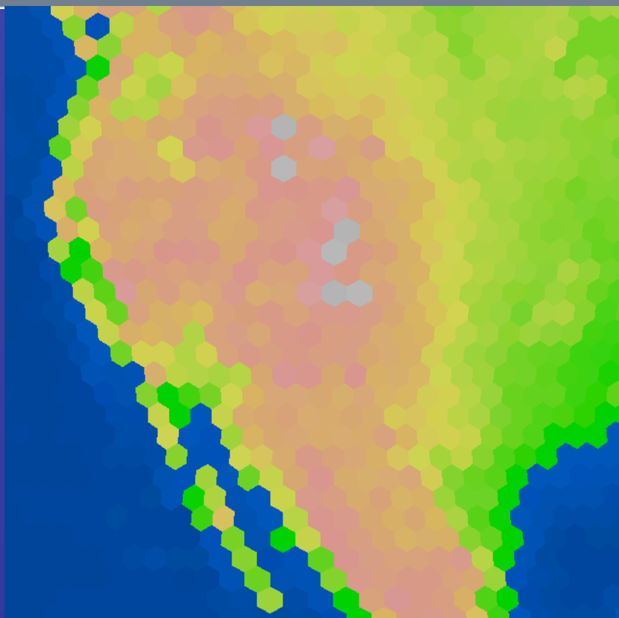
An unified model (dynamics)

Hiroaki Miura

(Colorado Sate University)

A geodesic model



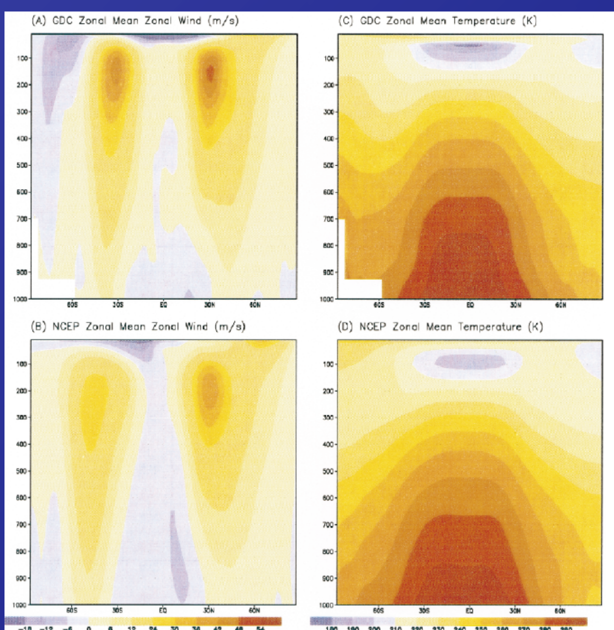
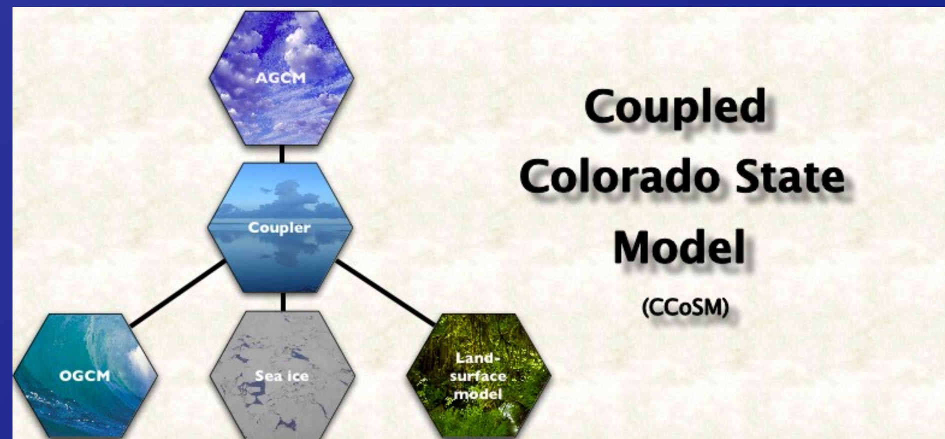
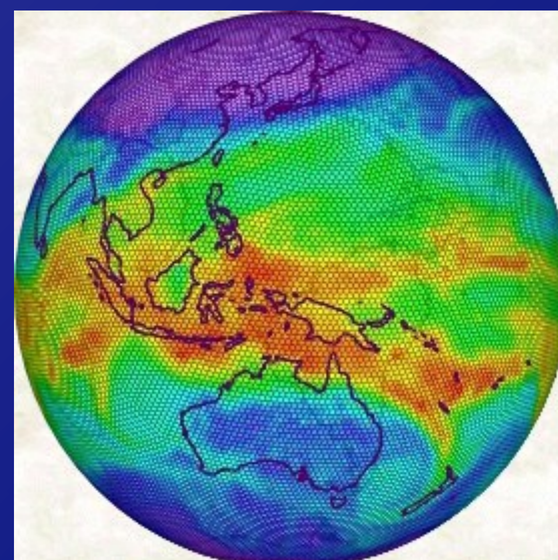


FIG. 9. DJF zonally averaged zonal wind (m s^{-1}) for the (a) GDC–AGCM and (b) NCEP–NCAR reanalysis datasets. DJF zonally averaged temperature (K) for the (c) GDC–AGCM and (d) NCEP–NCAR reanalysis datasets.

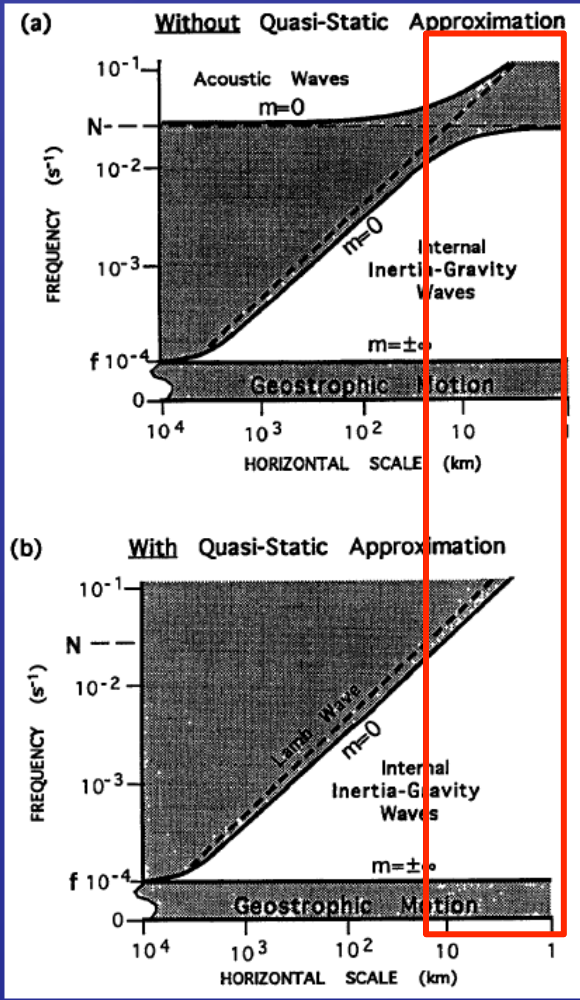
The first geodesic climate model



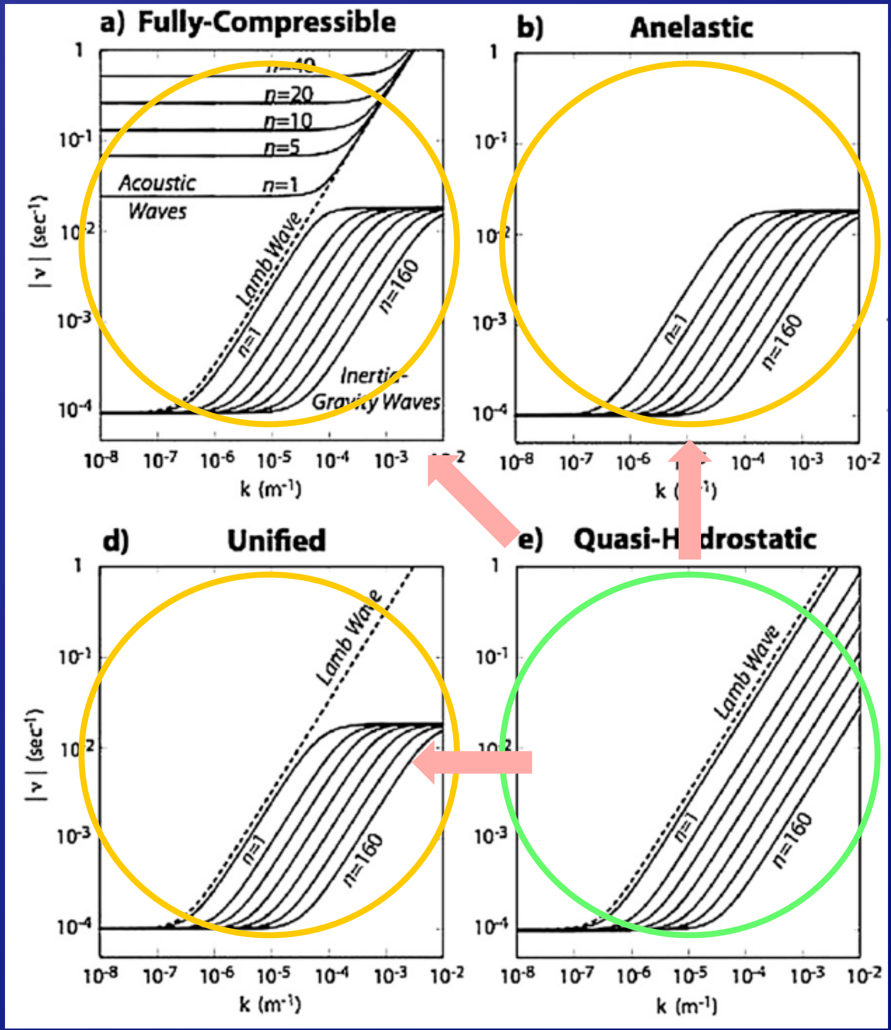


The first geodesic atmosphere model
Ringler et al. (2000)

A need for nonhydrostatic models



Arakawa (1997)



Arakawa and Konor (2009)

Update from hydrostatic to anelastic

Past work:

- Z-grid shallow water model (Heikes and Randall1995)
- Z-grid hydrostatic dynamical core (Ringler et al. 2000) updated to the generalized vertical coordinate (Koner and Heikes 2008)
- An anelastic vector-vorticity model (Jung and Arakawa 2008)

Present work:

- Z-grid nonhydrostatic (anelastic)dynamical core
- An anelastic system of Lipps and Hemler (1982) used by Jung and Arakawa (2008)
- A multigrid 3D Poisson solver developed by Ross

Model equations (vorticity-divergence form):

$$\frac{\partial \delta}{\partial t} = \nabla_h \bullet \left(\eta \nabla_h \psi\right) + \mathbf{J}\left(\eta, \chi\right) - \nabla_h \bullet \left(w \frac{\partial \mathbf{v}_h}{\partial z}\right) - \nabla_h^2 K_h - \nabla_h^2 \left(c_p \theta_0 \pi'\right) + F_\delta$$

$$\frac{\partial \eta}{\partial t} = -\nabla_h \bullet \left(\eta \mathbf{v}_h\right) - \nabla_h \times \left(w \frac{\partial \mathbf{v}_h}{\partial z}\right) + F_\eta$$

$$\frac{\partial w}{\partial t} = -\mathbf{v}_h \bullet \nabla w + g \frac{\theta'}{\theta_0} - \frac{\partial}{\partial z}\left(c_p \theta_0 \pi'\right) + F_w$$

$$\frac{\partial \theta}{\partial t} = -\mathbf{v}_h \bullet \nabla_h \theta - w \frac{\partial \theta}{\partial z} + \frac{Q}{c_p \pi_0} + F_\theta$$

A 3D Poisson's equation needs to be solved to get π':

$$\nabla_h^2 \left(c_p \theta_0 \pi'\right) + \frac{1}{\rho_0} \frac{\partial}{\partial z} \left(\rho_0 \frac{\partial}{\partial z} \left(c_p \theta_0 \pi'\right)\right) = A_\delta + \frac{1}{\rho_0} \frac{\partial}{\partial z} \left(\rho_0 A_w\right)$$

Reference profiles π_0, θ_0, and ρ_0 are needed.

Baroclinic wave test

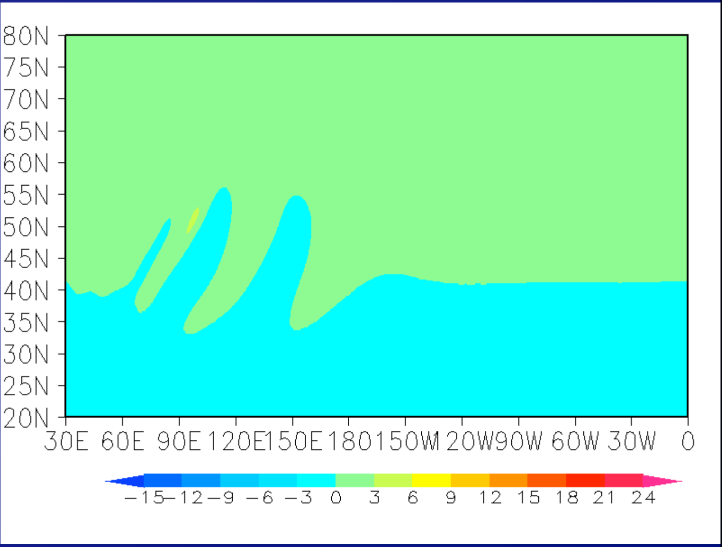
Jablonowski et al. (2008)

- Background fields that satisfy geostrophic and hydrostatic balances
  (thermodynamic field is modified to prevent an initial drift as discussed later.)
- Perturbations of relative vorticity and divergence

Settings:

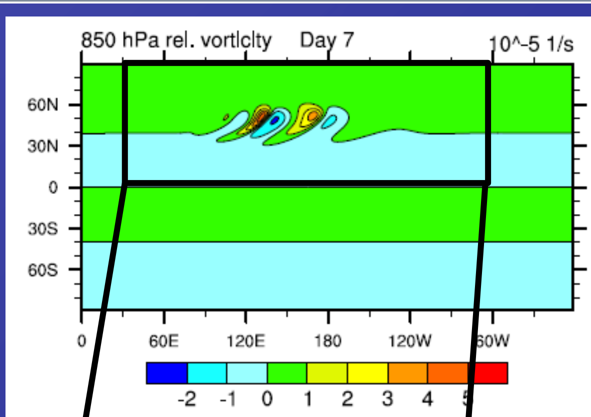
Grid	dx	dz	nz	dt	period
5	240 km	500 m	32	600 s	12 days
6	120 km	500 m	32	300 s	12 days
7	60 km	500 m	32	180 s	12 days
8	30 km	500 m	32	90 s	12 days
9	15 km	500 m	32	45 s	12 days
10	7.5 km	500 m	32	24 s	12 hours
11	3.75 km	500 m	32	12 s	12 hours

Evolution of vorticity for day 6-11 (Grid 8)



Simulations were performed on Franklin (Cray XT4) of NERSC.

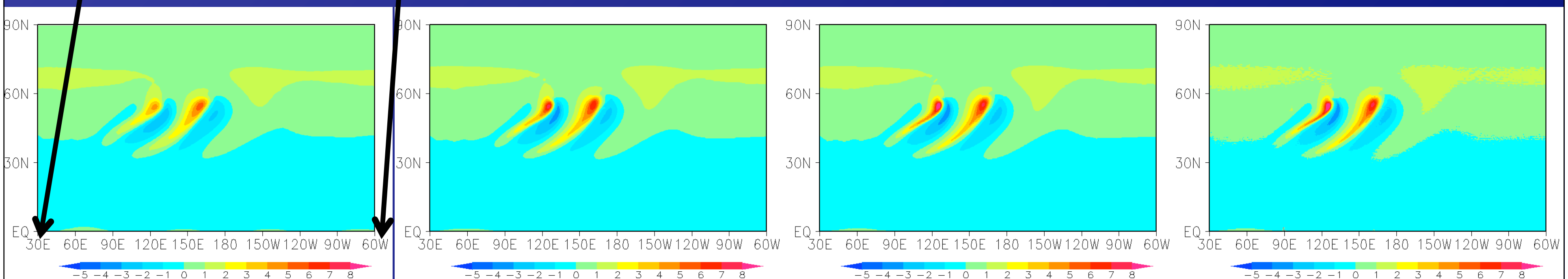
Day 7



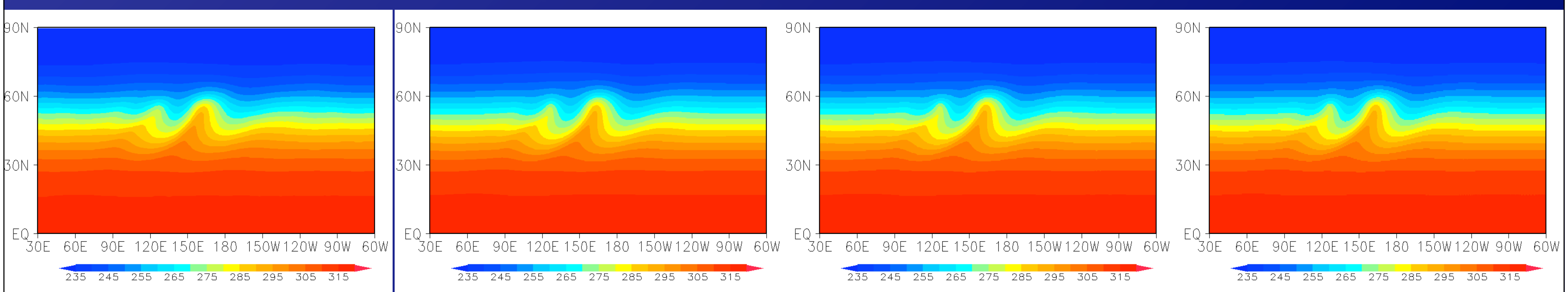
Jablonowski et al. (2008)

Grid 6 (120 km) Grid 7 (60 km) Grid 8 (30 km) Grid 9 (15 km)

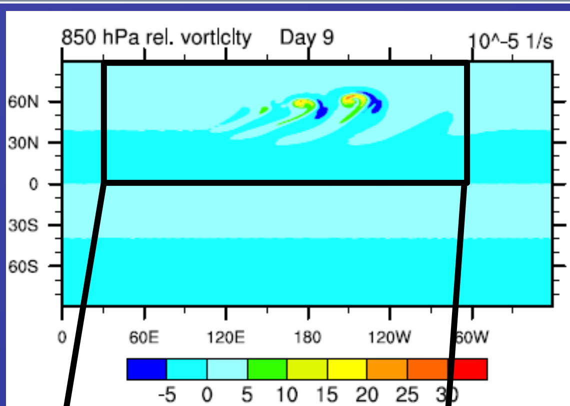
Relative vorticity (1750 m)



Potential temperature (1750 m)



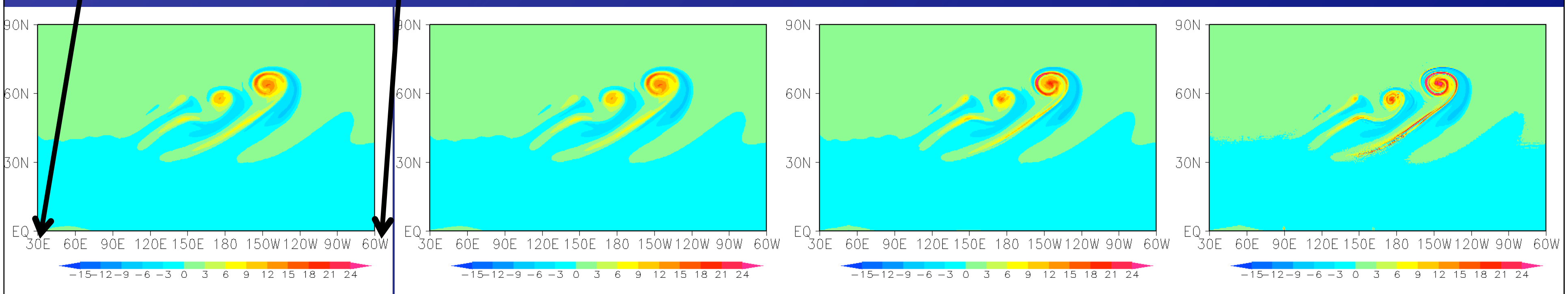
Day 9



Jablonowski et al. (2008)

Grid 6 (120 km) | Grid 7 (60 km) | Grid 8 (30 km) | Grid 9 (15 km)

Relative vorticity (1750 m)



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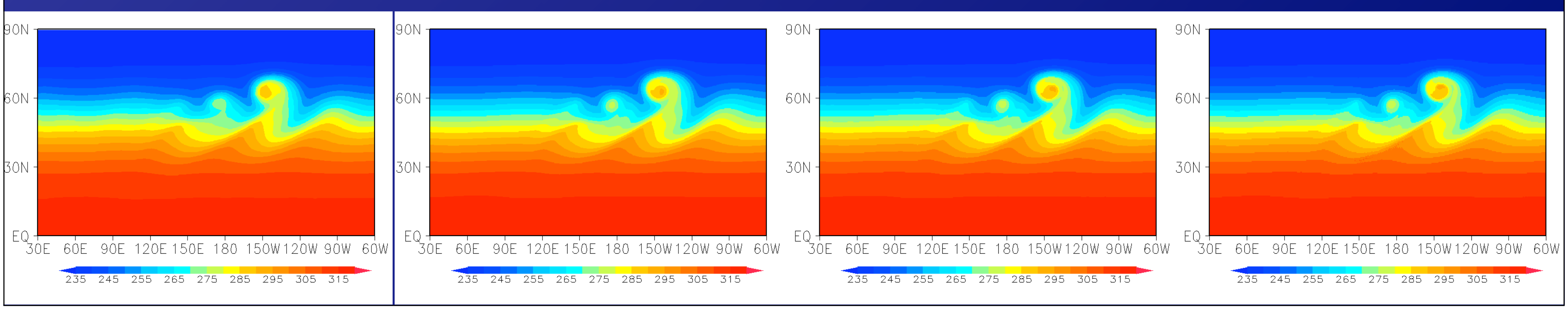


Problem of a hydrostatic balance breaking

The hydrostatic balance to be satisfied in an anelastic model is

$$\frac{\partial}{\partial z}\left(c_p\theta_0\pi'\right)=g\frac{\theta'}{\theta_0}.$$

If an initial field satisfys the hydrostatic balance,

$\pi'=0$ from the definition $\pi'\equiv\pi-\pi_0$.

However, $\theta'(\equiv\theta-\theta_0)\neq 0$ in usual

if the same vertical profile $\theta_0(z)$ is used globally.

Two tentative solutions:

If we assume $\frac{\partial\delta}{\partial t}=0$, we get a 2D Poisson's equation to compute π' that satisfies geostrophic balance:

$$\nabla_h^2\left(c_p\theta_0\pi'\right)=\nabla_h\bullet\left(\eta\nabla_h\psi\right)+\mathbf{J}(\eta,\chi)-\nabla_h\bullet\left(w\frac{\partial\mathbf{v}_h}{\partial z}\right)-\nabla_h^2K_h+F_\delta.$$

Using π' and assuming $\frac{\partial w}{\partial t}=0$ and $w=0$, we can compute θ' that satisfies hydrostatic balance from

$$\frac{\partial}{\partial z}\left(c_p\theta_0\pi'\right)=g\frac{\theta'}{\theta_0}.$$

→ Erro is accumulated in θ'.

By substituting the hydrostatic balance of the deviation parts into the 3D Poisson's equation, we get a 2D Poisson's equation

$$\nabla_h^2\left(c_p\theta_0\pi'\right)=A_\delta+\frac{1}{\rho_0}\frac{\partial}{\partial z}\left(\rho_0A_w\right)-\frac{1}{\rho_0}\frac{\partial}{\partial z}\left(g\rho_0\frac{\theta'}{\theta_0}\right)$$

to compute π'.

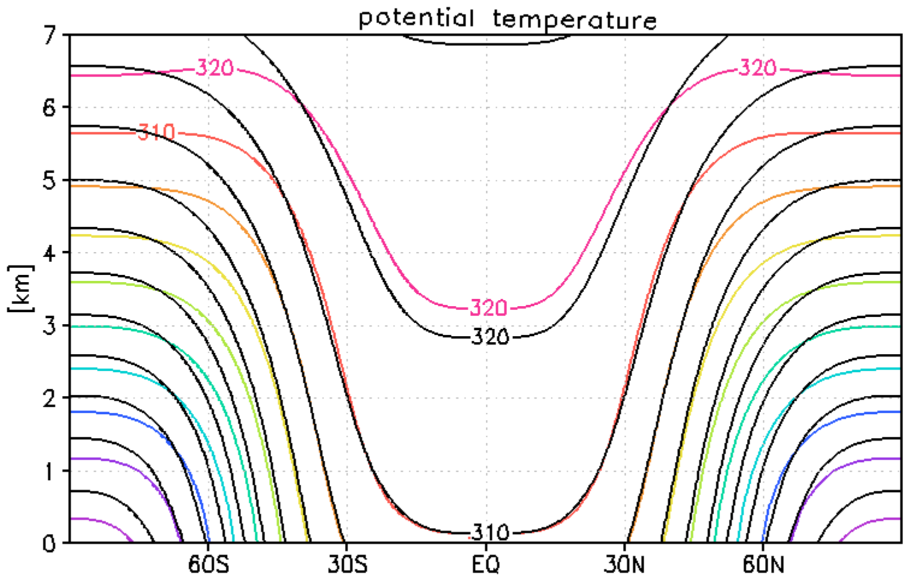
→ Erro is accumulated in π'.

Deformation in a field

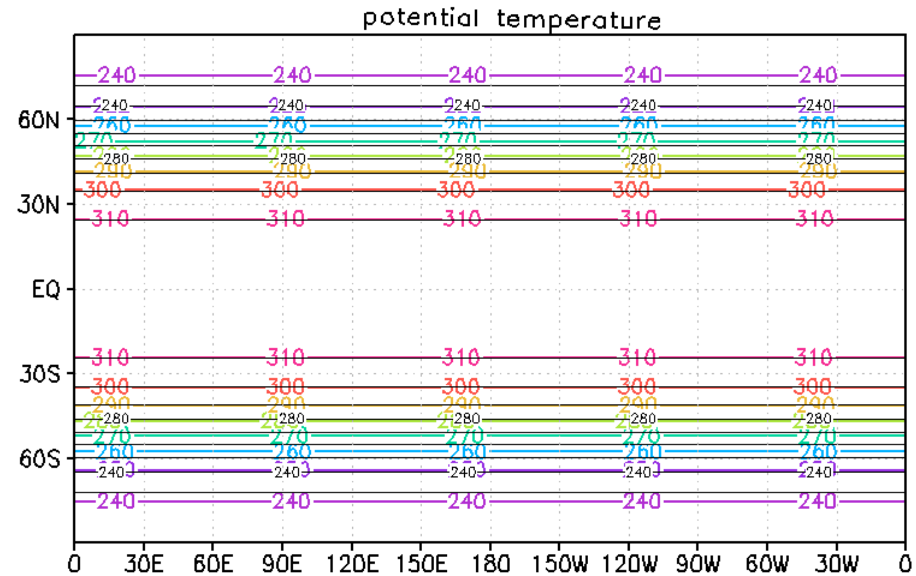
The first method is used to satisfy the hydrostatic balance of the deviation part.

$\theta'(z)$= 300 K is used as the reference profile.

Color: θ given by Jablonowski et al. (2008)
Black: modified θ



Lon = 180



Z = 1750 m

The difference is not large near the equator, but it is significantly large in higher latitudes.

Needs for another nonhydrostatic system

- An anelastic system cannot represent the "realistic" hydrostatic balance globally.
- The reason is that the balanced state depends on the reference profiles.

A question:
Is the anelastic model suitable for climate simulations?

Several concerns:

Because the horizontal and vertical distribution of the mean temperature (or pressure) field changes,

- ➢ behavior of mid-latitudes cyclones changes.
- ➢ moisture distribution changes.
- ➢ cloud distribution changes.

- We need a model that does not use any reference profiles.
- An unified system of Arakawa and Konor (2009) is an attractive choice.

Update from anelastic to unified

"Prognostic" equations (vorticity-divergence form):

$$\frac{\partial \delta}{\partial t} = \nabla_h \bullet (\eta \nabla_h \psi) + \mathbf{J}(\eta, \chi) - \nabla_h \bullet \left(w \frac{\partial \mathbf{v}_h}{\partial z} \right) - \nabla_h^2 K_h - \nabla_h \bullet (c_p \theta \nabla_h \pi_{qs}) - \nabla_h \bullet (c_p \theta \nabla_h \pi') + F_\delta$$

$$\frac{\partial \eta}{\partial t} = -\nabla_h \bullet (\eta \mathbf{v}_h) - \nabla_h \times \left(w \frac{\partial \mathbf{v}_h}{\partial z} \right) - \mathbf{J}(c_p \theta, \pi_{qs}) + F_\eta$$

$$\frac{\partial w}{\partial t} = -\mathbf{v}_h \bullet \nabla w - c_p \theta \frac{\partial \pi}{\partial z} + F_w$$

$$\frac{\partial \theta}{\partial t} = -\mathbf{v}_h \bullet \nabla_h \theta - w \frac{\partial \theta}{\partial z} + \frac{Q}{c_p \pi} + F_\theta$$

$$\frac{\partial \pi_{qs,sfc}}{\partial t} = \frac{1}{(p_{qs}/\pi_{qs})_{sfc} - (p_{qs}/\pi_{qs})_{top}} \left[(p_{qs}/\pi_{qs})_{top} \int_{z_{sfc}}^{z_{top}} \frac{g}{c_p \theta^2} \frac{\partial \theta}{\partial t} dz - \kappa g \int_{z_{sfc}}^{z_{top}} \nabla_h \bullet (\rho_{qs} \mathbf{v}_h) dz \right]$$

AB3 (blue boxes)

Forward (implicit) (red boxes)

Diagnostic equations:

$$\frac{\partial \pi_{qs}}{\partial z} \equiv -\frac{g}{c_p \theta}, \quad \pi_{qs} = \pi_{qs,sfc} - \int_{z_{sfc}}^{z} \frac{g}{c_p \theta} dz$$

$$p_{qs} \equiv p_{00} \pi_{qs}^{1/\kappa}$$

$$\frac{\partial p_{qs}}{\partial z} \equiv -\rho_{qs} g$$

1. Potential temperature and quasi-static exner function (surface) is predicted.
2. Quasi-static vertical profile is diagnosed.
3. Deviation part of exner function is diagnosed so that the system is soundproof.
4. Vorticity, divergence and vertical velocity is "predicted."

Diagnosis of deviation part of exner function

We require that $\frac{\partial \rho_{qs}}{\partial t} = -\nabla \bullet (\rho_{qs} \mathbf{V})$ is satisfied every time step.

About an update from a time level n to $n+1$, we descretize the above equation as

$$\frac{\rho_{qs}^{n+1} - \rho_{qs}^{n}}{\Delta t} = -\left(v \bullet \nabla \rho_{qs}\right)^{*} - \rho_{qs}^{n+1} \delta^{n+1}.$$

Then we get the following Poisson's equation :

$$\nabla_h \bullet \left(c_p \theta^n \nabla_h \pi'^n\right) + \frac{\partial}{\partial z}\left(c_p \theta^n \frac{\partial \pi'^n}{\partial z}\right) =$$

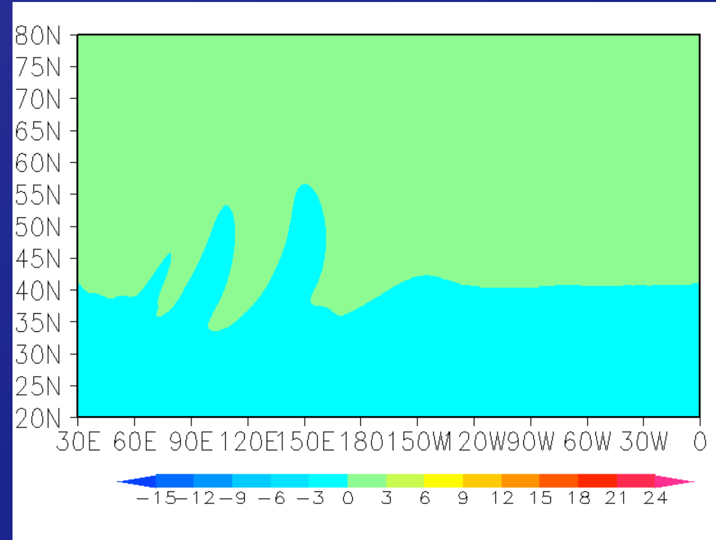
$$\frac{1}{\Delta t}\left[\left(\delta^n + A_\delta^n \Delta t\right) + \frac{\partial}{\partial z}\left(w^n + A_w^n \Delta t\right) + \left\{\frac{\rho_{qs}^{n+1} - \rho_{qs}^{n}}{\Delta t} + \left(v \bullet \nabla \rho_{qs}\right)^{*}\right\}\right]$$

Technically, we need to modify the linear operator assumed in the multi-grid solver from Jacobian to Flux-divergence.

Jablonowski test

Unified

Grid	dx	dz	nz	dt	period
5	240 km	500 m	32	600 s	12 days
6	120 km	500 m	32	300 s	12 days
7	60 km	500 m	32	150 s	12 days
8	30 km	500 m	32	75 s	12 days
9	15 km	500 m	32	36 s	12 days
10	7.5 km	500 m	32	18 s	12 hours
11	3.75 km	500 m	32	9 s	12 hours



Anelastic

Grid	dx	dz	nz	dt	period
5	240 km	500 m	32	600 s	12 days
6	120 km	500 m	32	300 s	12 days
7	60 km	500 m	32	180 s	12 days
8	30 km	500 m	32	90 s	12 days
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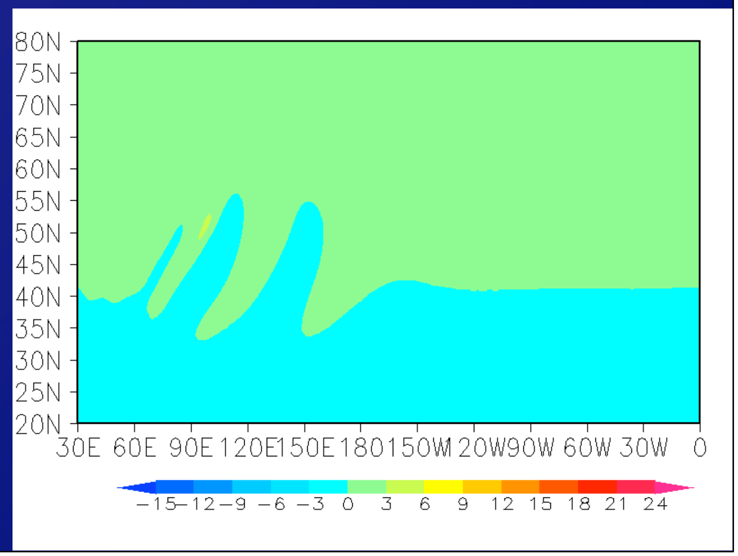
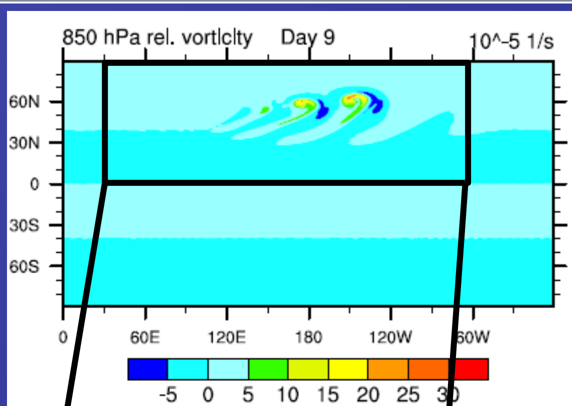


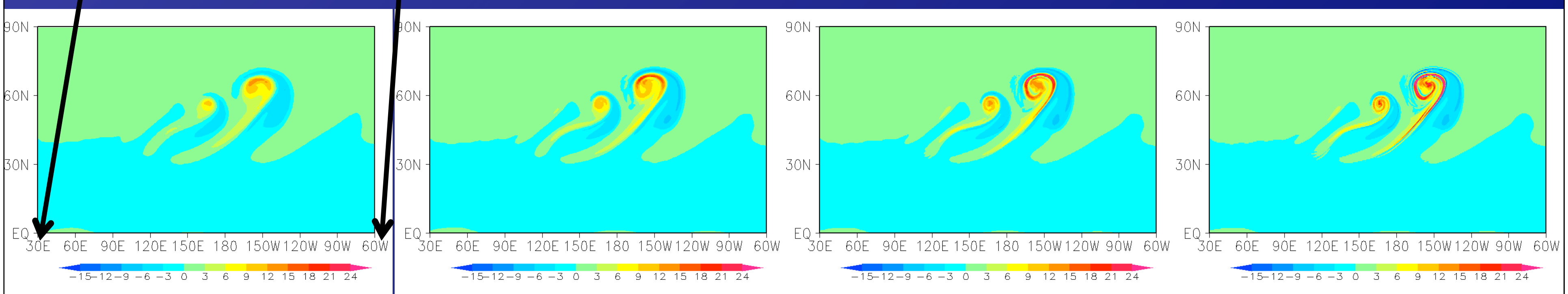
Results



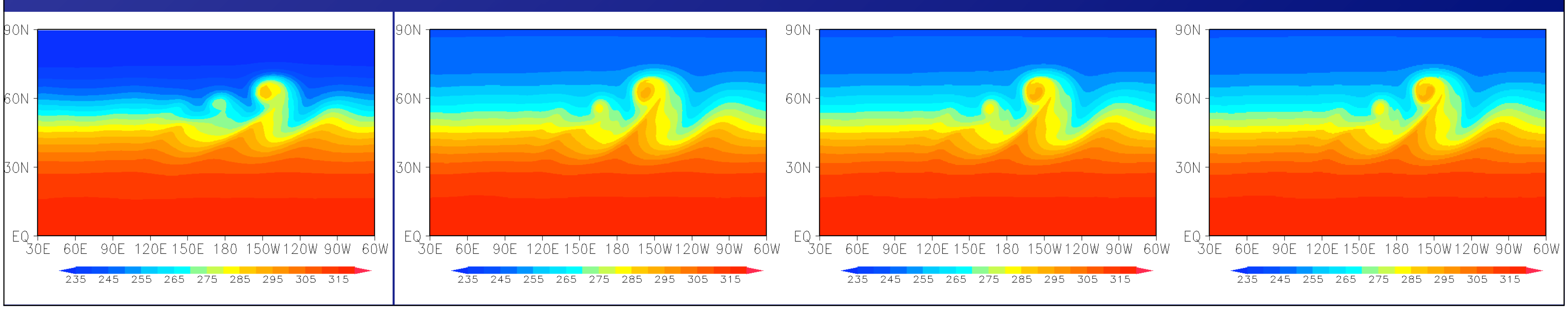
Jablonowski et al. (2008)

Grid 6 (120 km) Grid 7 (60 km) Grid 8 (30 km) Grid 9 (15 km)

Relative vorticity (1750 m)



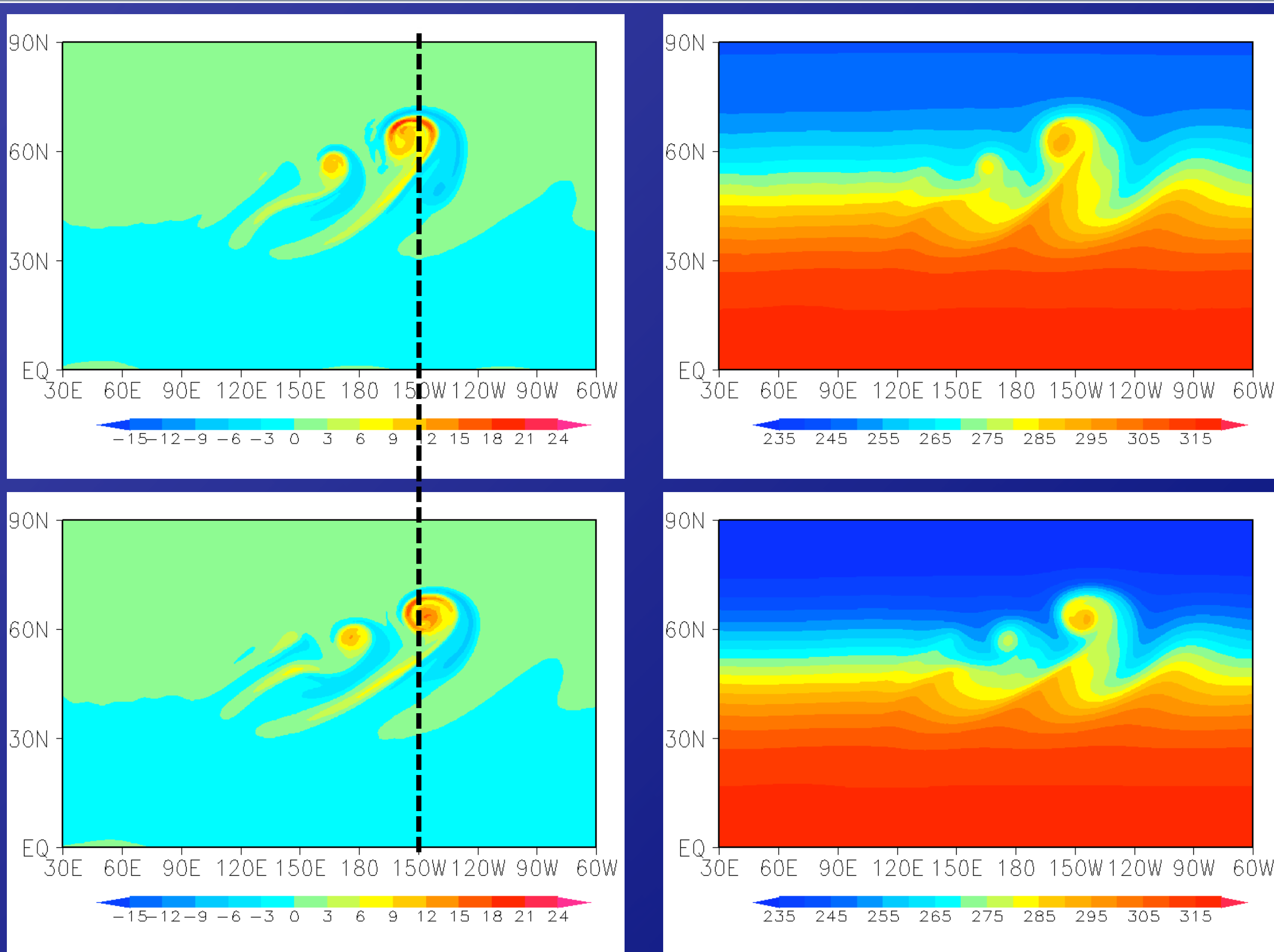
Potential temperature (1750 m)



Unified vs. Anelastic

Unified

Anelastic



Faster propagation of a cyclone and smaller potential temperature advection in aneastic than in unified.

Computing speed

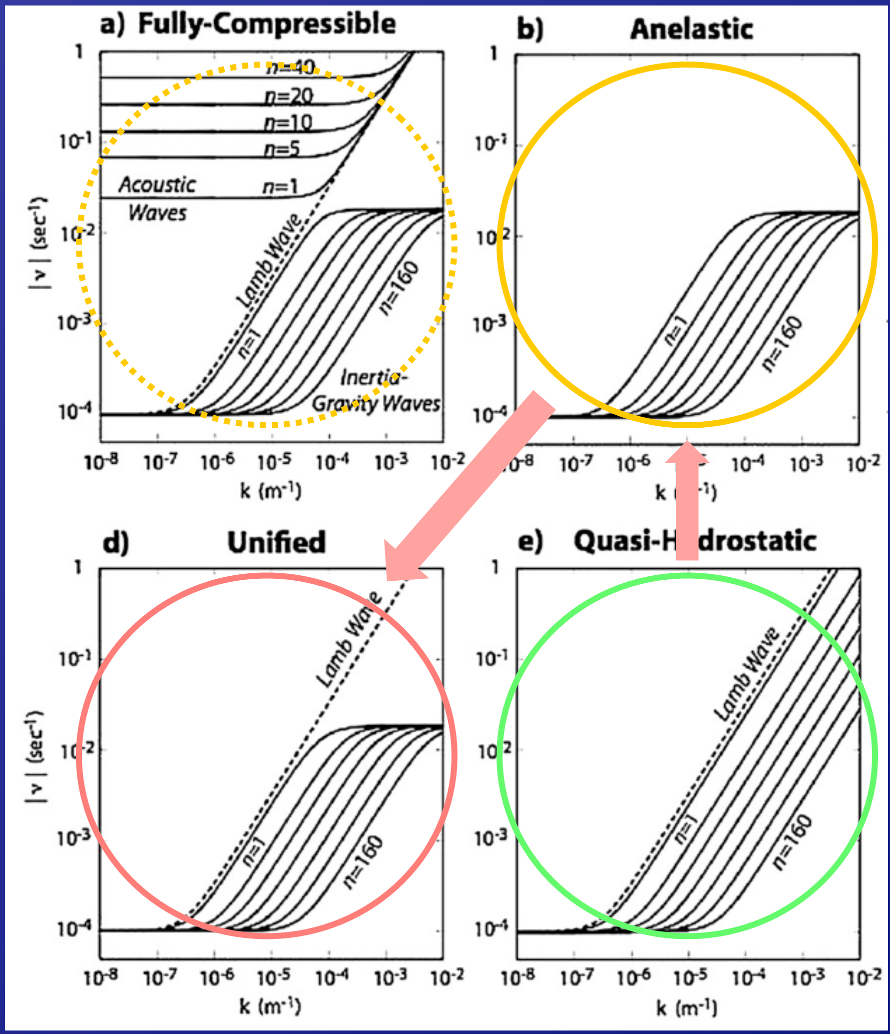
Grid	PEs (Nodes)	GFlop/sec	Time (sec/day)
5	40 (10)	5.62568 (6.1 %)	35.0308
6	160 (40)	18.1987 (4.9 %)	84.9001
7	640 (160)	63.8086 (4.3 %)	190.9769
8	2560 (640)	171.023 (2.9 %)	566.8823
9	2560 (640)	351.833 (6.0 %)	2287.4747
10	5120 (1280)	696.341 (5.9 %)	*9225.4175
11	10240 (2560)	1406.80 (6.0 %)	*37090.7180

over 1 TFlop/sec

*Estimates from a 12-hours simulation

Performance is a rate against 9.2 GFlop/sec * nodes

Summary



Arakawa and Konor (2009)