Beyond 1D atmospheres

Jérémy Leconte
Equations of motion

★ Mass conservation

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \]

★ Momentum conservation

\[ \frac{D\mathbf{v}}{Dt} + 2\Omega \times \mathbf{v} = -\frac{1}{\rho} \nabla p - \nabla \Phi \]

★ Equation of state

\[ p = \rho RT \]

★ Conservation of energy

\[ \frac{DS}{Dt} = H - Q \]
$p_{tro} = p_{eq} = p_{tro}$
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$p_{tro} > p_{eq} < p_{tro}$
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The critical insolation thresholds for these processes, how-

ever, remain uncertain because they have so far been evaluated using

one-dimensional models that cannot account for the dynamical and
cloud feedback effects that are key stabilizing features of the Earth's
climate. Here we use a three-dimensional global climate model to
ify the climate response of Earth-like planets to increased insolation
previously thought to occur is about 375 W m

The increase in solar luminosity over geological timescales should
correspond to present Earth (282 W m

2)

leaves the oceans to space before the runaway greenhouse state
sees in stratospheric humidity, warming may also cause evaporative
loss of the oceans to space before the runaway greenhouse state

The increase in solar luminosity over geological timescales should
Thermodynamic equilibrium is reached when the absorbed and the
global climate model is used to simulate the Earth's climate in a
 runaway greenhouse state.

This feedback is both strong enough to maintain clement

subtropical regions allow the

surface temperatures and weak enough for the climate to remain stable.

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sees in strato
Are the winds really like that?
GODAS Wind Stress, 1982–2004 Ann

unit: dyne/cm²
Friction
Coriolis Velocity
Pressure force
The low-latitude meridional momentum flux is poleward, resulting from the subtropical jets contracting toward the equator, an extratropical zone, with eddy-driven jet streams in the extratropics, and Hadley circulations, large-scale Kelvin waves, and Rossby waves, and (in some cases) equatorial superrotation in the tropics. The “X” at the equator marks the substellar point of the flow, meridional temperature gradients accompanying baroclinic eddies, Rossby waves, and eddy-driven jet streams in the extratropics, and Hadley circulations, large-scale Kelvin waves, and Rossby waves, and (in some cases) equatorial superrotation in the tropics. The “X” at the equator marks the substellar point of the flow, meridional temperature gradients accompanying baroclinic eddies, Rossby waves, and eddy-driven jet streams in the extratropics, and Hadley circulations, large-scale Kelvin waves, and Rossby waves, and (in some cases) equatorial superrotation in the tropics. The “X” at the equator marks the substellar point of the flow, meridional temperature gradients accompanying baroclinic eddies, Rossby waves, and eddy-driven jet streams in the extratropics, and Hadley circulations, large-scale Kelvin waves, and Rossby waves, and (in some cases) equatorial superrotation in the tropics. The “X” at the equator marks the substellar point of the flow, meridional temperature gradients accompanying baroclinic eddies, Rossby waves, and eddy-driven jet streams in the extratropics, and Hadley circulations, large-scale Kelvin waves, and Rossby waves, and (in some cases) equatorial superrotation in the tropics. The “X” at the equator marks the substellar point of the flow, meridional temperature gradients accompanying baroclinic eddies, Rossby waves, and eddy-driven jet streams in the extratropics, and Hadley circulations, large-scale Kelvin waves, and Rossby waves, and (in some cases) equatorial superrotation in the tropics.
Can we actually see it?
Relative Humidity
The impact of the Hadley cell

Relative Humidity

Precipitations during adiabatic ascent
Formation of unsaturated subsident regions

Leconte et al. (Nature, 2013)
Thermodynamics of the Hadley Cell

Pressure

Temperature
Thermodynamics of the Hadley Cell

Precipitations during ascent remove moisture and heat the gas.

Dry, hot air in the descending branch.

Water vapor saturation.
Rotational Force
Pressure force

Side view:

a) Top view, near top
Pressure force
Rotational Force
b) Top view, near bottom

Friction
What about **synchronously** rotating planets?
What about synchronously rotating planets?

Figure 1.— Schematic illustration of the regimes of extratropics (defined as latitude \(\sim 30^\circ\)) and tropics. Planets with rotation periods of about 1 Earth day or shorter are considered to be in the extratropical regime, whereas those with rotation periods of about 10 Earth days or longer are considered to be in the tropical regime. The left panel shows a meridional slice through the atmosphere, illustrating the key processes in each regime. The right panel shows the relationship between the rotation period of a planet and the boundary between the extratropical and tropical regimes.

Showman et al. (2013)
Two prototypes of synchronous planets

<table>
<thead>
<tr>
<th>Planet name</th>
<th>Gl 581 c</th>
<th>HD 85512 b</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stellar luminosity</td>
<td>$L_\star$ [$L_\odot$]</td>
<td>0.0135</td>
</tr>
<tr>
<td>Stellar mass</td>
<td>$M_\star$ [$M_\odot$]</td>
<td>0.31</td>
</tr>
<tr>
<td>Orbital semi-major axis</td>
<td>$a$ [AU]</td>
<td>0.073</td>
</tr>
<tr>
<td>Orbital period</td>
<td>$P_{\text{orb}}$ [d]</td>
<td>13</td>
</tr>
<tr>
<td>Orbital eccentricity</td>
<td>$e$</td>
<td>0-0.05</td>
</tr>
<tr>
<td>Mass</td>
<td>$M_p$ [$M_\oplus$]</td>
<td>6.25</td>
</tr>
<tr>
<td>Radius</td>
<td>$R_p$ [$R_\oplus$]</td>
<td>1.85</td>
</tr>
<tr>
<td>Surface gravity</td>
<td>$g$ [m s$^{-2}$]</td>
<td>18.4</td>
</tr>
<tr>
<td>Stellar Flux</td>
<td>$F_\star$ [W/m$^2$]</td>
<td>3300</td>
</tr>
<tr>
<td>Equilibrium temperature</td>
<td>$\bar{T}_{\text{equ}}$ [K]</td>
<td>317</td>
</tr>
</tbody>
</table>

$\bar{T}_{\text{equ}} = \left( \frac{(1 - \bar{A}) F_\star}{4 \sigma_{\text{SB}}} \right)^{1/4}$
Two prototypes of synchronous planets

Temperature maps (°C)

Gl 581 c

HD 85512 b

(dry earthlike atmosphere)

Leconte et al. (A&A, 2013a)
Super-rotation vs Stellar/Antistellar circulation!
Jets impede redistribution!

Leconte et al. (A&A, 2013a)
Circulation regime on synchronous exoplanets

Showman & Polvani (2011)

«Eastward Jets pumped by the interaction of the mean flow with planetary Rossby and Kelvin waves»

\[ L_{Ro} = \sqrt{\frac{N H R_p}{2 \Omega}} \implies \mathcal{L} = \sqrt{\frac{N H}{2 \Omega R_p}} \]

\[ H = \frac{k_B T}{m_a g} \]

\[ N^2 = \frac{g^2}{c_p T} \]

\[ \mathcal{L} = \sqrt{\frac{k_B}{m_a c_p^{1/2}}} \frac{T^{1/2}}{2 \Omega R_p} \]

\[ \mathcal{L} = 1.1 \text{ (Gl 581 c), } 2.5 \text{ (HD 85512 b)} \]

Mechanism too weak

Leconte et al. (A&A, 2013a)
wind maps (m/s)

~4km Altitude

Near Surface

Gl 581 c

HD 85512 b

Slow Gl 581 c

p = 900 mb

p = 200 mb

~4km Altitude

Near Surface

Gl 581 c

HD 85512 b

p = 900 mb

p = 200 mb

Gl 581 c, Ω/5

Gl 581 c, Ω/5

longitude (°)

latitude (°)
Does atmospheric dynamics affect observables?
Expected dynamics on **tidally locked** planets

Thermal contrast will depend on atmospheric mass.
Expected dynamics on tidally locked planets

Where will clouds form?
completely evaporated into the atmosphere (this study) (Yang et al., Way et al.). Their position (dayside or nightside), clouds have a very strong net cooling. Simulations between 300 and 750 bar (Fig. 2a, b, e, f). Depending on which planet, dayside cloud cover in fact decreases with increasing rotation speed and day duration. The absorption of sunlight by clouds preferentially reduces the insolation required to condense water on the surface, compared with previous 1D cloud-free calculations. This is because the stratosphere adjusts here quickly to the solar heat. As a direct consequence, the net warming effect of clouds marks a transition across GCMs. Preferential nightside cloud formation is likely to be a robust mechanism (driven by small convective cells, as in refs. 1b, e, f). This indicates that this direct subsolar absorption is up to about 10 W/m² and (2) that the mechanism differs from the stabilizing tropospheric subsolar cloud formation (that is, water vapour condensation driven by large-scale air movements, as illustrated in Fig. 3a). As a result, clouds have a strong net cooling to space. This peculiar distribution of clouds produces a strong net warming to the poles (Fig. 2a, b, e, f). The accumulation of clouds in the range of insolation – that is, about 244 times that of Earth) suggests that the mechanism is also robust to a wide range of rotation periods. A comprehensive sensitivity study is needed to quantitatively confirm this result, as it is also robust to a wide range of insolations (Fig. 2b). At high insolations, nightside temperatures increase with the poles (Fig. 2a, b, e, f). The accumulation of clouds in the range of insolation – that is, about 244 times that of Earth) suggests that the mechanism is also robust to a wide range of rotation periods. A comprehensive sensitivity study is needed to quantitatively confirm this result, as it is also robust to a wide range of insolations (Fig. 2b). At high insolations, nightside temperatures increase with the poles (Fig. 2a, b, e, f). The accumulation of clouds in the range of insolation – that is, about 244 times that of Earth) suggests that the mechanism is also robust to a wide range of rotation periods. A comprehensive sensitivity study is needed to quantitatively confirm this result, as it is also robust to a wide range of insolations (Fig. 2b). At high insolations, nightside temperatures increase with the poles (Fig. 2a, b, e, f). The accumulation of clouds in the range of insolation – that is, about 244 times that of Earth) suggests that the mechanism is also robust to a wide range of rotation periods. A comprehensive sensitivity study is needed to quantitatively confirm this result, as it is also robust to a wide range of insolations (Fig. 2b). At high insolations, nightside temperatures increase with the poles (Fig. 2a, b, e, f). The accumulation of clouds in the range of insolation – that is, about 244 times that of Earth) suggests that the mechanism is also robust to a wide range of rotation periods. A comprehensive sensitivity study is needed to quantitatively confirm this result, as it is also robust to a wide range of insolations (Fig. 2b). At high insolations, nightside temperatures increase with the poles (Fig. 2a, b, e, f). The accumulation of clouds in the range of insolation – that is, about 244 times that of Earth) suggests that the mechanism is also robust to a wide range of rotation periods. A comprehensive sensitivity study is needed to quantitatively confirm this result, as it is also robust to a wide range of insolations (Fig. 2b). At high insolations, nightside temperatures increase with the poles (Fig. 2a, b, e, f).
Phase curves are definitely affected
Observed trends in emission temperature...

Hotter planets have bigger day/night temperature contrasts

Komacek & Showman (2016)
...Explained by atmospheric dynamics

Figure 3. Equirectangular maps of steady-state geopotential ($gh$) contours for the equilibrated solutions of the shallow-water model for a fractional forcing amplitude of $\Delta h_{eq}/H = 1$. We have subtracted the constant value of $gH = 4 \times 10^6 \text{m}^2\text{s}^{-2}$ from each panel. Overplotted are vector fields of the steady-state winds. Each panel in the grid was computed for a different combination of radiative and drag timescales, $\tau_{\text{rad}}$ and $\tau_{\text{drag}}$, expressed in Earth days. Panels share the same scale for the geopotential, but wind speeds are normalized independently in each panel. The substellar point is located at the center of each panel, at a longitude and latitude of $(0^\circ, 0^\circ)$. Short radiative timescales result in steady-state $gh$ profiles dominated by stellar forcing with a hot dayside and a cold nightside (see Equation (3)), while the atmosphere relaxes to a constant $gh$ for long values of $\tau_{\text{rad}}$. In contrast, the dependence of $gh$ on $\tau_{\text{drag}}$ is weaker. The atmospheric circulation shifts from a zonal jet pattern at long $\tau_{\text{rad}}$ and $\tau_{\text{drag}}$ to day-to-night flow when either $\tau_{\text{rad}}$ or $\tau_{\text{drag}}$ is reduced, as explained in detail in Showman et al. (2013a).

(A color version of this figure is available in the online journal.)

The models in Figure 3 capture major transitions in both the structure of the flow and the amplitude of the day–night thickness contrast. When $\tau_{\text{rad}}$ is longer than one Earth day, longitudinal gradients of $gh$ are small. If $\tau_{\text{drag}}$ is also long compared to a day, the circulation primarily consists of east-west-aligned (zonal) flows varying little in longitude (upper right corner of Figure 3). Despite the lack of longitudinal variation, such models exhibit an equator-pole gradient in $gh$, albeit with an amplitude that remains small compared to the radiative-equilibrium gradient. When $\tau_{\text{rad}}$ is long but $\tau_{\text{drag}}$ is short, winds flow from the dayside to the nightside over both the eastern and western hemispheres, and $gh$ varies little in either longitude or latitude (lower right corner of Figure 3). Intermediate values of $\tau_{\text{rad}}$ (e.g., $\sim 1 \text{ day}$; middle column of Figure 3) lead to flows with greater day–night temperature differences and significant dynamical structure, including zonal-mean zonal winds that are eastward at the equator (i.e., equatorial superrotation). In contrast, when $\tau_{\text{rad}}$ is short (left column of Figure 3), the geopotential amplitude and morphology closely match the radiative forcing profile: a spherical bulge on the hot dayside and a flat, cold nightside (see Equation (3)). The circulation consists of strong airflow from day to night along both terminators. Showman & Polvani (2011) and Showman et al. (2013a) show that much of the wind behavior in Figure 3 (and in many published 3D global circulation models of hot Jupiters) can be understood in terms of the interaction of standing, planetary-scale waves with the mean flow.

Many of the characteristics of the full solution can be understood by studying the model under weak forcing ($\Delta h_{eq}/H \ll 1$). In this limit, the day–night variations in $h$ are much smaller than $H$, and terms in the shallow-water equation exhibit their linear response. For example, the term $\nabla \cdot (vh)$ in the continuity equation will behave approximately as $H \nabla \cdot v$. The balance between $H \nabla \cdot v$ and $Q$ in the continuity equation is linear. If the balance in the momentum equation is also linear, then wind speeds $v$ and amplitudes of $h$-variation should scale linearly with the forcing amplitude $\Delta h_{eq}/H$. In Figure 4 we present solutions of Perez Becker & Showman (2016).
What implications for transit spectroscopy?

\[ T \uparrow \Rightarrow \tau_{\text{rad}} \downarrow \]
Opening angle of the transmission region (limb)

Temperature maps for GJ1214b (transit photosphere)

3D approach

Need a 3D radiative transfer tool

Falco et al. (A&A, 2021) alias COVID GUY
What if there is also a chemical day-night contrast

**WASP-121b**

Temperature (K)

Abundance H2O

Water disappears on the dayside!
What if there is also a chemical day-night contrast

Results: Biases between 3D & 1D models

\[ \text{Log}\left(\frac{[\text{CO}]}{[\text{H}_2\text{O}]}\right) \approx 2 \text{ orders of magnitude} \]

\[ \text{H}_2\text{O} \text{ constant} \]
\[ \text{H}_2\text{O} \text{ variable} \]
\[ \text{Without CO} \]

William Pluriel
Pytmosph3R, Caldas et al. (2019)