Convection and waves on Small Earth and Deep Atmosphere

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"Time and space are modes by which we think and not conditions in which we live"
Albert Einstein

Don't be far from anything important

Outline

1)Motivation

2)Scale definitions/Characteristic numbers

3) IFS Aqua Planet Scaling

4) Summary and future work

Motivation

- ECMWF plans: Hor. resolution upgrade: 5km (2020) and 2.5 km (2025)
- Deep convection becomes gradually more resolved at such high resolutions:

→ Estimate hor. resolution beyond which IFS could eventually be run without a deep convection parametrization

But simulations/Data storage/Processing at high resolutions are extremely costly on current computer systems

Ideal prototype: IFS Aqua Planet Scaling

- with full physics but excludes land effects
- reduces the computational cost by reducing the scale difference between the synoptic and convection regimes

Scaling: external parameters

Horizontal length scale : L

L is reduced by a factor γ_R by reducing the Earth's radius by γ_R

$$\frac{R_a}{\gamma_R} \Rightarrow \frac{L}{\gamma_R}$$

Depth scale: H

H is reduced by a factor γ_g by increasing the gravity by γ_g

$$g * \gamma_g \Rightarrow \frac{H}{\gamma_g}$$

Time scale : τ

τ is reduced by a factor γ_Ω by increasing the rotation rate Ω of the planet by γ_Ω

$$\Omega * \gamma_\Omega \Rightarrow \frac{t}{\gamma_\Omega}$$

Scaling : charcteristic numbers

Earth Radius	Rotation speed	Gravity
R_a	Ω	g

Rossby number

$$R_o = \frac{U}{2\Omega R_a}$$

Richardson number

$$R_i = \frac{N^2 H^2}{U^2}$$

$$N^2 = \frac{g}{\theta}\frac{\Delta\theta}{H}$$

$$L_R = \frac{NH}{2\Omega}$$

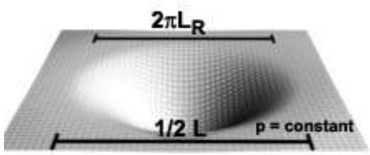
Lamb number

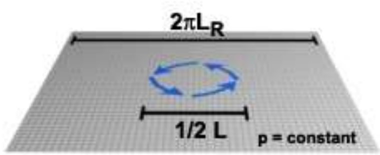
$$L_a = \frac{1}{R_i R_o^2} = \left(\frac{2\Omega R_a}{NH}\right)^2 = \left(\frac{R_a}{L_R}\right)^2$$

La: Ratio of the rotational force to the buoyancy force

Rossby Radius of Deformation L_R: Scale at which there is an equal inertial and gravity wave response

Convective scale vs synoptic scale





$$R_o = \frac{c_g}{c_r} = \frac{NH}{Lf}$$

$$c_r = \frac{f}{k} = \frac{fL}{2\pi} \qquad c_g = \frac{N}{k} = \frac{H}{2\pi}\sqrt{\frac{g}{\theta}\frac{\partial\theta}{\partial z}} \qquad L_R = \frac{NH}{f}$$

Rossby Radius of Deformation L_R: Scale at which there is an equal inertial and gravity wave response

- **Convective scale ($L \ll L_R$): Tendency toward hydrostatic balance with gravity the dominant restoring force for perturbations**
- **Synoptic scale ($L \gg L_R$): Tendency toward geostrophic balance with the Coriolis force the dominant restoring force for perturbations**

Scale difference reduction

The basic idea is to reduce the gap between the convective and synoptic scales. This can be achieved by reducing the synoptic scale, therefore bringing it closer to the convective scale, or by increasing the convective scale.

Shrink the scale of the synoptic regime

Smaller Earth with accelerated rotation/buoyancy forcing/ microphysics

Stretch the scale of the convective regime

Deep Atmosphere: Smaller gravity

Aqua-Planet
$\gamma_R = \gamma_\Omega = \gamma_g = 1$

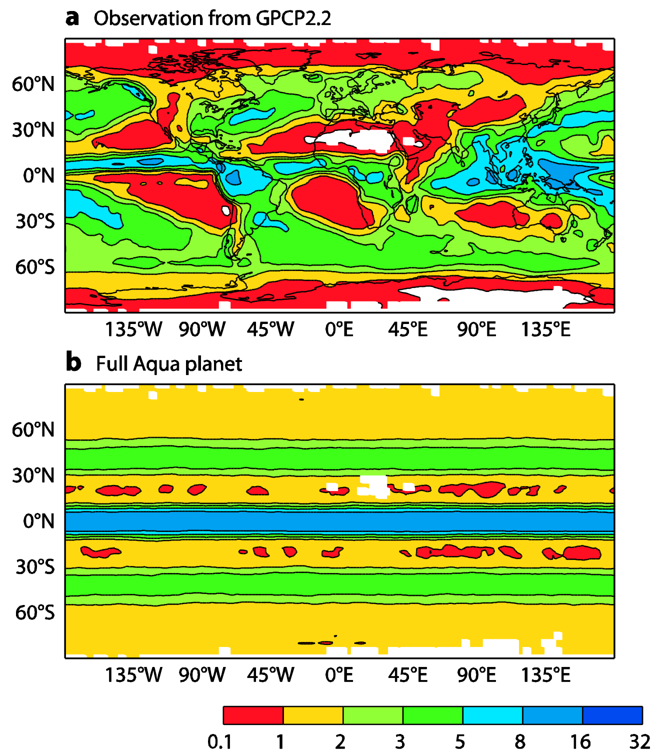
Setup

SST distribution
Balanced initial state
4-member ens. (1year)
Deep convection/T159 (125km)

Obs.

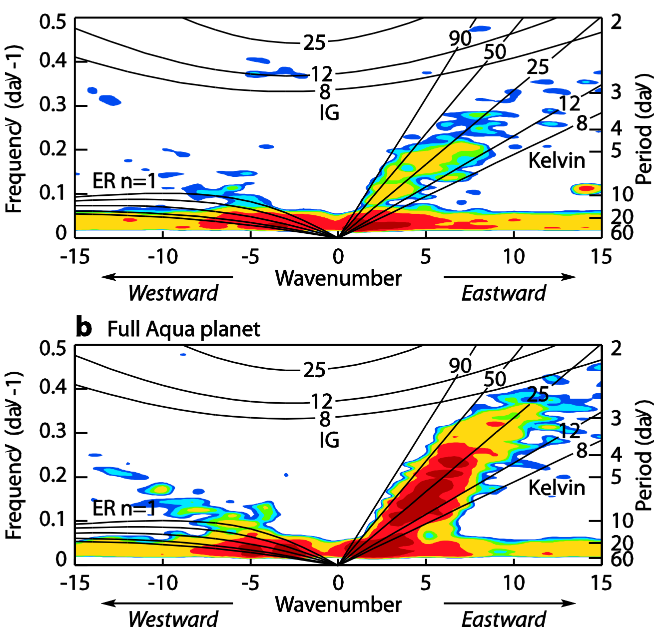
RR: GPCP2.2
w. n. f. spec. OLR (NOAA)

Annual mean precipitation (mm/day)



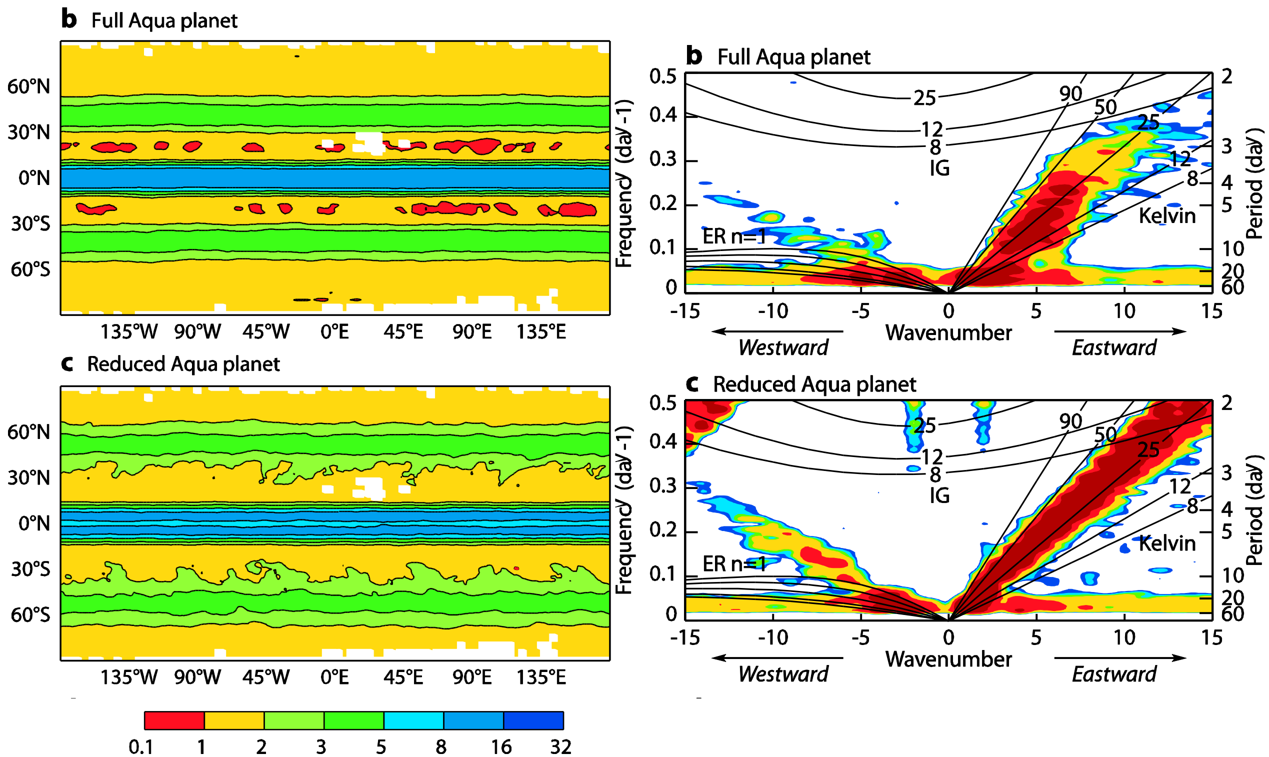
Wavenumber frequency diagrams of the outgoing longwave radiation.

a NOAA



Reduced Aqua-Planet

$\gamma_R = \gamma_\Omega = 8$ & $\gamma_g = 1$



No physics scaling

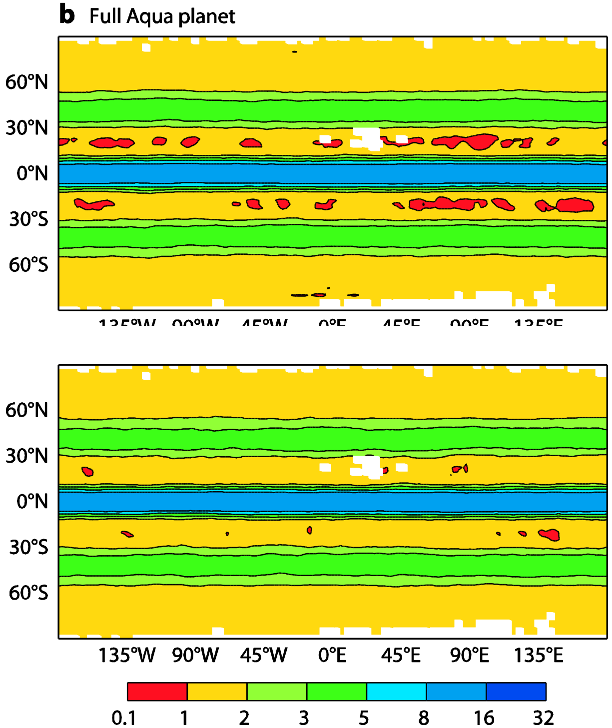
Reduced Aqua-Planet

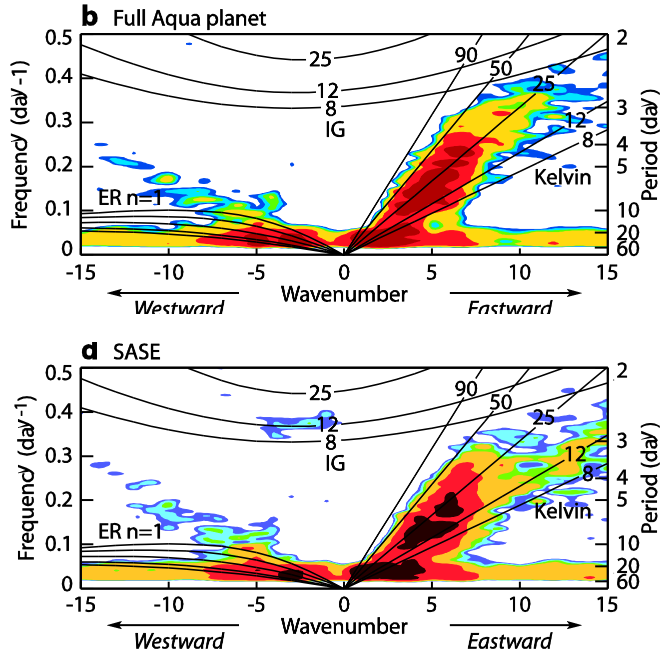
Split ITCZ & Shift ML Storm tracks too far poleward

Distorted Kelvin waves

Small Planet Shallow Atmosphere SPSA

$$\gamma_R=\gamma_\Omega=\gamma_g=8$$





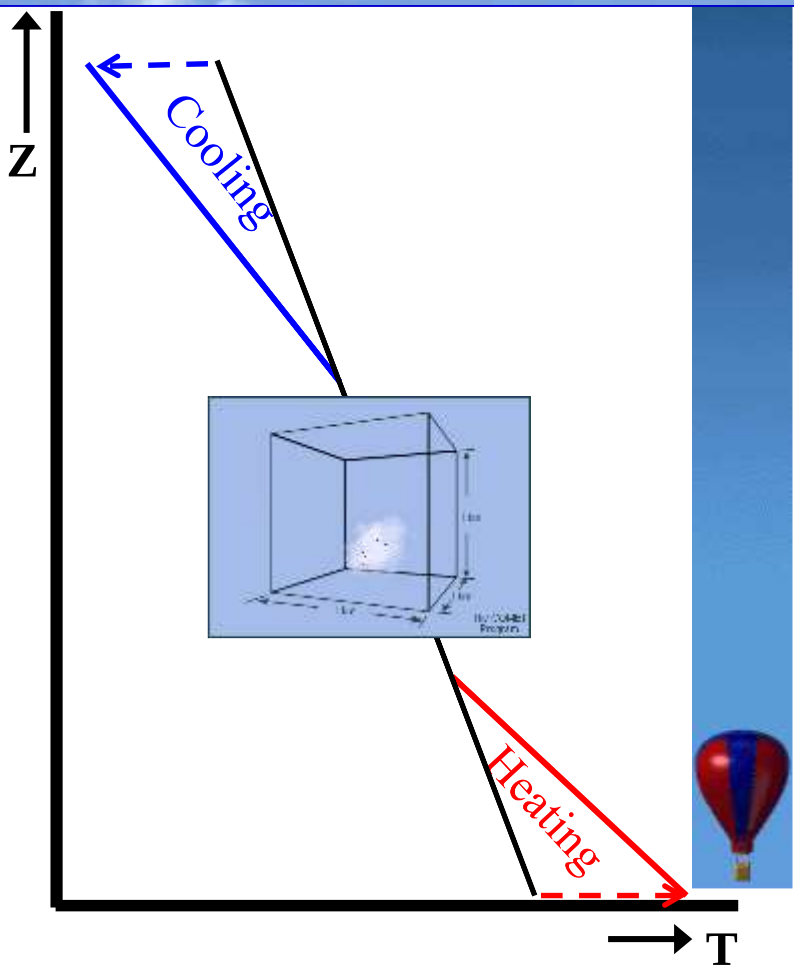
SPSA

- ✓ Adjusts the buoyancy forcing (BL +rad.) time-scale consistently with the advection time-scale via gravity scaling
- ✓ Requires Microphysics scaling Rescaling of internal constants with absolute values

Scale separation on SPSA ~ scale separation on the full planet

Small-scale version of the climate on the full planet

DARE/SMALL EARTH



DARE/SMALL EARTH

Accelerate advection forcing

Accelerate BL & radiation forcing

Accelerate microphysics

Kuang et al., GRL 2005

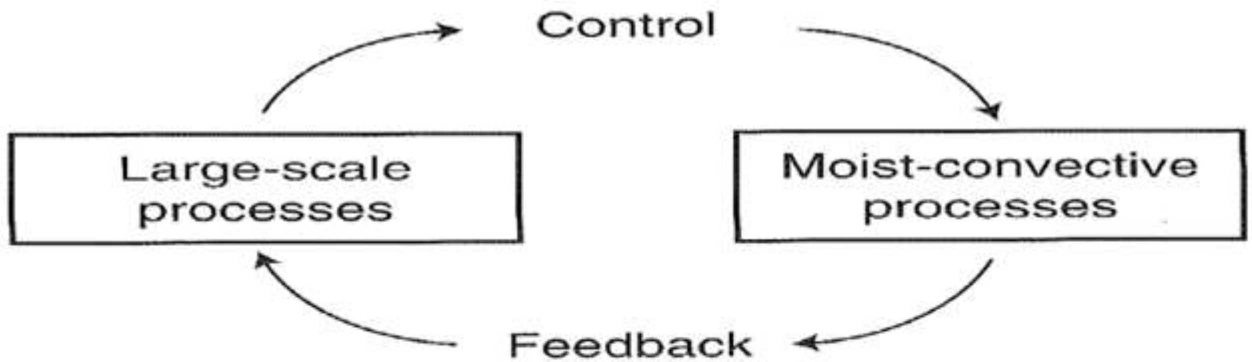
Garner et al., JAS 2007

$$\gamma_R = \gamma_\Omega = \gamma$$
$$\gamma_g = 1$$

→ Synoptic regime speeds up

Reproduce the response of natural convection by accelerating the buoyancy forcing by a factor γ

Grid-averaged equations



Schematic of the interaction between large-scale processes and moist convection. Adapted from Arakawa (1993).

$$\frac{\partial \overline{q}}{\partial t} = -\overline{\mathbf{v}} \cdot \nabla \overline{q} - \overline{w}\frac{\partial \overline{q}}{\partial z} + B_{\overline{q}} - C_{\overline{q}}$$

$$\frac{\partial \overline{T}}{\partial t} = -\overline{\mathbf{v}} \cdot \nabla \overline{T} - \overline{w}\frac{\partial \overline{T}}{\partial z} + B_{\overline{T}} + \frac{Q_{rad}}{c_p} + \frac{LC_{\overline{T}}}{c_p}$$

Advection forcing | BL forcing | Radiation forcing | Condensation/convection

DARE/SMALL EARTH

$$\left[B_{\bar{T}} + \frac{Q_{rad}}{c_p} \right] * \gamma \quad \& \quad B_{\bar{q}} * \gamma$$

Accelerate buoyancy forcing

Buoyancy forcing

Boundary-layer forcing B

Radiation forcing Q_{rad}

$$\left[\bar{\mathbf{v}} \cdot \nabla \bar{T} + \bar{w} \frac{\partial \bar{T}}{\partial z} \right] * \gamma \quad \& \quad \left[\bar{\mathbf{v}} \cdot \nabla \bar{q} + \bar{w} \frac{\partial \bar{q}}{\partial z} \right] * \gamma$$

Accelerate advection forcing

Accelerate the convective adjustment

$$\frac{CAPE}{\tau} * \gamma \Rightarrow \tau / \gamma$$

τ: Adjustment time-scale

DARE/SMALL EARTH

DARE /SMALL EARTH

$\gamma_R = \gamma_\Omega = \gamma = 8$

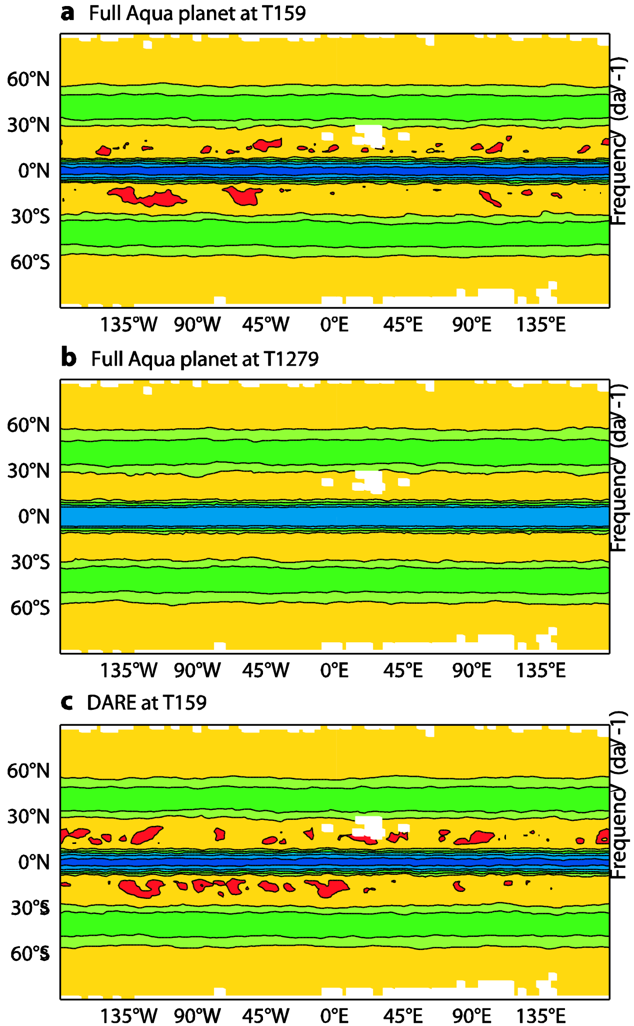
$\gamma_g = 1$

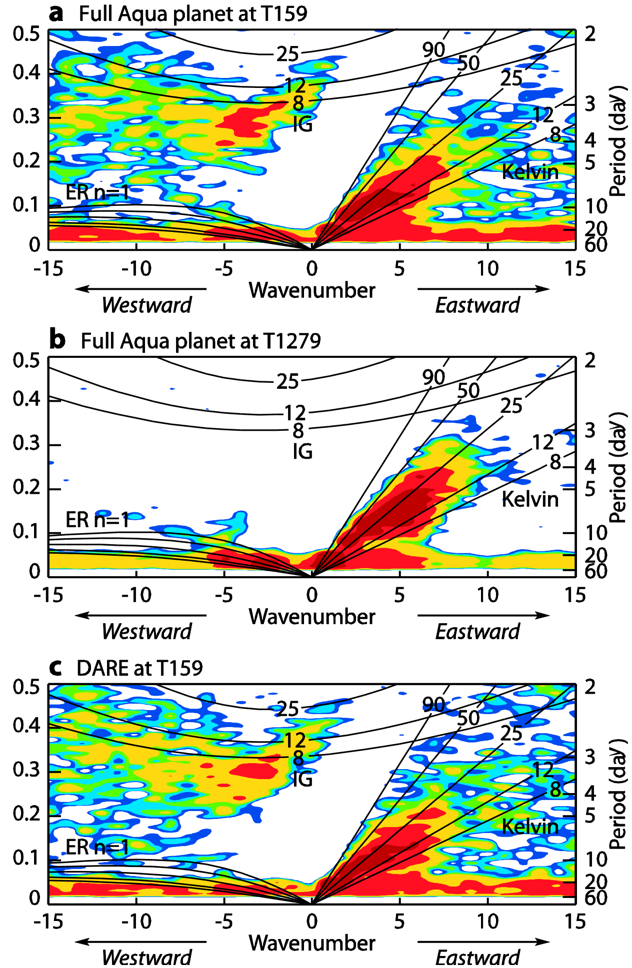
Experiments

No deep conv. /T159
No deep conv.T1279 (16km)
DARE /No deep conv. /T159

- ✓ Synoptic scale reduced by a factor γ
- ✓ Scale height unchanged
- ✓ Scale difference reduction factor γ
- ✓ Convective scale a factor γ closer to synoptic scale
- ✓ Convection is driven more strongly by a factor γ

DARE/SMALL EARTH





- ✓ T159 AQUA & DARE/SMALL EARTH integrations without convection parameterization overestimate the equatorial precipitation compared to the control run T1279
- ✓ T159 AQUA & DARE/SMALL EARTH wave spectra are broad and noisy

DARE/SMALL EARTH essentially only reproduces the results of the T159 integration

DARE/DEEP ATMOSPHERE

The convective tendency of CAPE= Heating through compensating environmental subsidence

$$\frac{CAPE}{\tau} = g \int_{z_{base}}^{z_{top}} \frac{M}{\overline{\rho}\overline{T_v}} \frac{\partial \overline{T_v}}{\partial z} dz$$

τ: Adjustment time-scale

$$g/\gamma \Rightarrow H*\gamma \Rightarrow \tau_c * \gamma$$

$$\tau_c \xrightarrow{g/\gamma} \tau$$

τ_c: Overturning time-scale

Stretch the scale of the convective regime by a factor γ

This results in a slowdown of convective motions, combined with an increase in their horizontal scale, without affecting the large-scale hydrostatic dynamics of the atmosphere

DARE/DEEP ATMOPSHERE

$$g/\gamma \Rightarrow H*\gamma$$

Scale height increased by a factor γ → Convective scale increased by a factor γ
Convective scale a factor γ closer to synoptic scale

The scale for the vertical velocity $$W = \frac{H}{L}U$$

- The stretching in the vertical axis increases the vertical velocity W
- Rescaling of the precipitation fall speed : This conserves the ratio between the precipitation speed and vertical velocity Pauluis et al., TCFD 2006

The scale for the buoyancy forcing $$\frac{U^3}{HL}$$ Garner et al., JAS 2007

- Rescaling of the buoyancy forcing in order to offset the stretching in H
- Rescaling of the physics internal constants that have been given absolute values instead of generally scaled values

DARE/DEEP ATMOSPHERE

DARE/DEEP ATM.
NO DCP T159

$\gamma_R = \gamma_\Omega = 1$

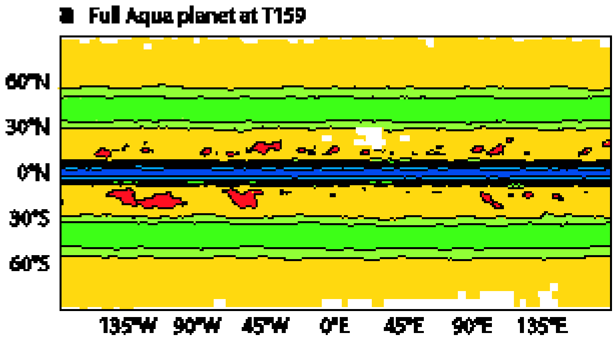
$\gamma = 8$

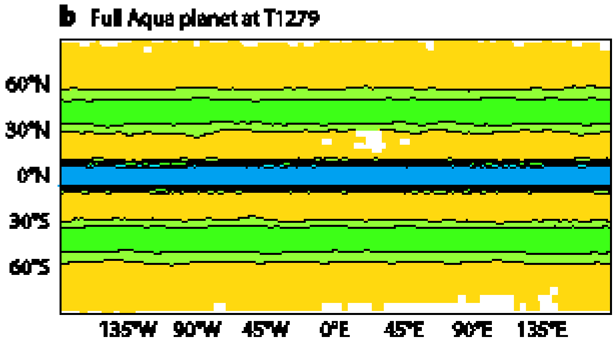
$\gamma_g = 1/\gamma$

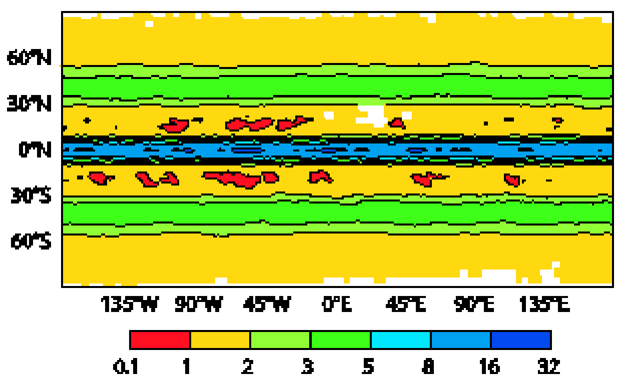
- ✓ Scale height increased by a factor γ
- ✓ Convective scale increased by a factor γ
- ✓ Scale difference reduction factor γ
- ✓ Convective scale a factor γ closer to synoptic scale

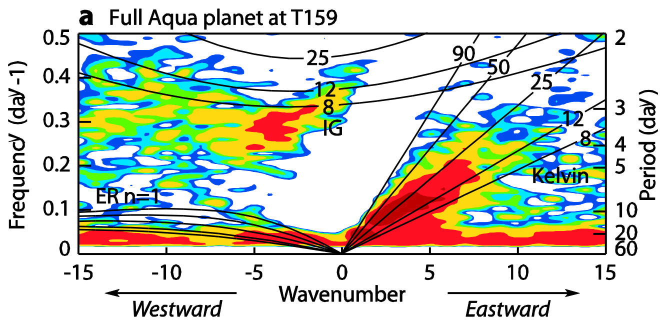
- IFS on an aqua-planet with smaller gravity
- The stretching in the vertical axis increases vertical velocity
- Rescaling of the physics internal constants that have been given absolute values instead of generally scaled values
- Rescaling of the precipitation fall speed
- DARE/DEEP ATMOSPHERE requires a buoyancy forcing adjustment in order to offset the stretching in the vertical axis

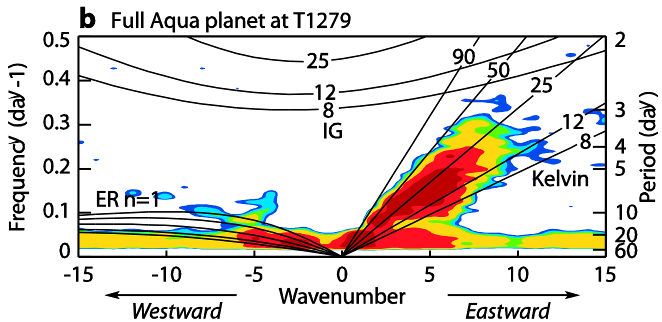
DARE/DEEP ATM. (γ=8) NO DCP

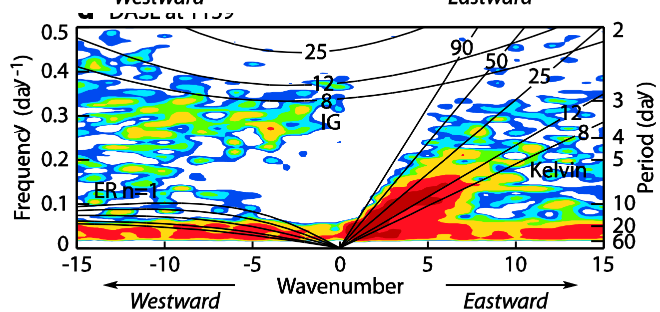












DARE/DEEP ATMOSPHERE-T159

- ✓ T1279 (16 km) FULL AQUA & T159 (125 km) DARE/DEEP ATMOSPHERE

DARE/DEEP ATMOSPHERE

does not hugely distort the deep convection and the large scale flows and allows the thermodynamics and dynamics to naturally interact.

Summary and future work

- By reducing the gravity, the horizontal scale of convection can be increased at will, without necessarily affecting the large-scale flow (Semane and Bechtold, Tellus 2015, will be published this month)

Future work

- Study the transition from parameterized to resolved deep convection in the 1-10km resolution range in a non-hydrostatic mode