temperature variation of about 100°C about the equator due the lack of atmospheric transport.

Venus surface temperature

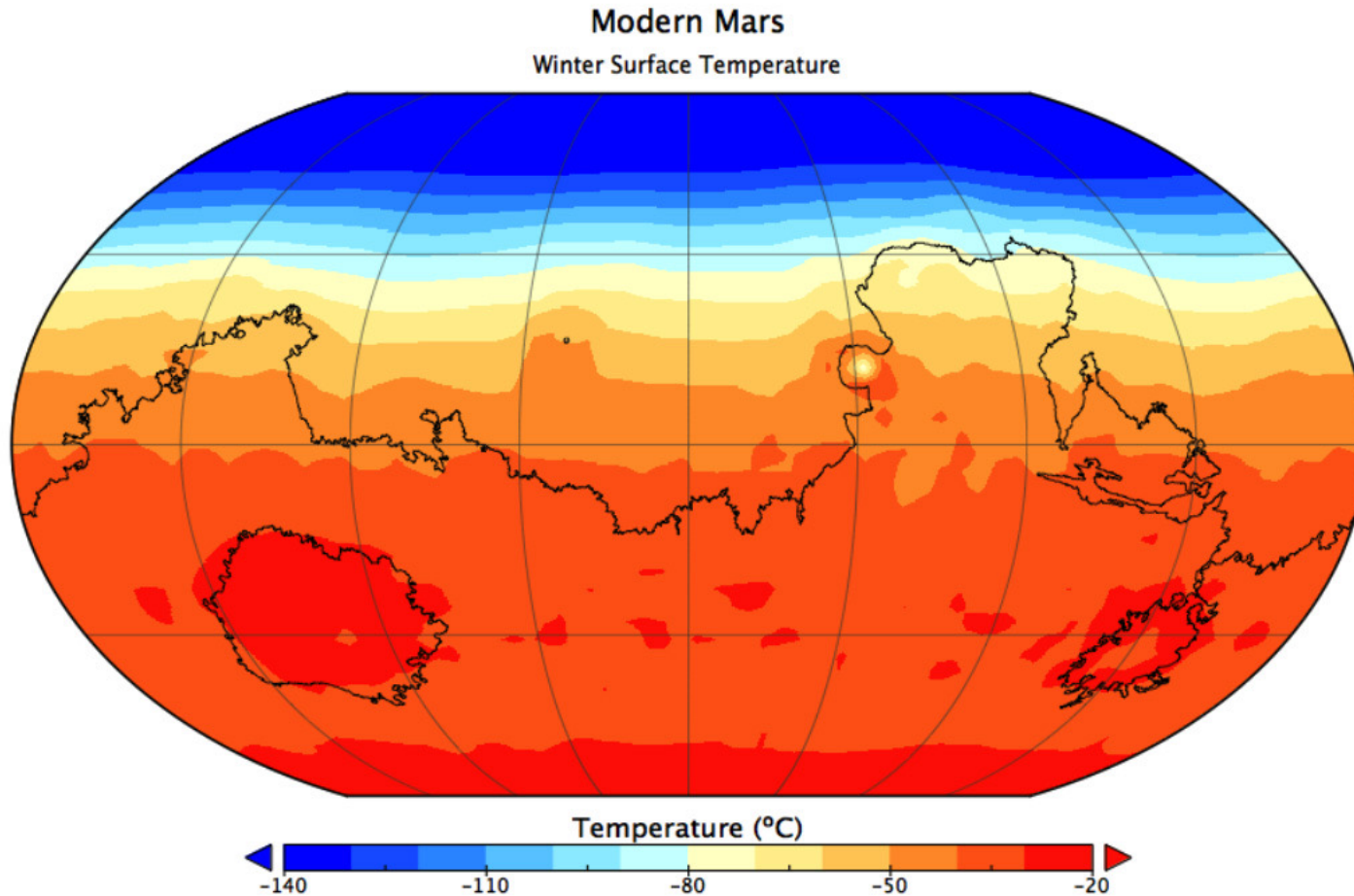
very uniform in latitude and time



The thick atmosphere, with a single cell, is extremely efficient in transporting energy along Venus surface

Mars surface temperature

seasonal and latitudinal temperature excursions are very large



<http://www.giss.nasa.gov/projects/astrobio/>

The horizontal energy transport is extremely inefficient because the atmosphere is very thin

The different components of rocky planets are interconnected

Interactions between the interior and the surface

Interactions between the surface and the atmosphere

Interactions between the planet and the interplanetary medium

“Space weather”

Besides solar radiation, also high energy particles of solar and Galactic origin affect the physical state of the planet

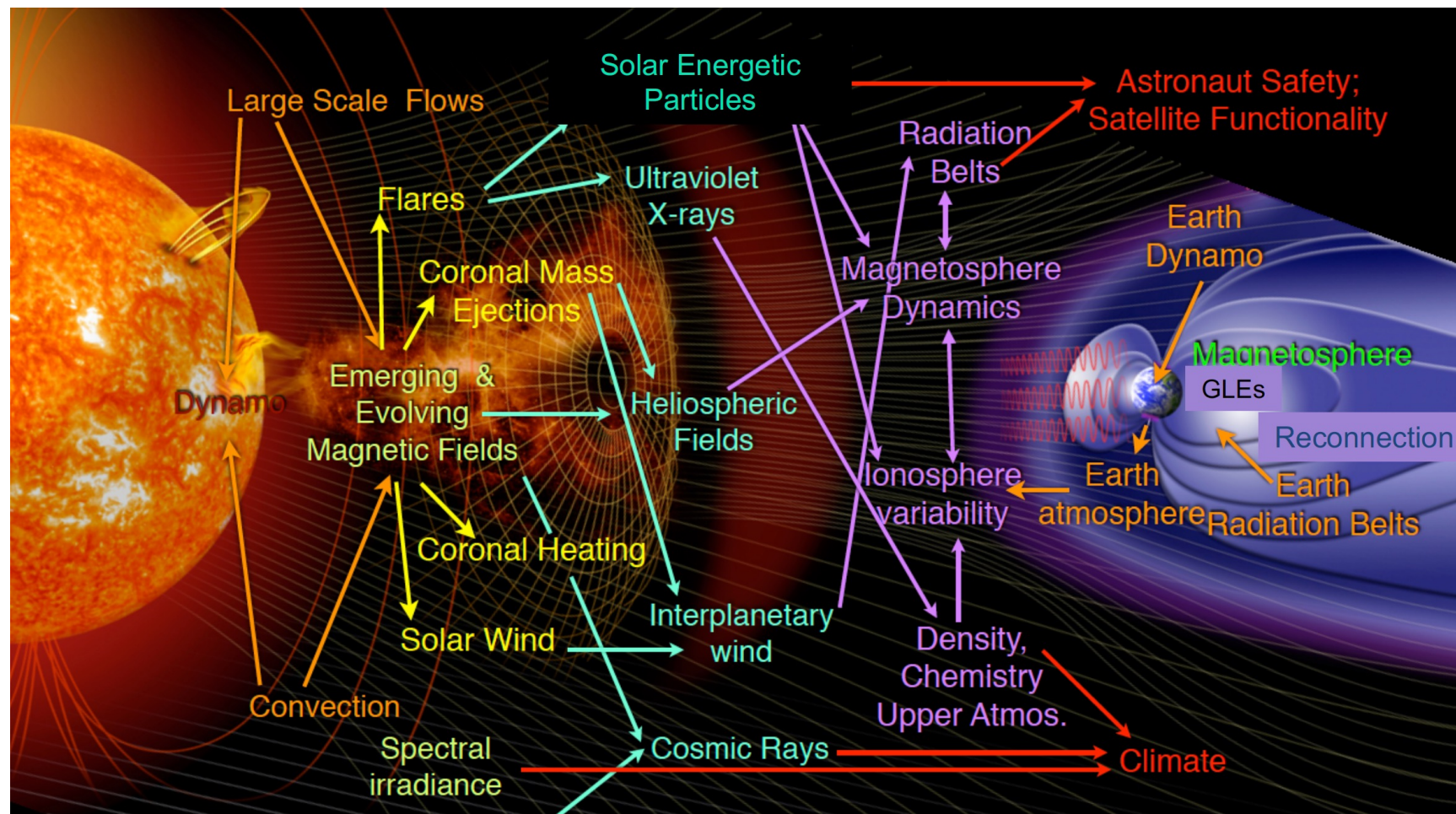
- Example: solar wind

High-energy ($\sim 10\text{-}100$ eV) charged particles originated in the external layers of the Sun

- The solar wind tends to erode planetary atmospheres

The effect is particularly important for planets with low escape velocity

The planet magnetic field, if present, protects the atmosphere from this effect by deflecting the charged particles



The Space Weather chain

Modified from Schrijver and Kauristie 2014 after www.nasa.gov