Grand Challenges in Global Circulation Dynamics

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(Source: CLAUS, http://badc.nerc.ac.uk/data/claus/)
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VI. Concerning the Cause of the General Trade-Winds: By Geo. Hadley, Esq; F. R. S.

I think the Causes of the General Trade-Winds have not been fully explained by any of those who have wrote on that Subject, for want of more particularly and distinctly considering the Share the diurnal Motion of the Earth has in the Production of them: For although this has been mention'd by
Post Newton: Hadley’s (1735) view of the winds
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Surface easterlies in the tropics must be compensated by westerlies elsewhere; otherwise Earth’s rotation rate would change.
Eastward wind (January)

(Schneider, Ann. Rev. Earth Planet. Sci., 2006)
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Eastward wind (January)

(Schneider, Ann. Rev. Earth Planet. Sci., 2006)
Eastward wind (January)

Pressure (mbar)

Zonal sfc. wind (m s⁻¹)

Latitude

Ferrel cells

Hadley cells

Easterlies

Westerlies

(Schneider, Ann. Rev. Earth Planet. Sci., 2006)
20th century: Hadley circulation only in tropics
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Extratropical *macroturbulence* transports angular momentum out of tropics into extratropics
Macroturbulence in control

Any theory of atmospheric circulations and of climate must be based on a theory of atmospheric macroturbulence.

Because we have no complete theory of macroturbulence, “the causes of the General Winds still have not been fully explained by any of those who have written on that Subject” (Hadley).

The Hadley circulation was generally thought not to depend strongly on atmospheric macroturbulence. But that is not the case.
Conserves angular momentum $m$ in upper branch

$\vec{v} \partial_y \bar{m} \approx 0$

Since $\partial_y \bar{m} \propto f + \bar{\zeta}$, this implies

$$(f + \bar{\zeta}) \bar{v} = f (1 - \text{Ro}) \bar{v} \approx 0$$

with local Rossby number $\text{Ro} = -\bar{\zeta} / f \to 1$

Is energetically closed (no heat export)

Responds directly to variations in thermal driving

Result:

$$\phi_h \sim \left(\frac{g H'_t}{\Omega^2 a^2 \Delta'_h}\right)^{1/2}$$

$$\Psi_{\text{max}} \sim \frac{(H'_t \Delta'_h)^{5/2}}{\Omega^3 a}$$

(Schneider 1977; Schneider & Lindzen 1976, 1977; Held & Hou 1980)
Ideal Hadley circulation theory...

- Is intuitively appealing (direct response to thermal driving)
- Appears to account for extent of circulation in Earth’s atmosphere

*But does it account for variations in Hadley circulation as climate varies?*
January streamfunction and angular momentum

Ro \lesssim 0.2

Ro \lesssim 0.5

(Figure adapted from Schneider 2006)
Earth-like Hadley circulations...

- In the annual mean or during equinox are close to limit $\text{Ro} \rightarrow 0$

- Do not respond directly to variations in thermal driving but respond via changes in eddy fluxes

*We need to rethink Hadley circulation response, for example, to ENSO and global warming*
Simulate circulations with idealized GCM ... 

Zonal wind (magenta) and potential temperature (blue)

(Schneider and Walker 2006)
Wider circulations with slower rotation rates
Hadley circulation width as a function of rotation rate

(Walker and Schneider 2006)
Hadley circulation width as a function of other parameters

Wider for more stable stratification

(Walker & Schneider 2006; Schneider 2006; Korty & Schneider 2008)
Hadley circulation strength in idealized GCM

Convective lapse rate \( \gamma \Gamma_d = \gamma \left( g / c_p \right) \)

(Walker & Schneider 2006; Schneider 2006)
Hadley circulation strength in moist GCM

Variations in optical thickness of longwave absorber

(O’Gorman & Schneider 2008; Schneider et al. 2010)
Terrestrial Hadley circulations

- During equinox, summer, and in annual mean controlled by eddy fluxes
- Eddy scaling imprinted on scalings
- Weaker in warmer and (much) colder climates
- Changes in width likewise eddy-controlled (but slowly rotating wider, and less influenced by eddies)

*Need theory that takes eddy effects into account (intermediate Rossby number)*
Jupiter from Cassini
Jupiter from Cassini
Winds on giant planets

(Based on data from Voyager, Cassini, HST; Liu & Schneider 2010)
Energy budget of giant planets

- Emit more energy than they receive from the sun
- **Internal heat flux** can generate convection
- **Differential solar radiative heating** from above

<table>
<thead>
<tr>
<th></th>
<th>Absorbed insolation</th>
<th>Internal heat flux</th>
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</thead>
<tbody>
<tr>
<td>Jupiter</td>
<td>8.1 Wm$^{-2}$</td>
<td>5.7 Wm$^{-2}$</td>
</tr>
<tr>
<td>Saturn</td>
<td>2.7 Wm$^{-2}$</td>
<td>2.0 Wm$^{-2}$</td>
</tr>
<tr>
<td>Uranus</td>
<td>0.7 Wm$^{-2}$</td>
<td>0.04 Wm$^{-2}$</td>
</tr>
<tr>
<td>Neptune</td>
<td>0.3 Wm$^{-2}$</td>
<td>0.4 Wm$^{-2}$</td>
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(Guillot 2005)
Giant planet properties

- Have similar radii and rotation rates
- Differ in energy budgets
- Very different flows:
  - Jupiter, Saturn superrotating
  - Uranus, Neptune subrotating

Differences in flows likely caused by differences in energy budgets and dissipation. How?
3D simulation of all giant planets

(Liu & Schneider 2010)
Jupiter control simulations

u, Eddy momentum divergence

T, N

Uniform solar radiation

No internal heatflux

(Schneider & Liu 2009)
Why is Uranus subrotating?

--- Almost no internal heat flux (0.042 W m\(^{-2}\)), the atmosphere is stably stratified.

(Liu & Schneider 2010)
How about Neptune?

--- Has significant internal heat flux (0.43 W m\(^{-2}\)), the atmosphere is neutrally stratified below tropopause.

(Liu & Schneider 2010)
(a) Neptune’s insolation and Saturn’s internal heat flux 2.01 W m$^{-2}$
(b) Uniform insolation and Neptune’s internal heat flux 0.43 W m$^{-2}$

(Liu & Schneider 2010)
Equatorial superrotation favored when...

- Planetary rotation rate low
- Convective (intrinsic) heating strong
- Baroclinicity low

Width and strength of SR jets can be understood from vorticity homogenization arguments

(Schneider & Liu 2009, Liu & Schneider 2010, 2011)
Drag dependence of off-equatorial jets

For strong drag, the global barotropic EKE spectrum flattens. No. 1678900
Drag dependence of off-equatorial jets

Figure 1: Left panels: mean zonal velocity (in the simulations increase from top to bottom: 0.1, 1, 3, 10, 30 bar) is used as a simple representation of the MHD drag the parameters relevant for Jupiter. Rayleigh drag at an artificial no-drag region, the drag time scale is set to a constant equatorial drag time scale (colors). The off-equatorial Rayleigh drag time scales of a giant planet, with flow defformation radius. For Jupiter and Saturn, these deformation radius. However, in the simulations, eddy–mean flow interactions flattening of global barotropic EKE spectra in the simulations are much less than barotropic energy (Fig. 3).

Figure 2: Left panels: mean zonal velocity (colors). The off-equatorial Rayleigh drag time scales of a giant planet, with flow defformation radius. For Jupiter and Saturn, these deformation radius. However, in the simulations, eddy–mean flow interactions flattening of global barotropic EKE spectra in the simulations are much less than barotropic energy (Fig. 3).

Figure 3: Left: Eddy length scale (Fig. 6). Right: Energy containing inertia (Fig. 3).
Conclusions

• Terrestrial tropical circulations are influenced by eddies, but mean meridional AM fluxes also play a role, so they are in intermediate Rossby number regime (theoretical terra incognita)

• Still need general theory for Hadley circulation

• Equatorial superrotation arises when baroclinicity is weak enough, heating strong enough, and rotation rate low enough

• Off-equatorial jets can be baroclinically generated (difficult to generate them otherwise!)

• Scaling of off-equatorial jets not entirely clear. Rossby radius and Rhines scale play a role; inverse cascades not necessarily