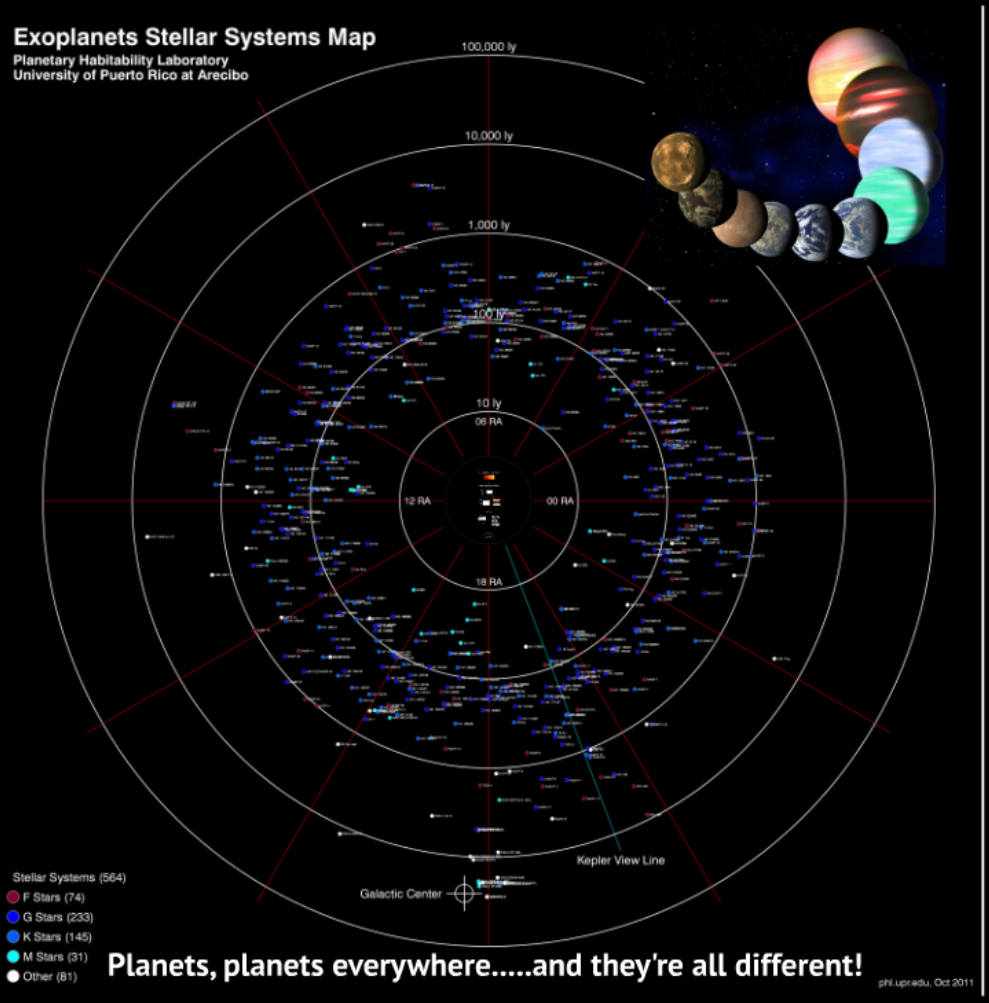
Dynamical Modeling of Hot Jupiters

UNIVERSITY OF EXETER + Met Office

Nathan Mayne, Isabelle Baraffe, Dave Acreman, David Skålid Amundsen, John Thurburn.

Chris Smith , Nigel Wood, David Jackson.



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+

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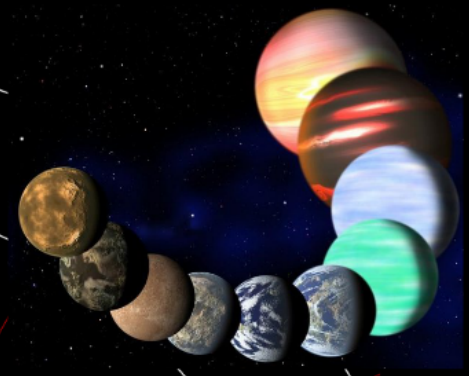
Exoplanets Stellar Systems Map

Planetary Habitability Laboratory
University of Puerto Rico at Arecibo

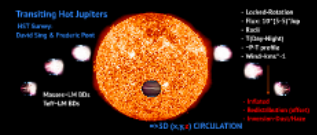


Stellar Systems (564)
- F Stars (74)
- G Stars (233)
- K Stars (145)
- M Stars (31)
- Other (81)

Planets, planets everywhere.....and they're all different!

phl.upr.edu, Oct 2011

Observational Constraints: Hot Jupiters



Global Circulation Models

GCM: Unified Model (UM)

Components:

- Ocean
- Land
- Sea Ice
- Atmosphere

- Dynamical core (momenta, continuity, EOS, thermodynamics)
- Radiative transfer (heating, clouds etc)
- Chemistry & Physics (condensation, photoionisation etc)

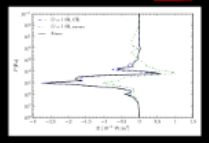
Radiative Transfer

David Skalidi Amundsen PhD

~1500-5000K (~BDs)

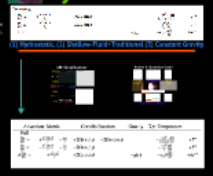
State-of-the-art:

- 2-stream approx
- Correlated-K
- Two-wavelength



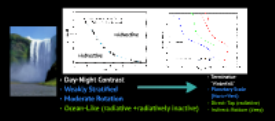
Amundsen et al (in prep): Finished -> Coupling

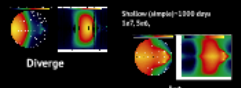
Dynamics



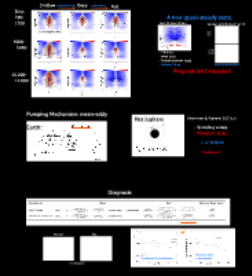
Results

Circulation:
Heng et al (2011)': H209458b





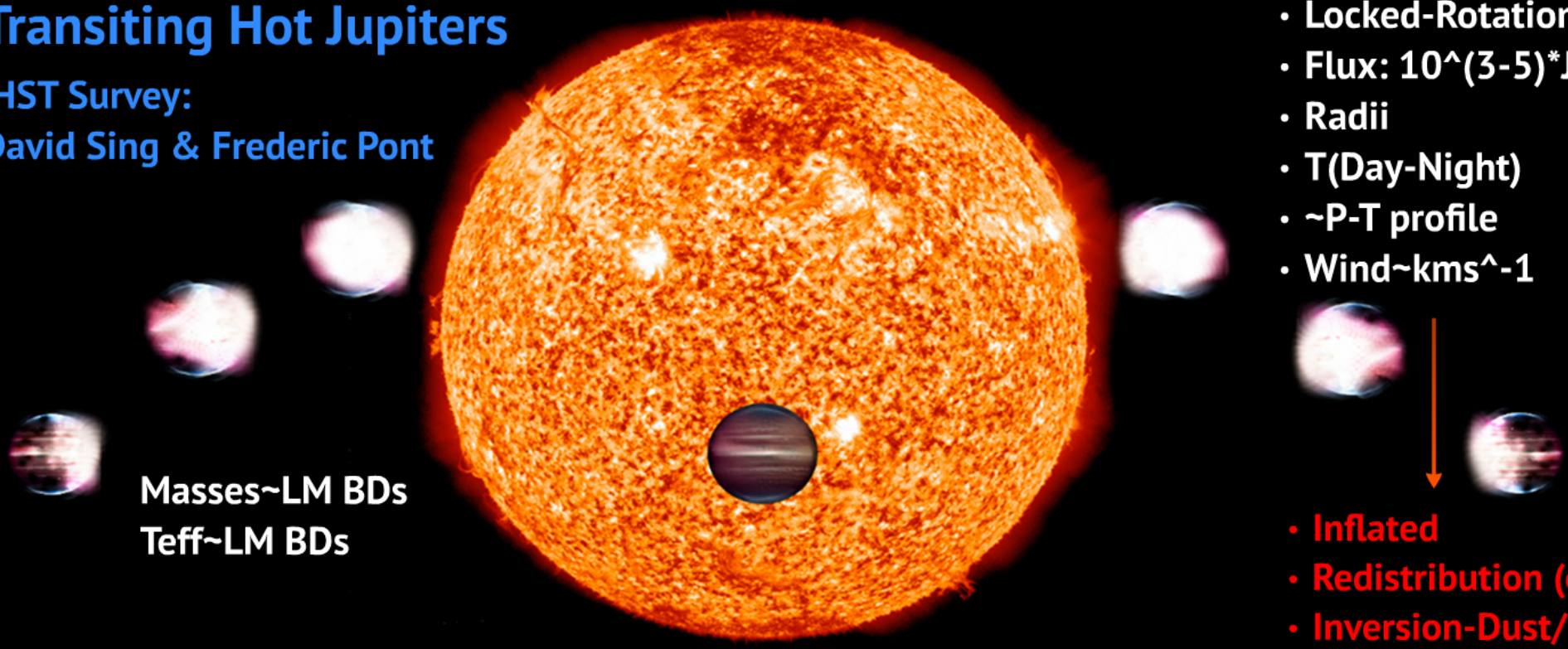
Simplifications: Equatorial Jet



tional Constraints: H

Transiting Hot Jupiters

HST Survey:
David Sing & Frederic Pont



- Locked-Rotation
- Flux: 10^(3-5)*Jup
- Radii
- T(Day-Night)
- ~P-T profile
- Wind~kms^-1

Masses~LM BDs
Teff~LM BDs

- Inflated
- Redistribution (offset)
- Inversion-Dust/Haze

=>3D (x,y,z) CIRCULATION

lobal Circulation Models

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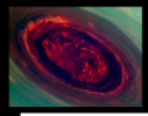
adiative Transfer



Dynamics (+ Forcing, Ti->T

Primitive

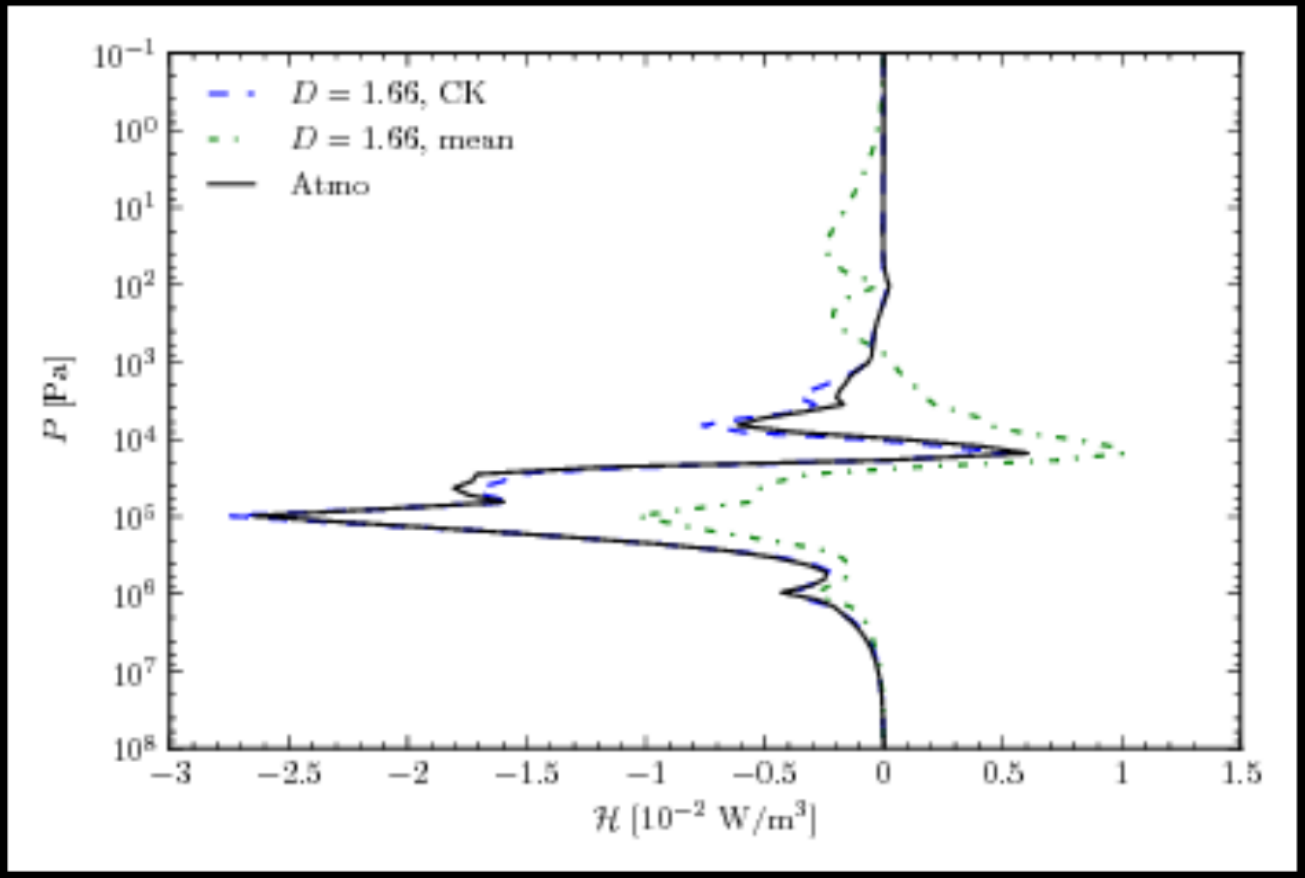
Radiative Transfer

David Skalid Amundsen PhD

~1500-3000K (~BDs)

State-of-the-art:

- 2-stream approx
- Correlated-K
- Two-wavelength



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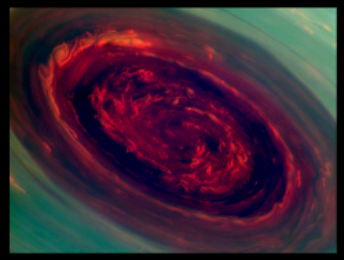


Dynamics (+ Forcing, Ti->Teq)

Eq:
Pole:
Vert:

Primitive

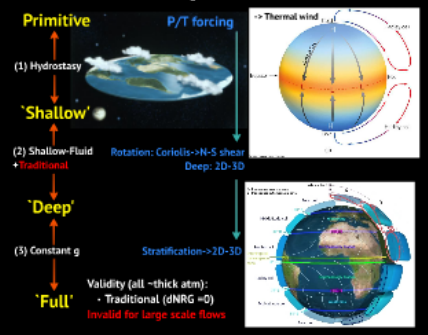
$$\frac{Du}{Dt} = +\frac{uv\tan\phi}{R_\mathrm{p}} + 2\Omega v\sin\phi - \frac{c_p\theta}{R_\mathrm{p}\cos\phi}\frac{\partial\Pi}{\partial\lambda} + F^u$$

$$\frac{Dv}{Dt} = -\frac{u^2\tan\phi}{R_\mathrm{p}} - 2\Omega u\sin\phi - \frac{c_p\theta}{R_\mathrm{p}}\frac{\partial\Pi}{\partial\phi} + F^v$$

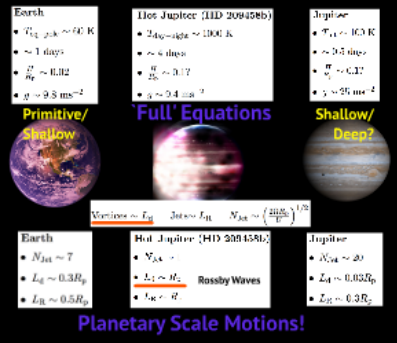
$$0 = -g_\mathrm{p} - c_p\theta\frac{\partial\Pi}{\partial z} + F^w$$

(1) Hydrostatic, (2) Shallow-Fluid+Traditional (3) Constant Gravity

UM: Simplifications



Regime & Dynamical Scales



Advection+Metric	Coriolis:Rotation	Gravity	∇p: Temperature

Eq:
Pole:
Vert:

Primitive

$$\frac{Du}{Dt} = +\frac{uv\tan\phi}{R_p} + 2\Omega v\sin\phi - \frac{c_p\theta}{R_p\cos\phi}\frac{\partial\Pi}{\partial\lambda} + F^u$$

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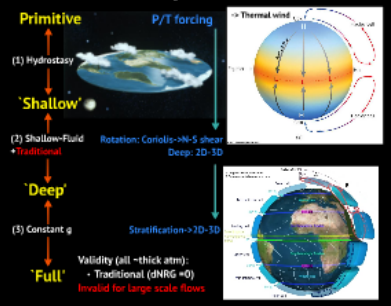
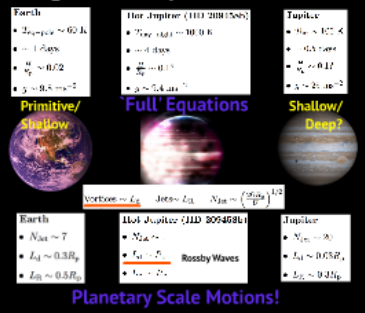
(1) Hydrostatic, (2) Shallow-Fluid+Traditional (3) Constant Gravity





Advection+Metric	Coriolis:Rotation	Gravity	∇p: Temperature

Full

$$\frac{Du}{Dt} = +\frac{uv\tan\phi}{r} - \frac{uw}{r} + 2\Omega v\sin\phi - 2\Omega w\cos\phi - \frac{c_p\theta}{r\cos\phi}\frac{\partial\Pi}{\partial\lambda} + F^u$$

$$\frac{Dv}{Dt} = -\frac{u^2\tan\phi}{r} - \frac{vw}{r} - 2\Omega u\sin\phi - \frac{c_p\theta}{r}\frac{\partial\Pi}{\partial\phi} + F^v$$

$$\delta\frac{Dw}{Dt} = +\frac{u^2+v^2}{r} + 2\Omega u\cos\phi - g(r) - c_p\theta\frac{\partial\Pi}{\partial r} + \delta F^w$$

UM: Simplifications

Primitive

(1) Hydrostasy

`Shallow'

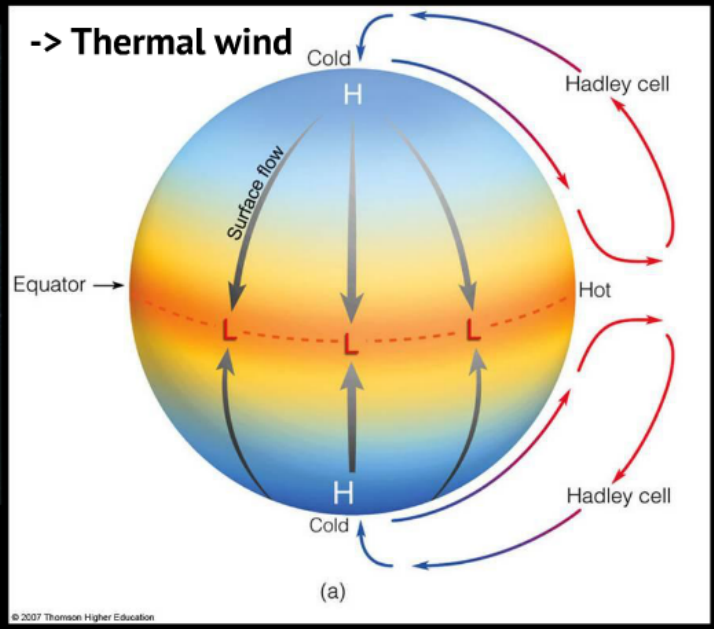
(2) Shallow-Fluid
+Traditional

`Deep'

(3) Constant g

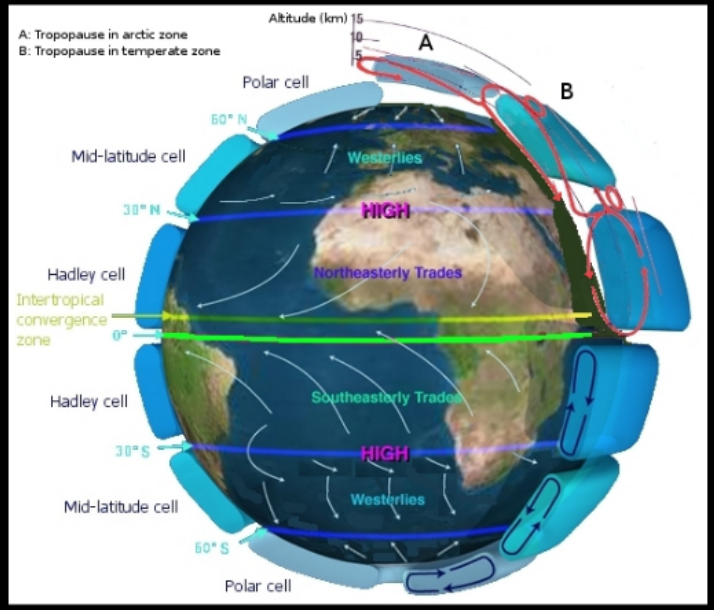
`Full'

P/T forcing



Rotation: Coriolis->N-S shear
Deep: 2D-3D

Stratification->2D-3D



Validity (all ~thick atm):

- Traditional (dNRG =0)

Invalid for large scale flows

Regime & Dynamical Scales

Earth

- $T_{\mathrm{eq-pole}} \sim 60$ K
- ~ 1 days
- $\frac{H}{R_{\mathrm{p}}} \sim 0.02$
- $g \sim 9.8$ ms^{-2}

Hot Jupiter (HD 209458b)

- $T_{\mathrm{day-night}} \sim 1000$ K
- ~ 4 days
- $\frac{H}{R_{\mathrm{p}}} \sim 0.1$?
- $g \sim 9.4$ ms^{-2}

Jupiter

- $T_{\mathrm{int}} \sim 100$ K
- ~ 0.5 days
- $\frac{H}{R_{\mathrm{p}}} \sim 0.1$?
- $g \sim 25$ ms^{-2}

Primitive/ Shallow

`Full' Equations

Shallow/ Deep?

- $g \sim 9.8\ \mathrm{ms}^{-2}$

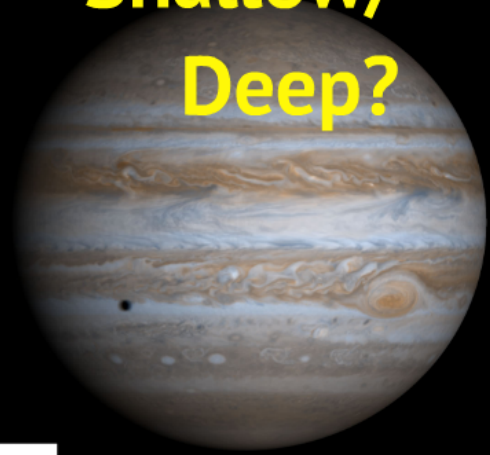
- $g \sim 9.4\ \mathrm{ms}^{-2}$

- $g \sim 25\ \mathrm{ms}^{-2}$

Primitive/ Shallow

`Full' Equations

Shallow/ Deep?



$\text{Vortices} \sim L_\mathrm{d}$ Jets$\sim L_\mathrm{R}$ $N_\mathrm{Jet} \sim \left(\frac{2\Omega R_\mathrm{p}}{U}\right)^{1/2}$

Earth

- $N_\mathrm{Jet} \sim 7$
- $L_\mathrm{d} \sim 0.3 R_\mathrm{p}$
- $L_\mathrm{R} \sim 0.5 R_\mathrm{p}$

Hot Jupiter (HD 209458b)

- $N_\mathrm{Jet} \sim 1$
- $L_\mathrm{d} \sim R_\mathrm{p}$
- $L_\mathrm{R} \sim R_\mathrm{p}$

Rossby Waves

Jupiter

- $N_\mathrm{Jet} \sim 20$
- $L_\mathrm{d} \sim 0.03 R_\mathrm{p}$
- $L_\mathrm{R} \sim 0.3 R_\mathrm{p}$

Planetary Scale Motions!

Eq:
Pole:
Vert:

Primitive

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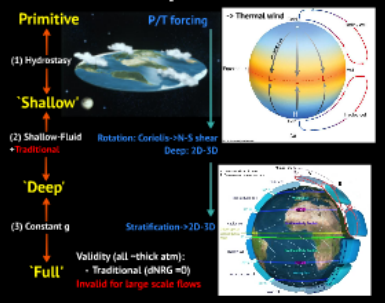

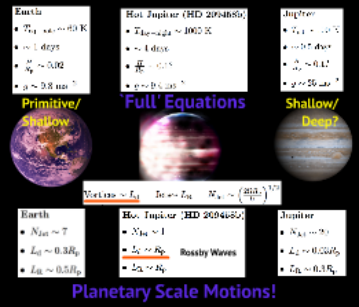

Advection+Metric	Coriolis:Rotation	Gravity	∇p: Temperature

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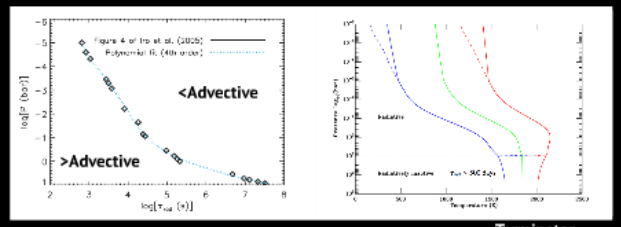
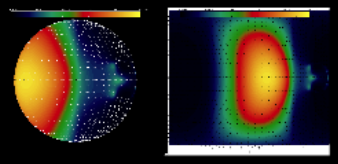
Results

Circulation:
Heng et al (2011)': H209458b



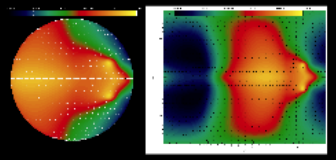
- Day-Night Contrast
- Weakly Stratified
- Moderate Rotation
- Ocean-Like (radiative +radiatively inactive)

- Terminator: 'Waterfall'
- Planetary Scale (Horiz+Vert)
- Direct: Top (radiative)
- Indirect: Bottom (deep)



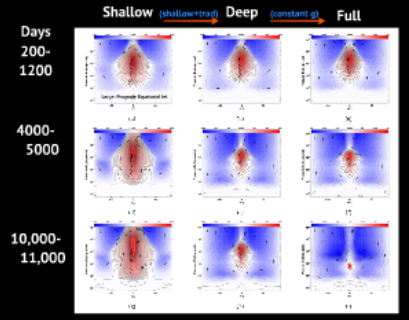
Diverge

Shallow (simple)~1000 days
1e7, 5e6,

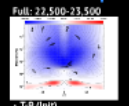


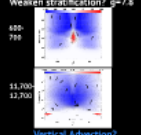
Jet

Simplifications: Equatorial Jet



A new quasi-steady state.

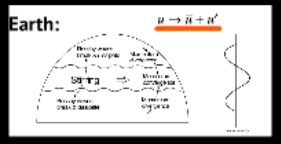


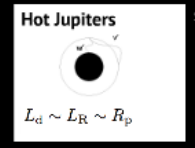


- T-P (Init)
- Wind (Init)
- Domain (remove deep)
- Activate: Deep

Prograde Jet Dissipates!

Pumping Mechanism: mean-eddy





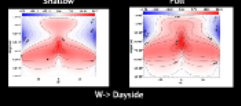
Showman & Polvani, 2011a,b

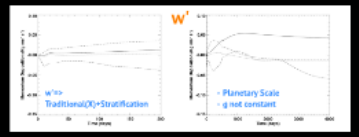
- Standing waves
- Planetary Scale

-> w' Critical

Traditional?

Diagnosis





Circulation:
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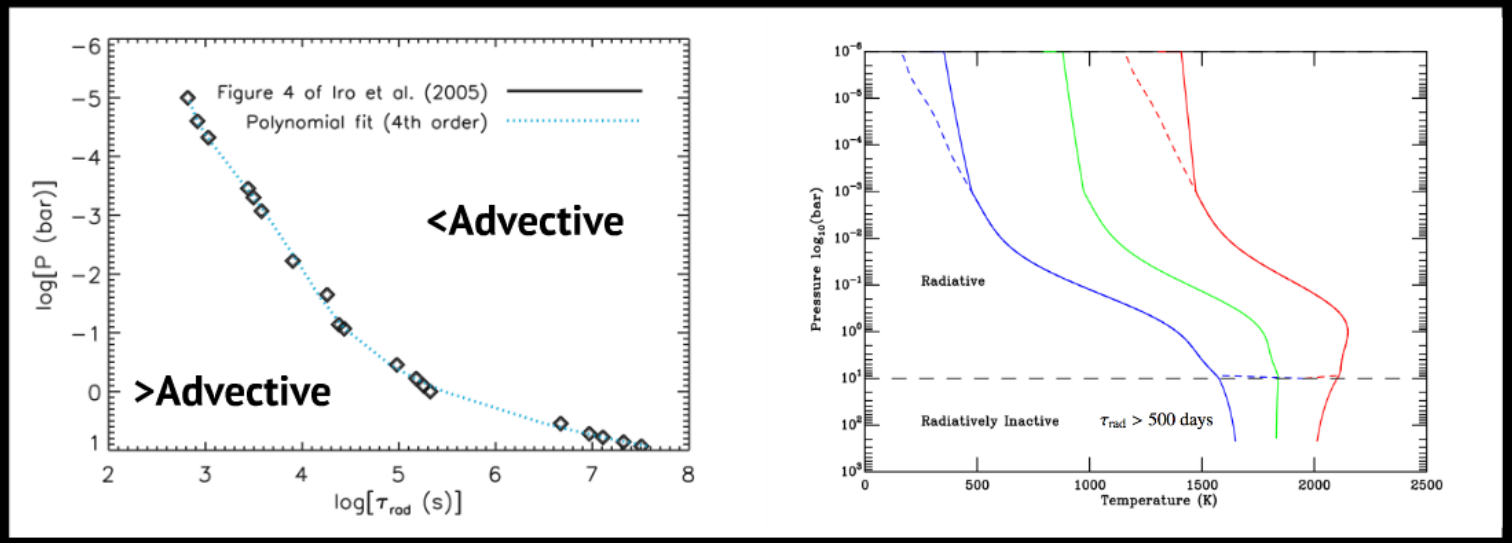

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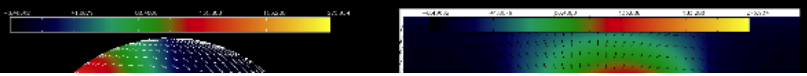

Shallow (simple)~1000 days

- Moderate Rotation
- Ocean-Like (radiative +radiatively inactive)

- Direct: Top (radiative)
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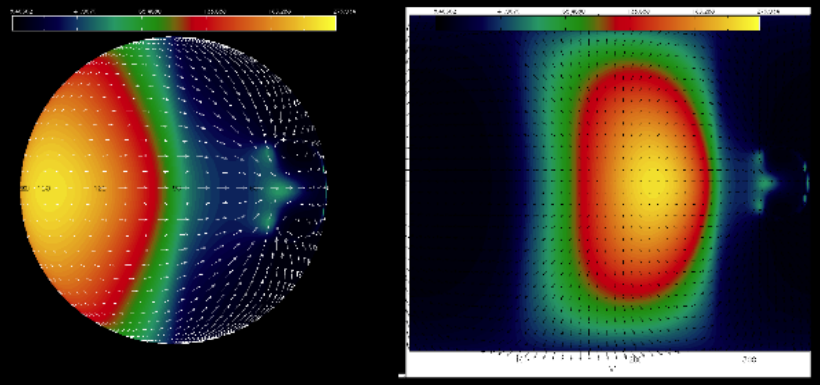
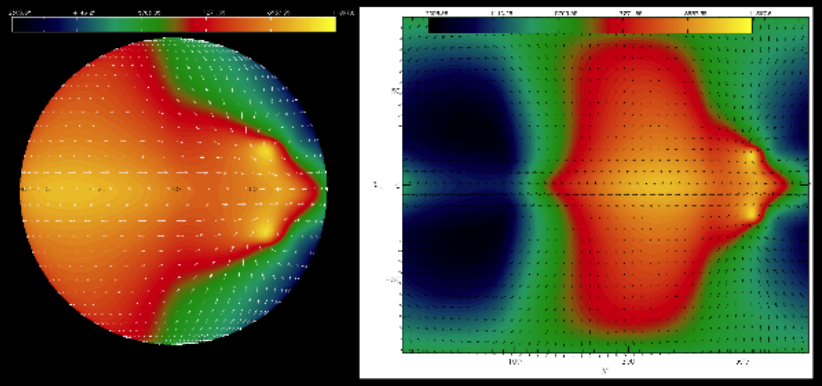
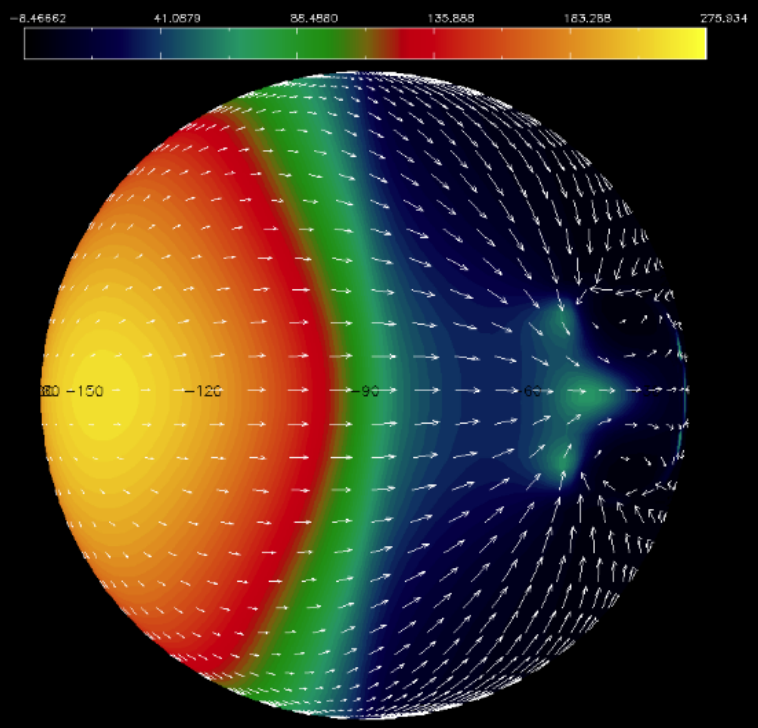


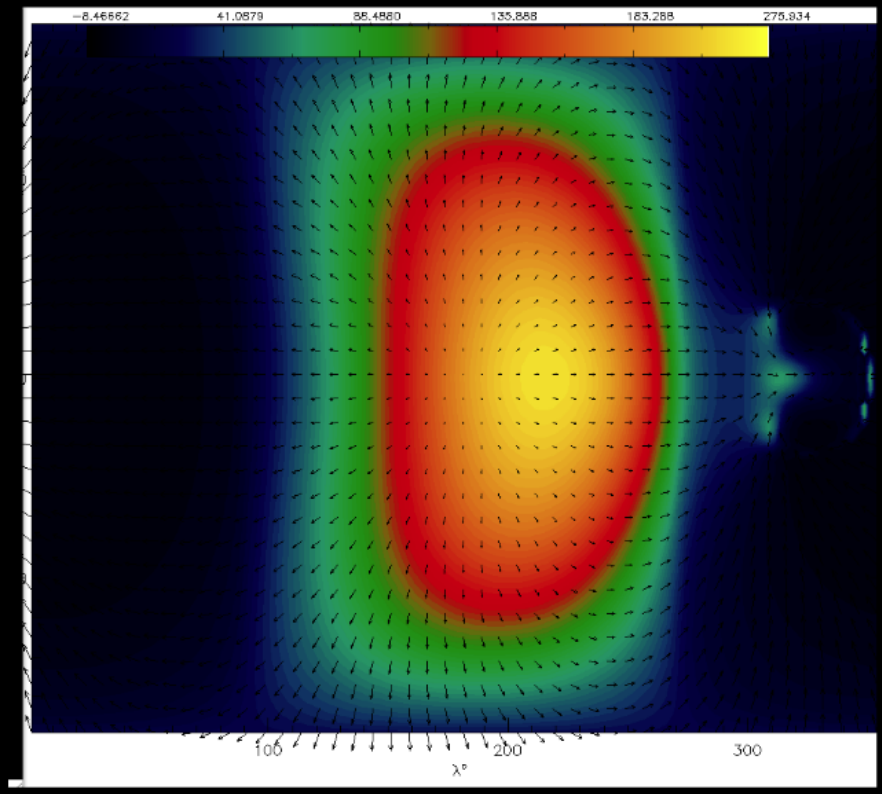
Diverge

Shallow (simple)~1000 days
1e7, 5e6,



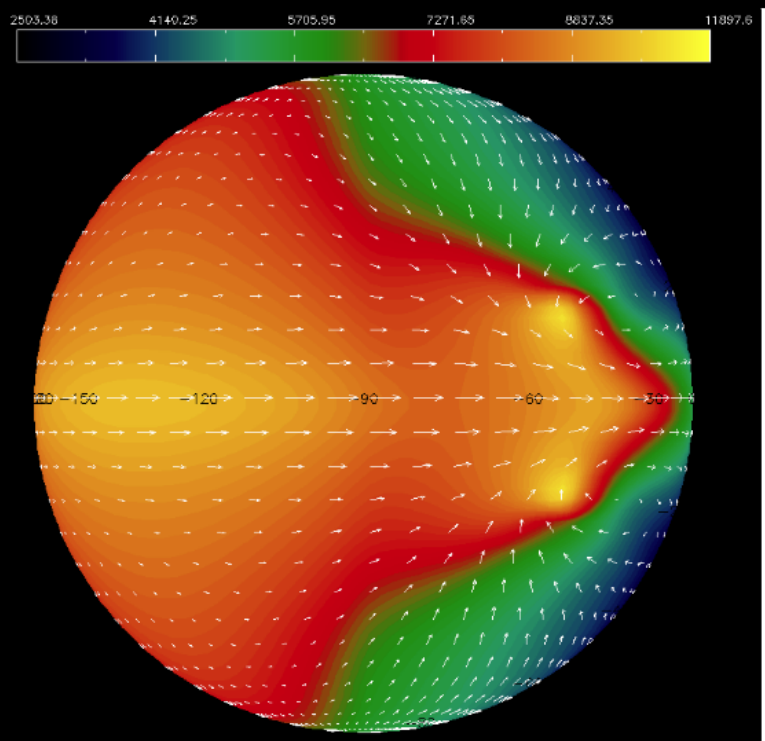
Jet

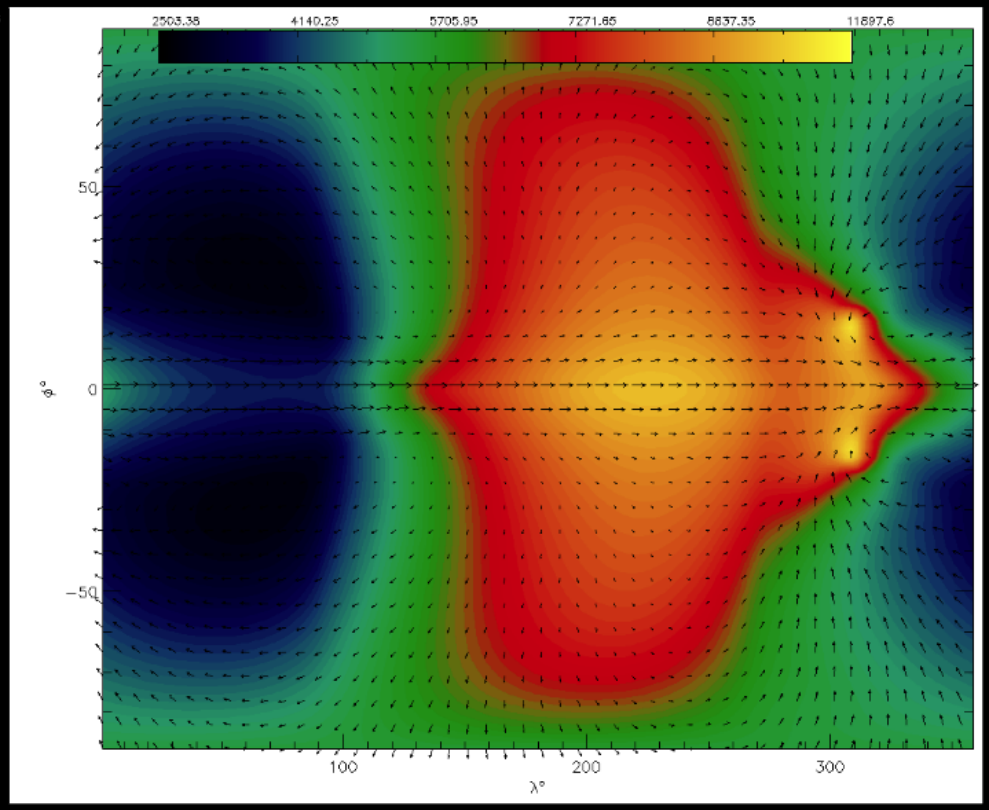

−8.46662
41.0879
88.4880
135.888
183.288
275.934
−150
−120
−90


−8.46662
41.0879
88.4880
135.888
183.288
275.934
100
200
300
λ°

Diverge

1e7, 5e6,


2503.38
4140.25
5705.95
7271.65
8837.35
11897.6
180
150
120
90
60
30


2503.38
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5705.95
7271.65
8837.35
11897.6
50
0
−50
100
200
300

Jet

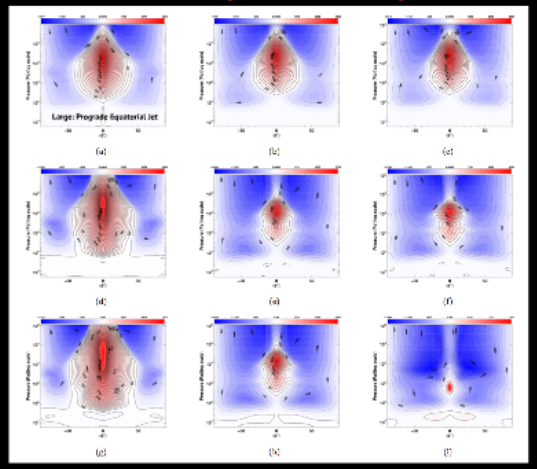
Simplifications: Equatorial Jet

Shallow (shallow+trad) Deep (constant g) Full

Days 200-1200

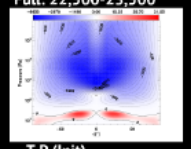
4000-5000

10,000-11,000



A new quasi-steady state.

Full: 22,500-23,500

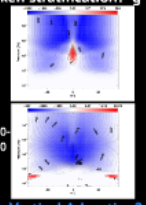


- T-P (Init)
- Wind (Init)
- Domain (remove deep)
- Activate: Deep

Weaken stratification? g=7.8

600-700

11,700-12,700

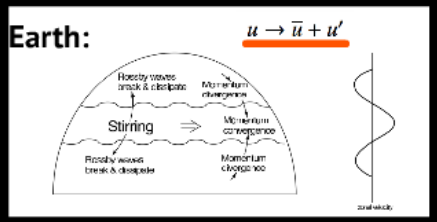


Vertical Advection?

Prograde Jet Dissipates!

Pumping Mechanism: mean-eddy

Earth: $u \rightarrow \bar{u} + u'$



Hot Jupiters

$L_{\mathrm{d}} \sim L_{\mathrm{R}} \sim R_{\mathrm{p}}$

Showman & Polvani, 2011a,b

- Standing waves
- Planetary Scale

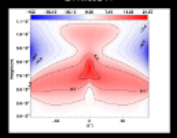
-> w' Critical

Traditional?

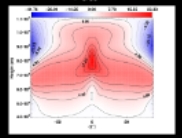
Diagnosis

Equation set			Mean				Eddy		External Zonal forces
Full & Deep	$(\bar{\rho}\bar{u})_{,t}$	=	$-\frac{(\overline{\rho v}\,\overline{u}\cos^2\phi)_{,\phi}}{r\cos^2\phi}$	$-\frac{(\overline{\rho w}\,\overline{u}r^3)_{,r}}{r^3}$	$+2\Omega\overline{\rho v}\sin\phi$	$-2\Omega\overline{\rho w}\cos\phi$	$-(\overline{\rho' u'})_{,t}$	$-\frac{\left[(\rho v)' u' \cos^2\phi\right]_{,\phi}}{r\cos^2\phi}$ $-\frac{\left[(\rho w)' u' r^3\right]_{,r}}{r^3}$	$+\overline{\rho G_\lambda}$
Shallow & Primitive	$(\bar{\rho}\bar{u})_{,t}$	=	$-\frac{(\overline{\rho v}\,\overline{u}\cos^2\phi)_{,\phi}}{R_{\mathrm{p}}\cos^2\phi}$	$-(\overline{\rho w}\,\overline{u})_{,z}$	$+2\Omega\overline{\rho v}\sin\phi$		$-(\overline{\rho' u'})_{,t}$	$-\frac{\left[(\rho v)' u' \cos^2\phi\right]_{,\phi}}{R_{\mathrm{p}}\cos^2\phi}$ $-\left[(\rho w)' u'\right]_{,z}$	$+\overline{\rho G_\lambda}$

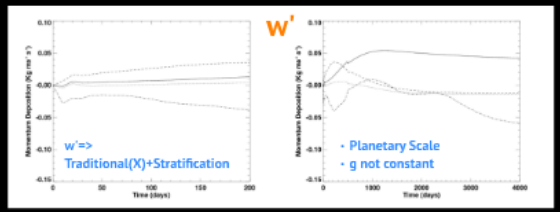
Shallow

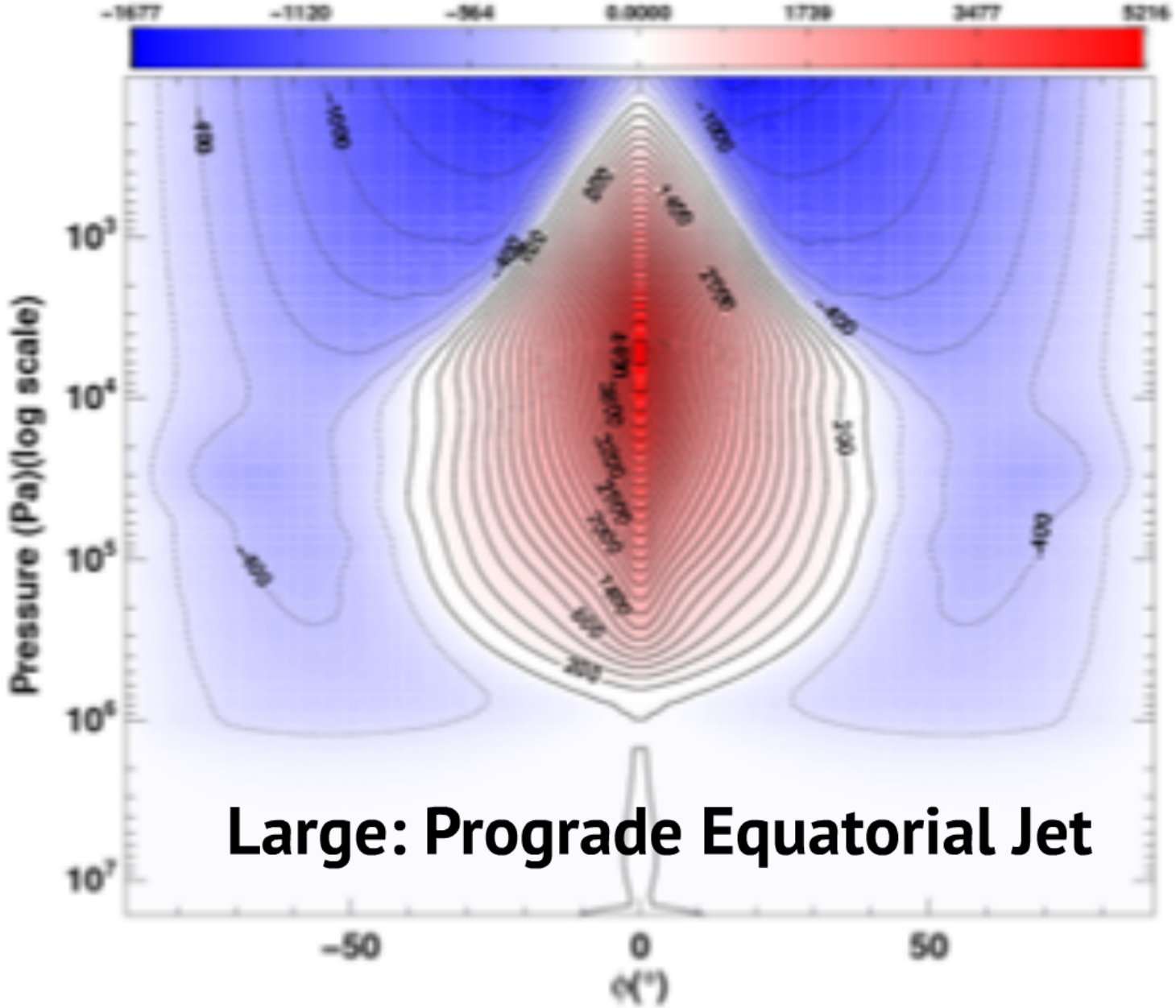


Full



W-> Dayside





Large: Prograde Equatorial Jet

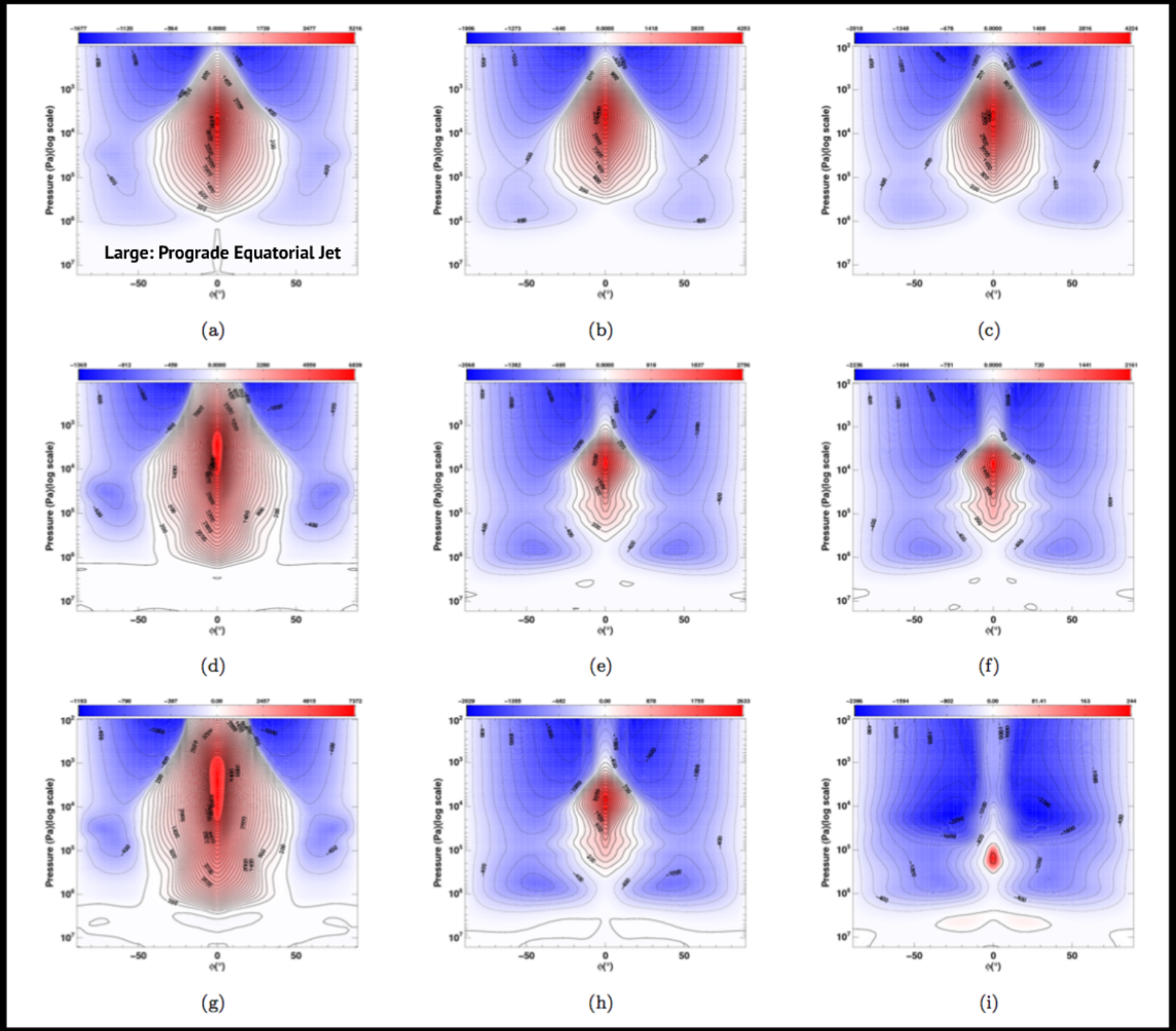
(a)

Shallow (shallow+trad) Deep (constant g) Full

Days 200-1200

4000-5000

10,000-11,000



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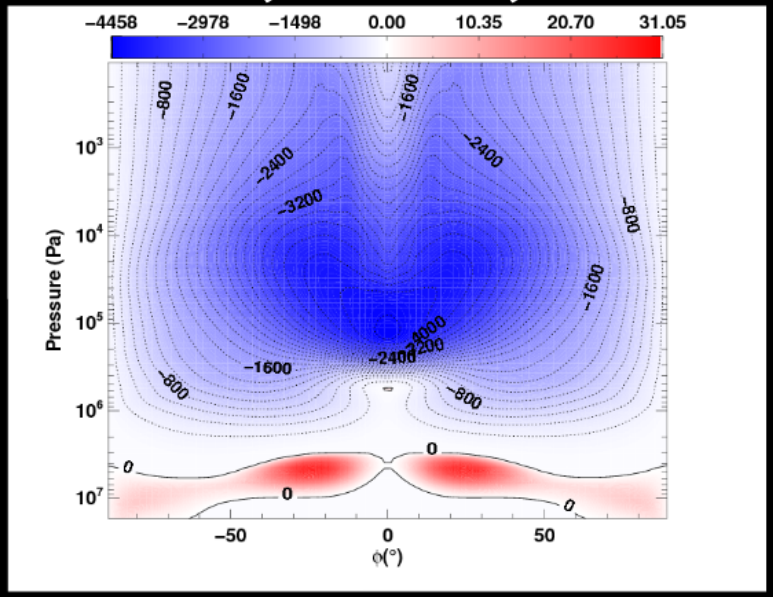

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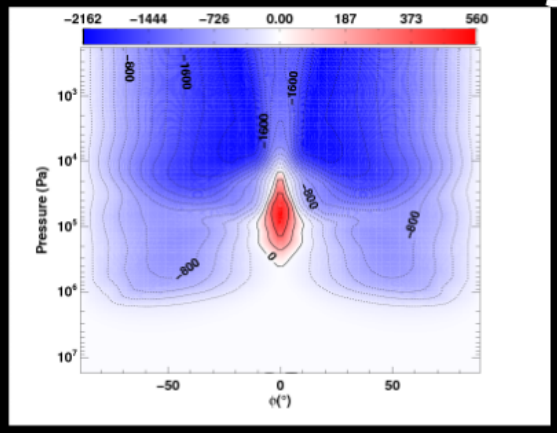
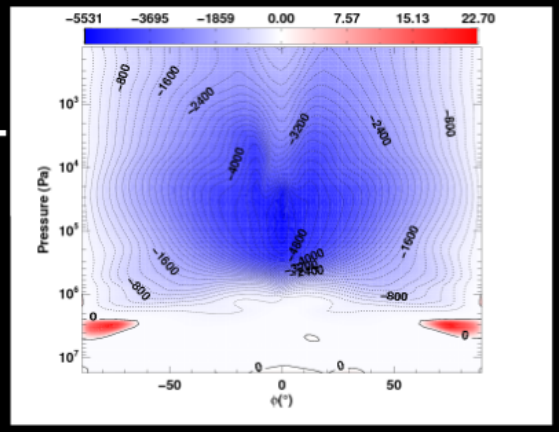


11,700-12,700



Vertical Advection?

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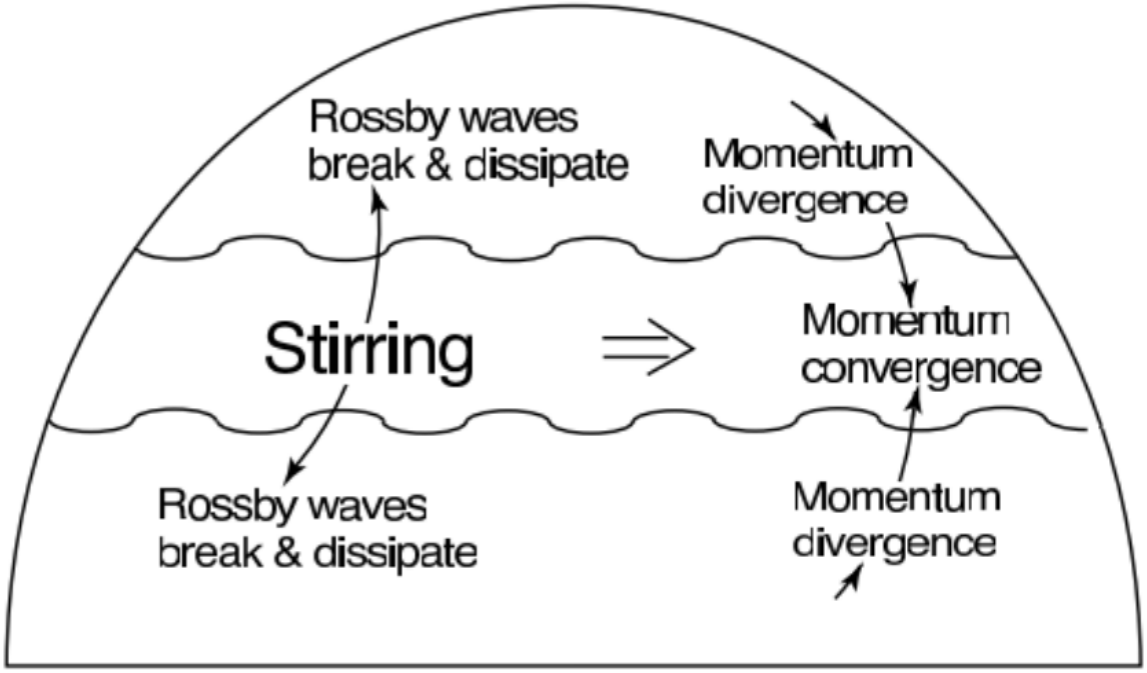
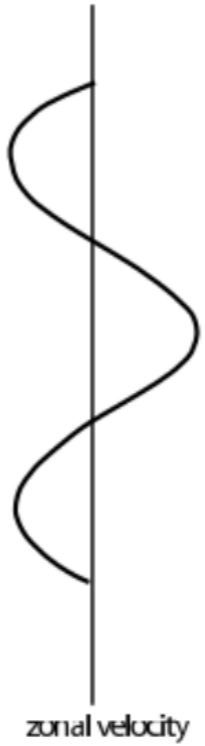
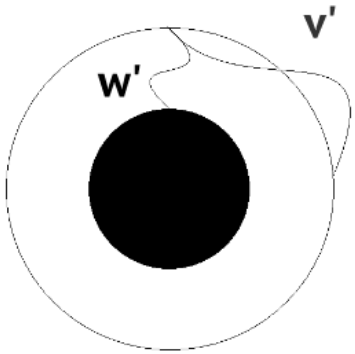
Earth:

$$u \rightarrow \bar{u} + u'$$





Hot Jupiters



$$L_{\mathrm{d}} \sim L_{\mathrm{R}} \sim R_{\mathrm{p}}$$

Showman & Polvani, 2011a,b

- Standing waves
- Planetary Scale

-> w' Critical

Traditional?

Traditional?

Diagnosis

Equation set			Mean				Eddy		External Zonal forces
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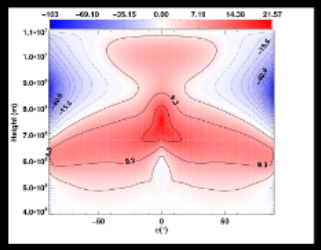
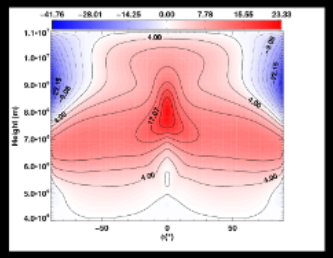
Shallow & Primitive	$(\overline{\rho}\,\overline{u})_{,t}$	$=$	$-\frac{(\overline{\rho v}\,\overline{u}\cos^2\phi)_{,\phi}}{R_p\cos^2\phi}$	$-(\overline{\rho w}\,\overline{u})_{,z}$	$+2\Omega\overline{\rho v}\sin\phi$		$-(\overline{\rho' u'})_{,t}$	$-\frac{\left[\overline{(\rho v)' u'}\cos^2\phi\right]_{,\phi}}{R_p\cos^2\phi}$	$-\left[\overline{(\rho w)' u'}\right]_{,z}$	$+\overline{\rho G_\lambda}$

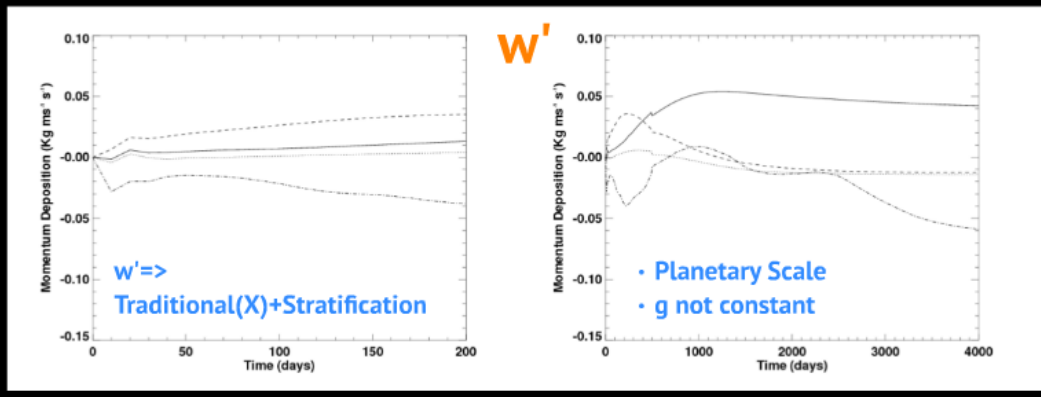
Shallow



Full

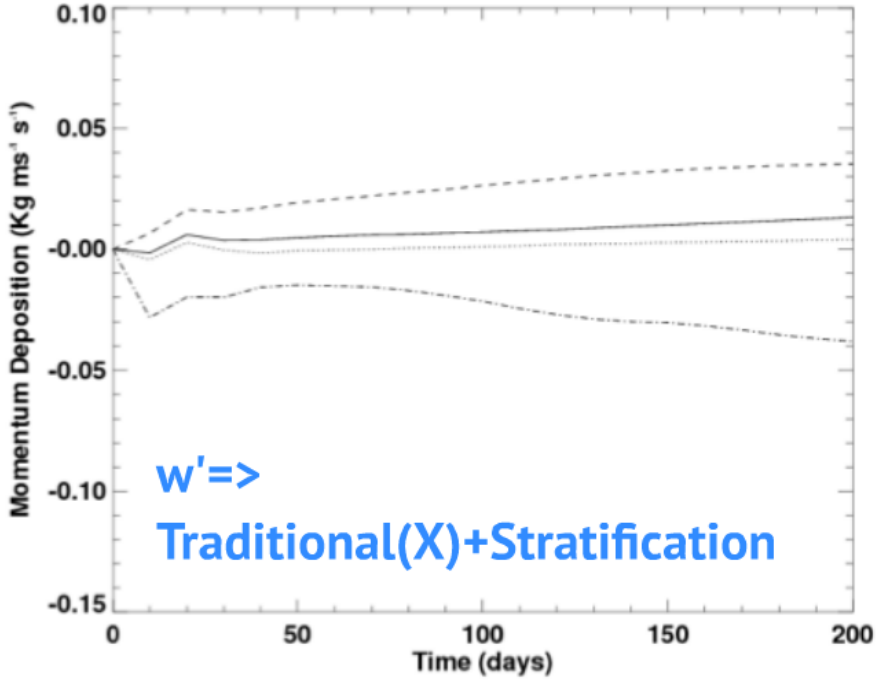


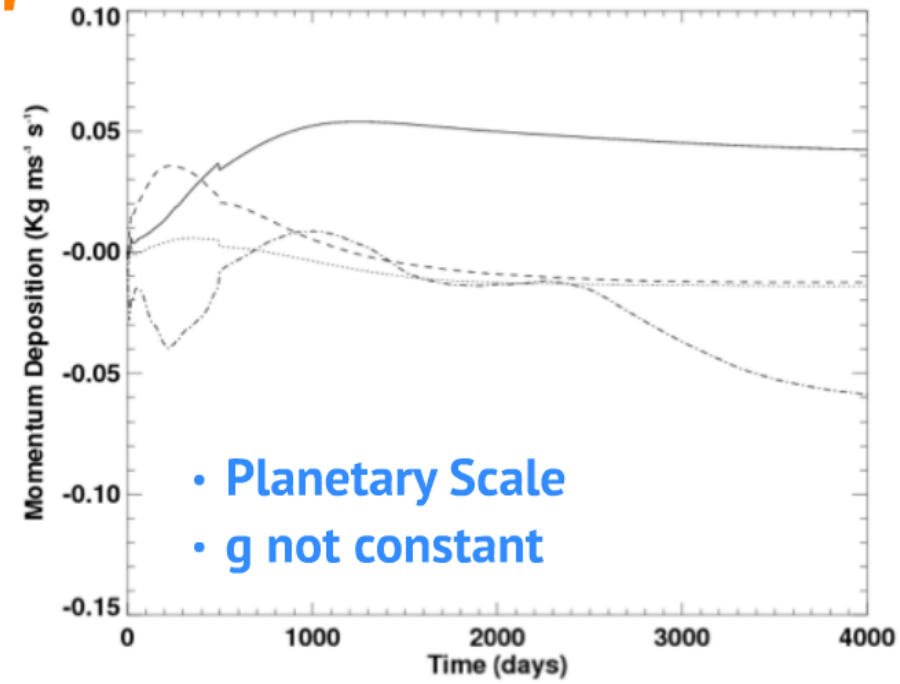
W-> Dayside



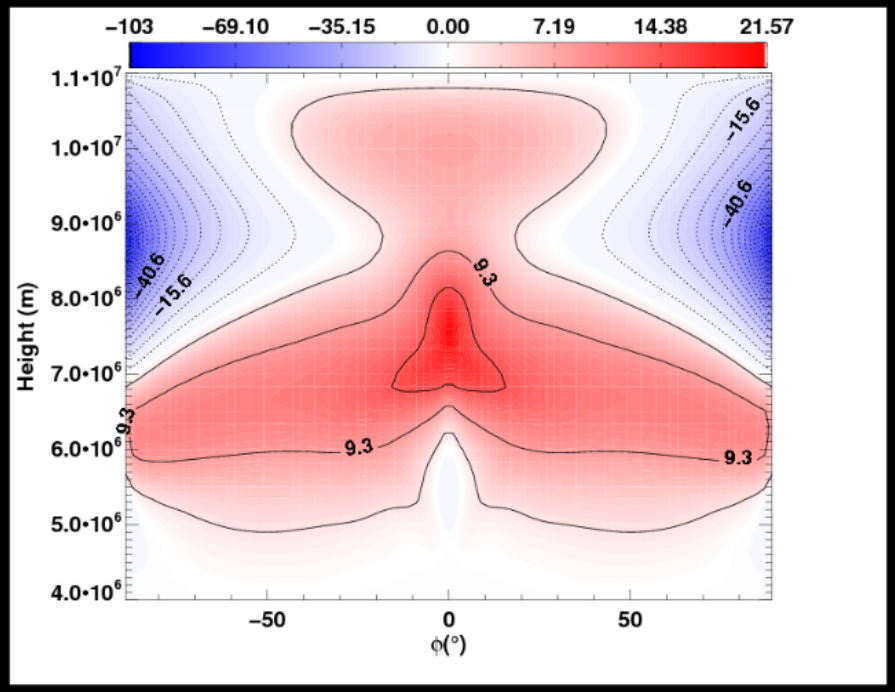
		Eddy		External Zonal forces
$2\overline{\rho w}\cos\phi$	$-(\overline{\rho' u'})_{,t}$	$-\dfrac{\left[\overline{(\rho v)' u'}\cos^2\phi\right]_{,\phi}}{r\cos^2\phi}$	$-\dfrac{\left[\overline{(\rho w)' u'} r^3\right]_{,r}}{r^3}$	$+\overline{\rho G_\lambda}$
	$-(\overline{\rho' u'})_{,t}$	$-\dfrac{\left[\overline{(\rho v)' u'}\cos^2\phi\right]_{,\phi}}{R_p\cos^2\phi}$	$-\left[\overline{(\rho w)' u'}\right]_{,z}$	$+\overline{\rho G_\lambda}$

w'

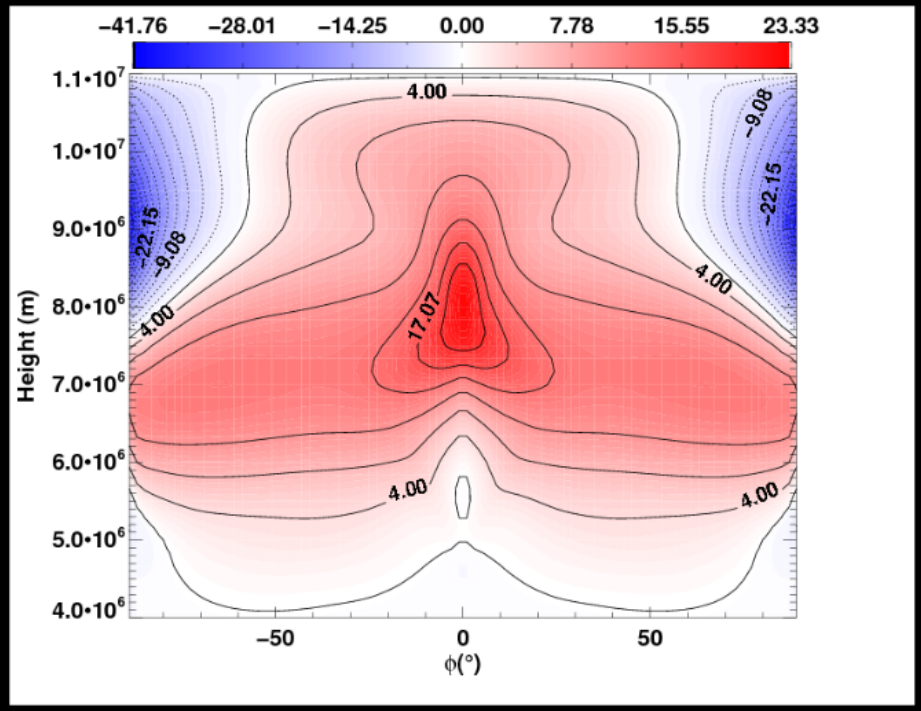




Shallow



Full



W-> Dayside

Conclusions & Future Work

Done!

- Code Works!
- 'Full', Long => New state (Lit: Prim or short)
- Pumping => Vertical circulations

To Do!

Inflated Radii?-> Couple RT, Deeper (Cp=F(p)) (short)
Redistribution efficiency?-> Parameter space (short-mid)
Thermal Inversions?-> Compositional changes (mid)
Dust and Hazes?-> tracers+sim obs (mid-David Sing)

Papers:

- Test Cases (Earth, Hot Jupiters): Mayne et al (2013a,b-Ref report)
- Pumping Mechanism, New state: Mayne et al (2013c, in prep)
- Radiative Transfer: Amundsen et al (in prep)