Détectabilité des exoplanètes telluriques au stade océan de magma

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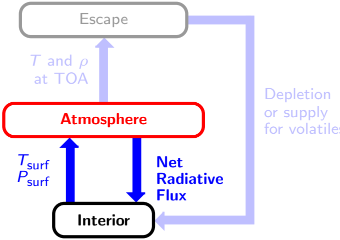
- Atmospheric submodel designed for coupling in order to study a generic telluric planet early evolution.
  - Interior – **Atmosphere** – Escape
  - Atmospheric module (Marcq, 2012) is operational, but work still ongoing.
- Inputs
  - Surface temperature
  - Surface pressures (H_2O, CO_2, N_2).
- Outputs
  - **OLR**: how fast does the magma ocean cool? Which **thermal spectrum** can be observed?
  - **TOA**: Z, T, ρ and composition at 0.1 Pa level: lower boundary condition for escape module.



Escape

T and ρ at TOA

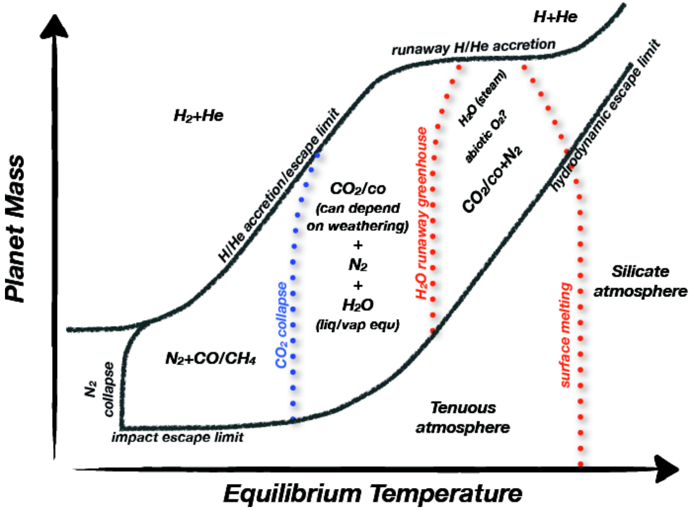
Atmosphere

T_{surf}
P_{surf}

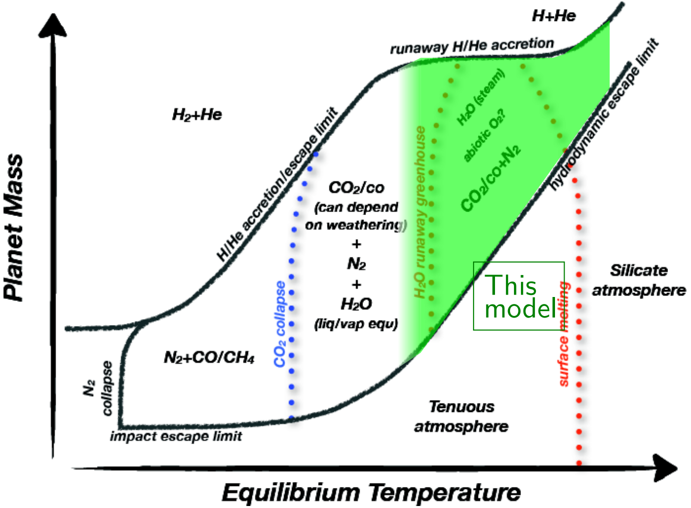
Net Radiative Flux

Interior

Depletion or supply for volatile



From Forget and Leconte (2013)



From Forget and Leconte (2013)

- Radiative–convective 1D model
  - Inspired from Abe & Matsui (1988) and Kasting (1988)
  - Main difference **no mandatory radiative balance ($T_{\text{eff}} \geq T_{\text{eq}}$)!**
    - Surface temperature prescribed by interior model.
- Algorithm
  1. Prescribed P grid up to 0.1 Pa.
  2. Prescribed $T(P)$ profile.
  3. Computation of $Z(P)$ et $\rho_i(P)$ according to equations of state and hydrostatic equilibrium.
     - CO_2 and N_2 considered as ideal gases.
     - H_2O is **not** ! $P > P_c$ and/or $T > T_c$ common.
  4. Computation of IR opacities from 0 to 10^4 cm^{-1}.
  5. Computation of radiative properties of possible clouds.
  6. Computation of IR radiative flux with DISORT (4 streams).
  7. Alteration of $T(P)$ for self-consistency: back to step 2.

- 3 layers from surface up to mesopause

  Dry Troposphere follows a dry adiabat.

  Moist Troposphere follows a moist adiabat. Clouds are located there.

  Mesosphere considered isothermal.

- Boundaries

  Dry/Moist where H_2O reaches saturation (if already occuring at surface ⇒ no dry troposphere and formation of a H_2O ocean).

  Moist/Mesosphere where $T < T_0 =$ TOA temperature determined by **local** radiative equilibrium (null divergence of OLR at $\tau \rightarrow 0$).

- $\alpha_v = \rho_{H_2O}/(\rho_{CO_2} + \rho_{N_2})$
  - Vertically uniform within dry troposphere and mesosphere.
  - Decreasing with increasing height within moist troposphere.

Dry Adiabat

Based on Kasting (1988):

$$\frac{dT}{dP}_{|S} = \frac{\rho_{\mathrm{H_2O}}\, T \left(\frac{\partial v_{\mathrm{H_2O}}}{\partial T}\right)_{|P}}{\rho_{\mathrm{H_2O}}\, C_{P,\mathrm{H_2O}} + \rho_{\mathrm{CO_2}}\, C_{P,\mathrm{CO_2}} + \rho_{\mathrm{N_2}}\, C_{P,\mathrm{N_2}}}$$

Moist Adiabat

From Kasting (1988):

$$\frac{dT}{dP}_{|S} = \left[\frac{dP_{sat}}{dT} + \frac{R\rho_{\mathrm{CO_2+N_2}}}{M_{\mathrm{CO_2+N_2}}}\left(1 + \frac{d\ln\rho_{\mathrm{H_2O}}}{d\ln T} - \frac{d\ln\alpha_v}{d\ln T}\right)\right]^{-1}$$

where

$$\frac{d\ln\alpha_v}{d\ln T} = \frac{\frac{R}{M_{\mathrm{CO_2+N_2}}}\frac{d\ln\rho_{\mathrm{H_2O}}}{d\ln T} - C_{v,\mathrm{CO_2+N_2}}(T) - \alpha_v \frac{ds_{\mathrm{H_2O}}}{d\ln T}}{\alpha_v\left[s_{\mathrm{H_2O}(g)} - s_{\mathrm{H_2O}(l)}\right] + R/M_{\mathrm{CO_2+N_2}}}$$

- Only the thermal component is presently modeled
  - Possible since the temperature profile does not depend on radiative fluxes (except at TOA).
  - $\lambda > 1\,\mu\text{m}$: contribution functions peaking high enough so that emitting layers always relatively cool ($T < 1000\,\text{K}$).
  - Solar component only taken into account for an integrated radiative balance (parametrized through albedo and solar constant).
- Scattering
  - No Rayleigh scattering (yet).
  - **Clouds (optional)**.
    - Present throughout the moist troposphere
    - Optical properties (τ, ϖ_0, g) similar to present day Earth's or Venus' clouds.
    - Henyey-Greenstein phase function
    - Mass loading from Kasting (1988) for Earth-like clouds, or similar to Venus upper clouds for Venus-like clouds.

- Spectral Lines
  - High-resolution spectra computed with KSPECTRUM [Eymet 2009].
  - Yields a (α_v, T, P) grid of 16 k-coefficients [Wordsworth et al., 2010].
  - Reverting to “grey” opacities possible
    - if approximate, fast computations are needed with no need for any spectral output.
- Continuum opacities
  - CO_2-CO_2: derived from Venus measurements (Bézard, priv. comm.)
  - H_2O-H_2O: from MT_CKD v2.5 [Clough et al., 2005]
  - CO_2-H_2O: not taken into account yet.

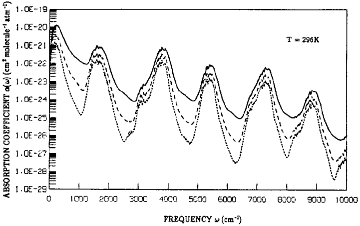
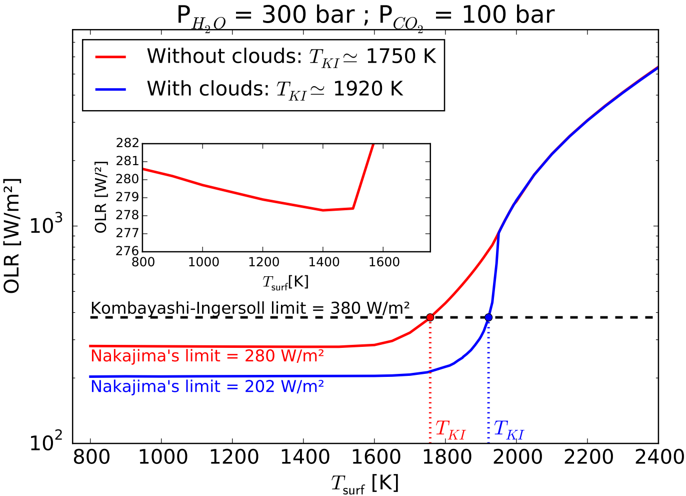


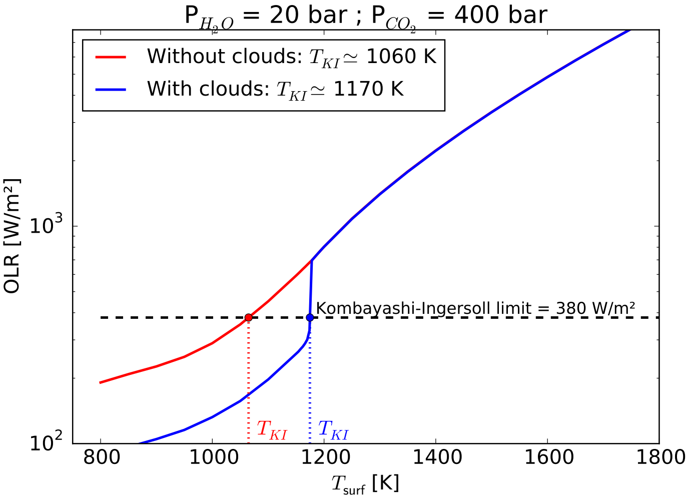
Figure: Continua for H_2O-H_2O (solid) and H_2O-CO_2 (dashed) from Ma & Tipping (1992)

- Two regimes depending on T_{surf} vs. a critical value T_{KI}.

$T_{\text{surf}} \ll T_{KI}$	OLR at **Nakajima's limit** ($\approx 280\,\text{W/m}^2$ for a H_2O-rich atmosphere neglecting clouds)
Clouds	Strong blanketing effect

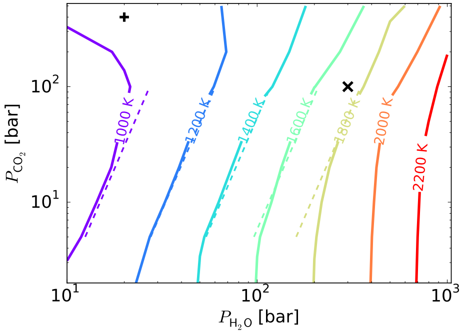


- No such asymptotical regime for relatively dry atmospheres
  - T_{KI} not so meaningful in such a case

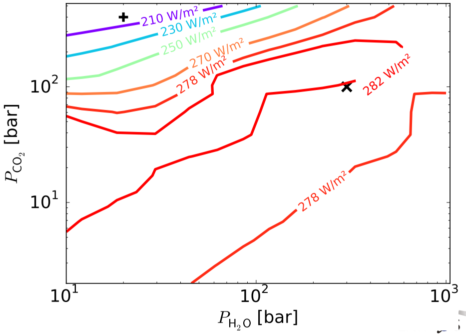


- T_C primarily depends on H_2O
  - Increasing P_{CO_2} while keeping P_{H_2O} constant actually decreases T_{KI}!
  - $\Rightarrow$ Upper relative humidity more important
- Bifurcation between two domains
  - "marginal runaway" H_2O-dominated regime, with $\mathrm{OLR}(T \ll T_{KI}) \approx 280\,\mathrm{W/m^2}$;
  - "Venus-like" CO_2-dominated atmospheres, without $T \ll T_{KI}$ asymptot.

$$T_{KI} \approx 1450\,\mathrm{K} \left(\frac{P_{H_2O}}{100\,\mathrm{bar}}\right)^{0.23} \left(\frac{P_{CO_2}}{30\,\mathrm{bar}}\right)^{-0.06}$$



OLR(700 K) wrt. P_{H_2O} & P_{CO_2}



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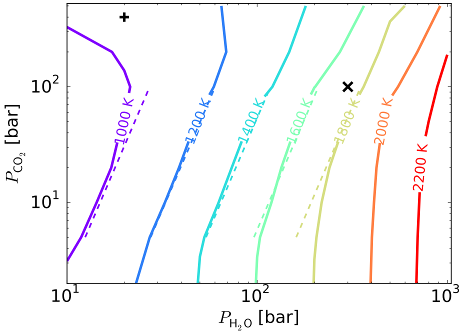

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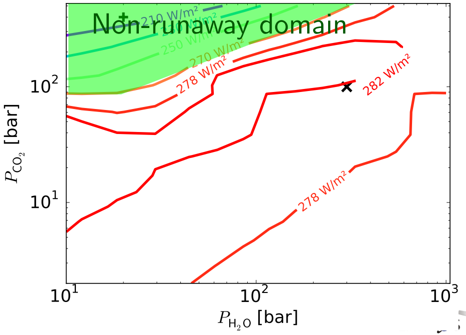


$T_{\mathrm{surf}} > T_{KI}$ Unefficient blanketing. No condensation, warm mesosphere. Large OLR.

$T_{\mathrm{surf}} < T_{KI}$ Efficient blanketing. Thick clouds, cold mesosphere. Small OLR, approximately constant wrt. T_{surf}. Similar to marginally runaway H_2O atmospheres.

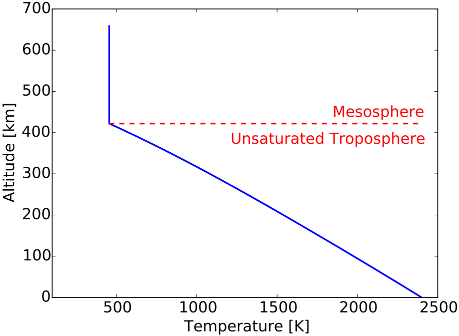


Figure: $T(z)$ for $T_s > T_{KI}$

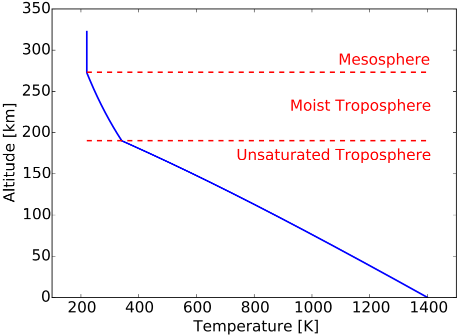


Figure: $T(z)$ for $T_s < T_{KI}$

Warm mesosphere $T > T_{KI}$

- Thermal flux concentrated in narrow near-IR windows.
- Good detectability

Cold mesosphere $T < T_{KI}$

- Spectrum dominated by H_2O ; some CO_2 features (15 and 4.3 µm)
- $T_B \gg T_0$ in some near IR windows (Venus-like)
- Clouds mask gaseous features ; poor detectability

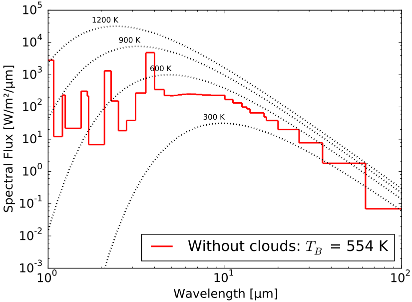


Figure: $T_s = 2400\,\mathrm{K} > T_{KI}$

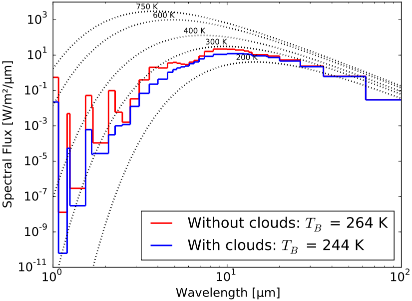
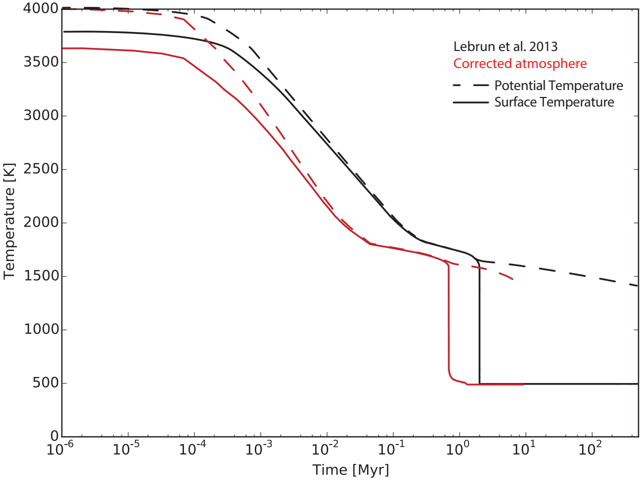


Figure: $T_s = 1400\,\mathrm{K} < T_{KI}$

- **$T > T_{Kl}$ only lasts for abour 10^4 yr!** for an Earth-like planet.
- Longer for a super-Earth and/or closer to its host star.



From Salvador et al. (2016, submitted)

- Plane-parallel approximation fails for:
    - Small planets (radius, gravity);
    - with large volatile inventories;
    - and high surface temperatures.

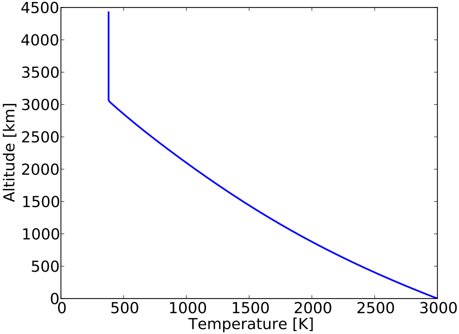


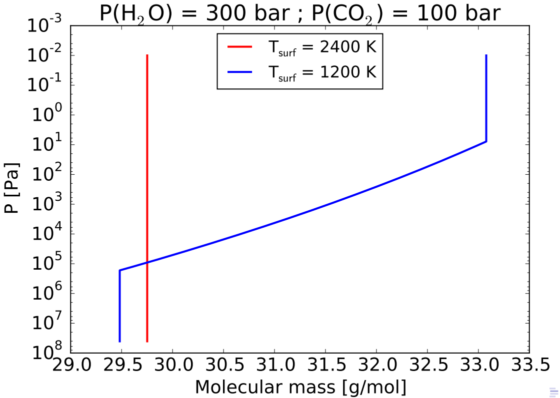
Figure: Mars, $P_{H_2O} = 52\,\text{bar}$, $P_{CO_2} = 11\,\text{bar}$

Hydrostatic
- Should not change: $\vec{\nabla} f = \frac{\partial f}{\partial z}\vec{u}_z \rightarrow \frac{\partial f}{\partial r}\vec{u}_r$
- But $m = \frac{P_0}{g}\left(1 + 2\frac{H}{R} + 2\frac{H^2}{R^2}\right)$ (if H constant)

Radiative transfer
- Switching to full spherical SPSDISORT radiative core

1st order
- Weight OLR according to $\left(1 + \frac{Z_{\tau=1}{}^{2}}{R^2}\right)$?
  - $Z_{\tau=1}$ being computed for each bin in g-space and spectral interval.
- Treat incoming solar radiation in a similar way
- $T(z = \text{TOA})$ determined by $\partial_\tau F_{\text{IR}} = 0$.
  - 1D spherical: $\frac{1}{r}\frac{\partial(rF_{\text{IR}})}{\partial r} = 0$
  - yields $\partial_\tau F_{\text{IR}} + (R + z)k_{\text{ext}}F_{\text{IR}} = 0$ to estimate at mesopause?

- Current parameterization of $\alpha_v(z) = \rho_{H_2O}(z)/\rho_{CO_2+N_2}(z)$ is fine:
  - when H_2O is a **trace species** (as on present day Earth)
  - or when H_2O is dominating the inventory (steam atmospheres)
- Troublesome whenever α_v crosses unity threshold
  - results in a CO_2-enriched mesosphere overlying a H_2O-enriched troposphere.
  - **Impossible** within the homosphere!



- Summary
  - Simple atmospheric 1D model already operational [Lebrun et al., 2013]
    - Like Hamano et al. (2013,2015), can be made more complex than atmospheric parametrizations usually embedded in coupled magma ocean cooling studies [Elkins-Tanton 2008]
  - Exoplanets at a magma ocean stage are observationally similar to mature telluric planets **unless very young ($t < 10^5$ yr) or very close to their host stars**.
    - **Efficiency of the blanketing effect directly linked to H_2O content**.
    - Comparison between cooling time (inventory limited) and characteristic atmospheric escape time to be investigated!
- To do
  - Publish results [Marcq et al., 2016, submitted]
  - Smoothing the mesospheric temperature profile $T(z)$
  - Implement corrections to plane-parallel geometry for small planets and very hot atmospheres.
  - **Modeling stellar radiation** (Rayleigh scattering, computation of spectral albedo).
  - Longer simulations possible once coupled with an escape model.