Energy budget and surface temperature of rocky planets

Bibliographic material:
Pierrehumbert (2010) Principles of Planetary Climate
Neelin (2011) Climate Change and Climate Modeling

Planets and Astrobiology (2018-2019)
G. Vladilo

zero-order, global planetary Energy Balance

PLANETARY ALBEDO

OUTGOING PLANETARY RADIATION (thermal IR)

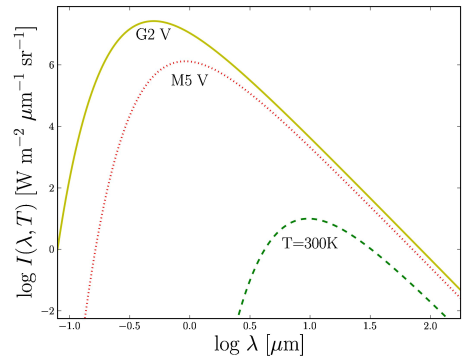
$$I = S(1 - A)$$

INCOMING STELLAR RADIATION (visible/UV)

W/m^2

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

Simple calculation used to obtain a general indication of the planet temperature and habitability

From the energy equilibrium equation, assuming black body emission

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

where

S: insolation ("solar costant", in the case of the Earth)
stellar flux (W/m^2) received by the planet

A: planetary albedo
fraction of stellar radiation reflected back into space

Energy balance

$$\sigma T^4_{eff} = \tfrac{1}{4} S (1-A)$$

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"

$S = 1361$ W/m^2
$d = a = 1$ AU $= 1.495 \times 10^{11}$ 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(ice) ~ 0.5/0.6

      A(snow) ~ 0.8/0.9

      A(sand) ~ 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*

Planetary albedo

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

Allen (2000)

Insolation and planet temperature

$$\sigma T^4_{eff} = \tfrac{1}{4}\, S\, (1-A)$$

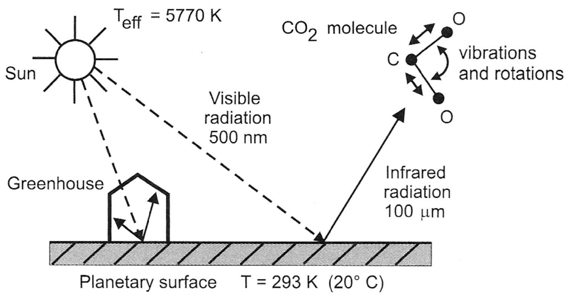
$$S = L_* / (4\pi d^2)$$

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
and the surface temperature rises

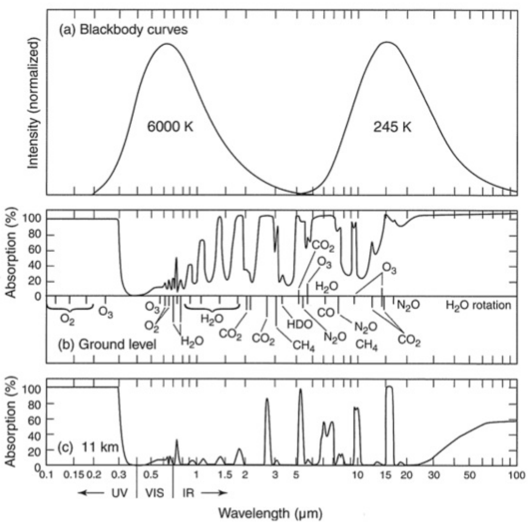
Greenhouse effect

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}

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

Earth: ΔT=+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

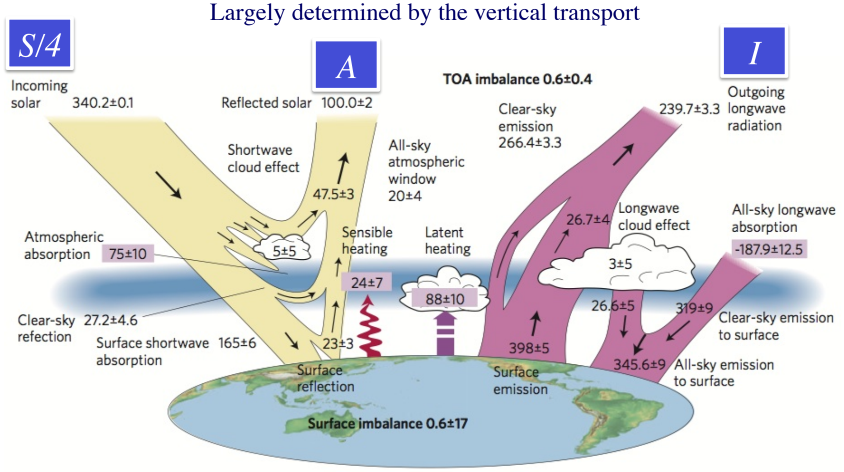
    The vertical transport is largely determined by the radiative transfer of incoming stellar radiation and outgoing planetary radiation

    Also convection plays an important role
  - 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

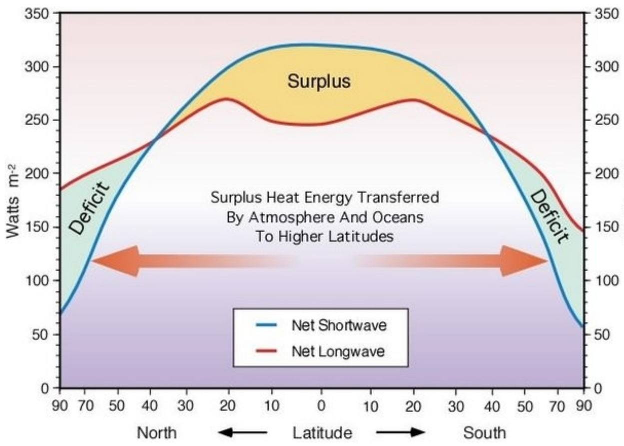


Stephens at al. (2012)

Radiation balance at different latitudes

–– Incoming stellar radiation

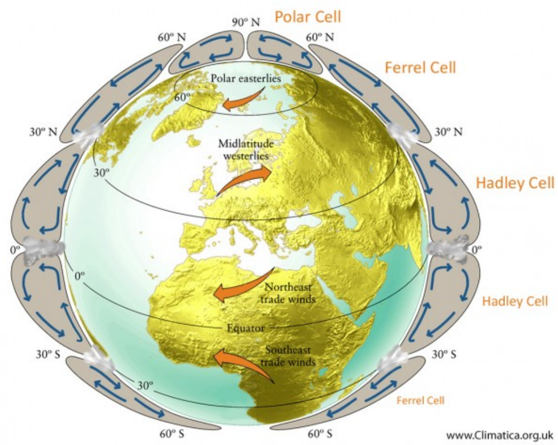
–– OLR (Outgoing Long-wavelength Radiation)



Atmospheric circulation and horizontal transport

- The horizontal structure of the atmosphere is determined by the atmospheric circulation
- The atmospheric circulation is driven by the latitudinal temperature gradient and is influenced by 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 rotates faster than the surface, developing east-west streams

Earth’s atmospheric transport

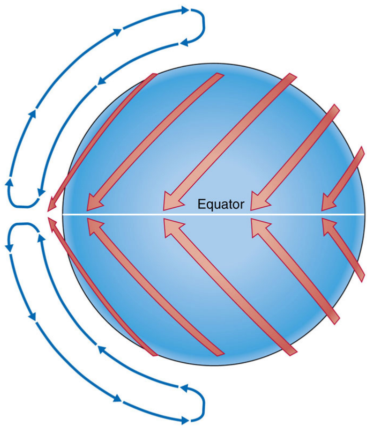


Coriolis forces prevent the direct transport from the equator to the poles

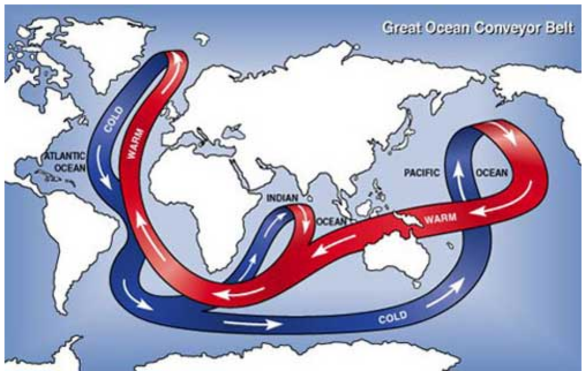
The transport takes place via convection cells created in each hemisphere

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)

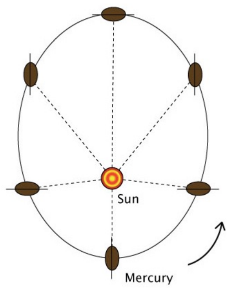
Due to the high thermal capacity of water, oceans stabilize the climate

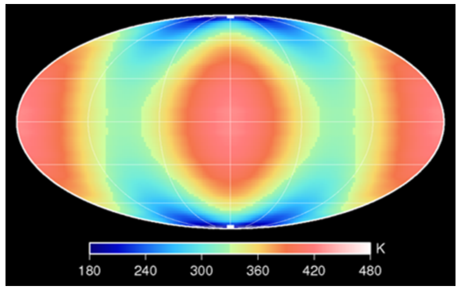
The surface temperature of rocky planets

- The possibility for a rocky planet to host life is influenced by its surface temperature
- The surface temperature of rocky planets is determined by the planetary energy budget and 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 definition of "habitable zone" should take into account all these factors, besides the distance from the star
  - 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

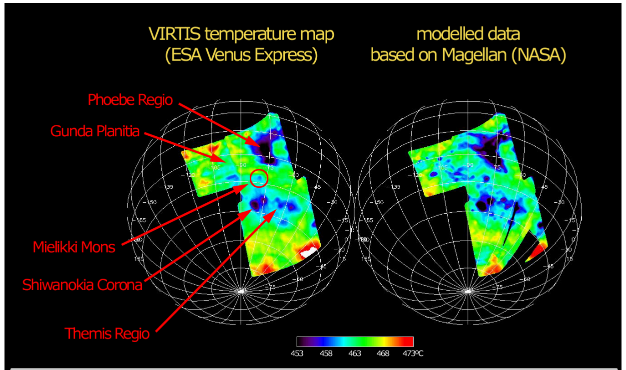




http://diviner.ucla.edu/mercury/posters/Poster-03/poster-03.html

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 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.

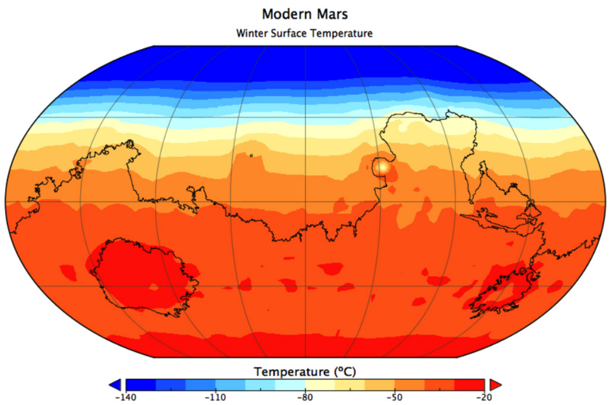
Venus surface temperature
very uniform in latitude and time



http://www.esa.int/Our_Activities/Space_Science/Venus_Express/

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

Interactions between interior, surface, atmospheres, and interplanetary medium

The different constituents of rocky planets are interconnected through several processes

Interaction between the surface and the atmosphere

Interactions between the interior and the surface

All components, and in particular the atmosphere, interact with the interplanetary medium

Solar wind

- Besides solar radiation, also the solar wind affects the physical state of the planet and, in particular, of the planetary atmosphere
  - Solar wind

    High-energy (~10-100 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