Atmospheric dynamical models
from solar system planets to exoplanets observed by ARIEL

Aymeric Spiga

ARIEL workshop January 15, 2020
ARIEL will allow for unprecedented analysis of atmospheric composition and thermal structure of exoplanets – especially warm exo-giants but also telluric planets with an atmosphere.

Both are influenced by, and influence,

- dynamics
  - large-scale & synoptic circulations
  - gravity waves – especially when breaking
  - small-scale turbulence (“mixing”)
- radiative transfer
- photo-chemistry
- clouds
- magneto-hydrodynamic processes
- ...

A. Spiga (LMD / Sorbonne Univ.)
Global Climate Model vs. Mesoscale Model

Grid spacing \( \sim 200 \, \text{km} \)

Grid spacing \( \sim 10 \, \text{km} \)
<table>
<thead>
<tr>
<th>acronym</th>
<th>type of model</th>
<th>runtime</th>
<th>“dynamics”</th>
<th>“physics”</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>syn</td>
<td>Ro</td>
</tr>
<tr>
<td>EBM</td>
<td>energy-balance model</td>
<td>⬣���</td>
<td>❌</td>
<td>❌</td>
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<tr>
<td>SWM</td>
<td>shallow-water model</td>
<td>⬣�</td>
<td>❌</td>
<td>❌</td>
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<tr>
<td>RCM</td>
<td>radiative-convective mod</td>
<td>⬣</td>
<td>❌</td>
<td>❌</td>
</tr>
<tr>
<td>φχM</td>
<td>photochemical model</td>
<td>⬣</td>
<td>❌</td>
<td>❌</td>
</tr>
<tr>
<td>PE</td>
<td>primitive equations</td>
<td>⬣</td>
<td>✓</td>
<td>❌</td>
</tr>
<tr>
<td>iMM</td>
<td>idealized mesoscale</td>
<td>⬣</td>
<td>❌</td>
<td>✓</td>
</tr>
<tr>
<td>GCM</td>
<td>global climate model</td>
<td>⬣</td>
<td>✓</td>
<td>❌</td>
</tr>
<tr>
<td>MM</td>
<td>mesoscale model</td>
<td>⬣</td>
<td>❌</td>
<td>✓</td>
</tr>
<tr>
<td>hrGCM</td>
<td>high-resolution GCM</td>
<td>⬣ ⬣</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>LES</td>
<td>large-eddy simulations</td>
<td>⬣ ⬣</td>
<td>❌</td>
<td>❌</td>
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<tr>
<td>DNS</td>
<td>direct numerical simul.</td>
<td>⬣ ⬣ ⬣</td>
<td>❌</td>
<td>❌</td>
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<tr>
<td>WTF</td>
<td>perfect reality model</td>
<td>∞</td>
<td>✓</td>
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syn ⇒ synoptic (large-scale weather); Ro ⇒ sub-Rossby scales (e.g. gravity waves); Re ⇒ sub-Reynolds scales (e.g. turbulence); RT ⇒ radiative transfer; φχ ⇒ photo-chemistry
“Global” dust storms

Mars • Global Dust Storm

June 26, 2001

Hubble Space Telescope • WFPC2

September 4, 2001

NASA, J. Bell (Cornell), M. Wolff (SSI), and the Hubble Heritage Team (STScI/AURA) • STScI-PRC01-31
Dust vertical distribution: MRO/MCS observations

[Heavens et al. JGR 2011]
The Rise and (moderate) Fall of a Rocket Dust Storm

[Spiga et al. JGR planets 2013; see Madeleine et al. JGR planets 2011 for dust scheme]
Pyro-cumulonimbus on Earth . . .

. . . and detached layers of aerosols

When fires initiate or intensify towering thunderstorms, they can inject aerosols into the lower stratosphere that were once thought to originate only from volcanic plumes (Fromm et al. BAMS 2010)

[Courtesy New South Wales Rural Fire Service]
Raised hygropause during Global Dust Events
Observations by Mars Express / SPICAM

[Fedorova et al. Icarus 2018]
Gas giants: jets & eddies

Jupiter

Saturn

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Atmospheric dynamical models for ARIEL
Global Climate Modeling for giant planets
see Spiga et al. Icarus 2020
Saturn 1/2° GCM after 3.5 simulated Saturn years

An animation over 1000 Saturn days (one frame each 20 days)

[Spiga et al. Icarus 2020, arxiv 1811.01250]
Eulerian-mean acceleration terms

Analysis after 1.6 simulated year, during an eddy burst

\[
\frac{\partial \bar{u}}{\partial t} = \left[ \frac{\partial \bar{u}}{\partial t} \right]_R + \left[ \frac{\partial \bar{u}}{\partial t} \right]_E + \chi
\]

\[
- \left[ \frac{1}{a \cos \varphi} \frac{\partial \bar{u} \cos \varphi}{\partial \varphi} - f \right] \bar{v} - \frac{\partial \bar{u}}{\partial \rho} \bar{\omega}
\]

\[
- \frac{1}{a \cos^2 \varphi} \frac{\partial u' v' \cos^2 \varphi}{\partial \varphi} - \frac{\partial u' \omega'}{\partial \rho}
\]

[Spiga et al. Icarus 2020, arxiv 1811.01250]
Brewer-Dobson circulation
Wave-driven transport in the Earth’s stratosphere and mesosphere

Planètes extrasolaires

Hot Jupiters! ex: 189733b ... Super Earths! ex: Gliese 581d
Evolution of atmospheric models for (exo)planets

Assume a primitive-equation model.

<table>
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<tr>
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<th>Sophisticated approach</th>
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<td>Newtonian cooling: [ \frac{dT}{dt} = - \frac{T_{\text{ref}} - T}{\tau_{\text{relax}}} ]</td>
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| Momentum           | Rayleigh drag \[
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<td>Hi-res models (eddies, waves, shocks, turbulence, ...)</td>
</tr>
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Recent studies about hot Jupiter’s atmospheres

<table>
<thead>
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<th>Phenomena</th>
<th>Authors and Journals</th>
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<tr>
<td>mixing by large-scale circulations</td>
<td>Sainsbury-Martinez et al. A&amp;A 2019</td>
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<td>thermal tides</td>
<td>Auclair-Desrotour and Leconte A&amp;A 2018</td>
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<td>Mendonça MNRAS 2020</td>
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<td>shear-driven instabilities and shocks</td>
<td>Fromang et al. A&amp;A 2018</td>
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Opening angle of the transmission region (limb)


Borrowed from Jeremy Leconte (Université de Bordeaux)
Why we need real 3D (and not (1+1)D)

Temperature maps for GJ1214b (transit photosphere)

3D approach


Borrowed from Jeremy Leconte (Université de Bordeaux)
Why we need real 3D (and not (1+1)D)

Deepest crossing ray


Borrowed from Jeremy Leconte (Université de Bordeaux)
Day-night contrast increases transit depth

\[
\beta = 15^\circ
\]

Relative Transit Depth (ppm)

Wavelength (\(\mu m\))

Borrowed from Jeremy Leconte (Université de Bordeaux)
Take-away points

three-dimensional contributions at all scales to circulations, thermal structure and composition – with spatial & temporal variability

modeling tools and expertise from solar-system planets and Earth; the right model for the right level of sophistication