Reference Stratification Subtraction (RSS) in the Community Atmosphere Model (CAM) Spectral Dynamical Core

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Motivation

Reference Stratification Subtraction (RSS) can reduce the model numerical errors, especially the errors in calculating the pressure gradient force over steep slopes in terrain-following coordinate (Zeng, 1963). The RSS method with different versions has been implemented in many weather forecasting and climate models (e.g. ECMWF IFS, FGOLAS, BCC-CSM, IAP-AGCM, AREM).

Dynamical core

$$T_v = T^r(p) + T_v^p$$
$$\Phi = \Phi^r(p) + \Phi^p$$

$$\frac{d\Phi^r(p)}{d\ln p} = -RT^r(p)$$

Reference atmosphere + Perturbation atmosphere

(e.g. hydrostatic balance)

$$\nabla_p^2\Phi = \nabla_\sigma\cdot(\underbrace{\nabla_\sigma\Phi + RT_v\nabla_\sigma}_{\text{subtraction between two large terms}}\ln p_s)$$

$$\nabla_p^2\Phi = \nabla_\sigma\cdot(\cancel{\nabla_\sigma\Phi^r} + \cancel{RT^r}\nabla_\sigma\ln p_s) + \nabla_\sigma\cdot(\nabla_\sigma\Phi^p + RT_v^p\nabla_\sigma\ln p_s)$$

Numerical Test Cases

1) Impact of orography on a non-rotating steady-state (DCMIP 2012: 2-0-x)
   - Evaluate the accuracy of pressure gradient calculation after introducing RSS
   - Hydrostatic scale, oscillated terrain, without Earth's rotation (omega=0)
2) Propagation of gravity waves (DCMIP 2008: 6-0-0)
   - Evaluate the simulation of the propagation of pure internal gravity waves
   - No terrain, without Earth's rotation (omega=0)
3) Held-Suarez forcing experiments (Held and Suarez, 1994)
   - Evaluate model stability and convergence over a long-term time integration
   - No terrain, idealized symmetric heating and linear friction
4) Aqua-planet experiments (Neale and Hoskins, 2001)
   - Comprehensive evaluation of model dynamics and physics coupling
   - Full physics, no terrain, no land; fixed zenith angle, CO_2, O_3; "control" SST distribution

Implementation of RSS in CAM3.0 Eulerian Spectral Dynamical Core

CAM3.0

$$\begin{cases}
\dfrac{\partial\zeta}{\partial t} = \dfrac{1}{a(1-\mu^2)}\dfrac{\partial n_v}{\partial\lambda} - \dfrac{1}{a}\dfrac{\partial n_u}{\partial\mu} + H_\zeta \\
\dfrac{\partial\delta}{\partial t} = \dfrac{1}{a(1-\mu^2)}\dfrac{\partial n_u}{\partial\lambda} + \dfrac{1}{a}\dfrac{\partial n_v}{\partial\mu} - \nabla^2(E+\Phi) + H_\delta \\
\dfrac{\partial T}{\partial t} = -\dfrac{1}{a(1-\mu^2)}\dfrac{\partial(TU)}{\partial\lambda} - \dfrac{1}{a}\dfrac{\partial(TV)}{\partial\mu} + T\delta - \dot\eta\dfrac{\partial p}{\partial\eta}\dfrac{\partial T}{\partial p} + \dfrac{RT_v}{c_p^*}\left(\dfrac{\omega}{p}\right) + Q + F_T + H_T \\
\dfrac{\partial\ln p_s}{\partial t} = -\displaystyle\int_{(\eta_t)}^{(1)}(\vec V\cdot\nabla_\eta\ln p_s)d\left(\dfrac{\partial p}{\partial p_s}\right) - \dfrac{1}{p_s}\int_{p(\eta_t)}^{p(1)}\delta dp \\
\dfrac{\partial\Phi}{\partial\ln p} = -RT_v
\end{cases}$$

Where,

$$n_u = (\zeta+f)V - \dot\eta\frac{\partial p}{\partial\eta}\frac{\partial U}{\partial p} - \frac{RT_v}{a}\frac{p_s}{p}\frac{\partial p}{\partial p_s}\frac{\partial\ln p_s}{\partial\lambda} + F_U$$

$$n_v = -(\zeta+f)U - \dot\eta\frac{\partial p}{\partial\eta}\frac{\partial V}{\partial p} - \frac{RT_v}{a}\frac{p_s}{p}\frac{\partial p}{\partial p_s}(1-\mu^2)\frac{\partial\ln p_s}{\partial\mu} + F_V$$

Diagnostic equations:

$$\omega = \frac{\partial p}{\partial p_s}p_s(\vec V\cdot\nabla_\eta\ln p_s) - p_s\int_{(\eta_t)}^{(\eta)}(\vec V\cdot\nabla_\eta\ln p_s)d\left(\frac{\partial p}{\partial p_s}\right) - \int_{p(\eta_t)}^{p(\eta)}\delta dp$$

$$\dot\eta\frac{\partial p}{\partial\eta} = \frac{\partial p}{\partial p_s}\left[p_s\int_{(\eta_t)}^{(1)}(\vec V\cdot\nabla_\eta\ln p_s)d\left(\frac{\partial p}{\partial p_s}\right) + \int_{p(\eta_t)}^{p(1)}\delta dp\right] - \left[p_s\int_{(\eta_t)}^{(\eta)}(\vec V\cdot\nabla_\eta\ln p_s)d\left(\frac{\partial p}{\partial p_s}\right) + \int_{p(\eta_t)}^{p(\eta)}\delta dp\right]$$

RSS

$$\begin{cases}
\dfrac{\partial\zeta}{\partial t} = \dfrac{1}{a(1-\mu^2)}\dfrac{\partial n_v^p}{\partial\lambda} - \dfrac{1}{a}\dfrac{\partial n_u^p}{\partial\mu} + H_\zeta \\
\dfrac{\partial\delta}{\partial t} = \dfrac{1}{a(1-\mu^2)}\dfrac{\partial n_u^p}{\partial\lambda} + \dfrac{1}{a}\dfrac{\partial n_v^p}{\partial\mu} - \nabla^2(E+\Phi^p) + H_\delta \\
\dfrac{\partial T^p}{\partial t} = -\dfrac{1}{a(1-\mu^2)}\dfrac{\partial(T^pU)}{\partial\lambda} - \dfrac{1}{a}\dfrac{\partial(T^pV)}{\partial\mu} + T^p\delta - \dot\eta\dfrac{\partial p}{\partial\eta}\dfrac{\partial T^p}{\partial p} + \dfrac{RT_v^p}{c_p^*}\left(\dfrac{\omega}{p}\right) + \left(\dfrac{RT^r}{c_p^*} - p\dfrac{\partial T^r}{\partial p}\right)\left(\dfrac{\omega}{p}\right) + Q + F_T + H_T \\
\dfrac{\partial(\ln p_s)^p}{\partial t} = -\displaystyle\int_{(\eta_t)}^{(1)}\vec V\cdot\nabla_\eta[\ln(p_s^r) + (\ln p_s)^p]d\left(\dfrac{\partial p}{\partial p_s}\right) - \dfrac{1}{p_s}\int_{p(\eta_t)}^{p(1)}\delta dp \\
\dfrac{\partial\Phi^p}{\partial\ln p} = -RT_v^p;\quad \dfrac{\partial\Phi^r}{\partial\ln p} = -RT^r
\end{cases}$$

Where,

$$n_u^p = (\zeta+f)V - \dot\eta\frac{\partial p}{\partial\eta}\frac{\partial U}{\partial p} - \frac{RT_v^p}{a}\frac{p_s}{p}\frac{\partial p}{\partial p_s}\left[\frac{\partial\ln p_s^r}{\partial\lambda} + \frac{\partial(\ln p_s)^p}{\partial\lambda}\right] + F_U$$

$$n_v^p = -(\zeta+f)U - \dot\eta\frac{\partial p}{\partial\eta}\frac{\partial V}{\partial p} - \frac{RT_v^p}{a}\frac{p_s}{p}\frac{\partial p}{\partial p_s}(1-\mu^2)\left[\frac{\partial\ln p_s^r}{\partial\mu} + \frac{\partial(\ln p_s)^p}{\partial\mu}\right] + F_V$$

Diagnostic equations:

$$\omega = \frac{\partial p}{\partial p_s}p_s(\vec V\cdot\nabla_\eta[\ln p_s^r + (\ln p_s)^p]) - p_s\int_{(\eta_t)}^{(\eta)}\vec V\cdot\nabla_\eta[\ln p_s^r + (\ln p_s)^p]d\left(\frac{\partial p}{\partial p_s}\right) - \int_{p(\eta_t)}^{p(\eta)}\delta dp$$

$$\dot\eta\frac{\partial p}{\partial\eta} = \frac{\partial p}{\partial p_s}\left[p_s\int_{(\eta_t)}^{(1)}\vec V\cdot\nabla_\eta[\ln p_s^r + (\ln p_s)^p]d\left(\frac{\partial p}{\partial p_s}\right) + \int_{p(\eta_t)}^{p(1)}\delta dp\right] - \left[p_s\int_{(\eta_t)}^{(\eta)}\vec V\cdot\nabla_\eta[\ln p_s^r + (\ln p_s)^p]d\left(\frac{\partial p}{\partial p_s}\right) + \int_{p(\eta_t)}^{p(\eta)}\delta dp\right]$$

Numerical Results

1) Steady flow over oscillated terrain

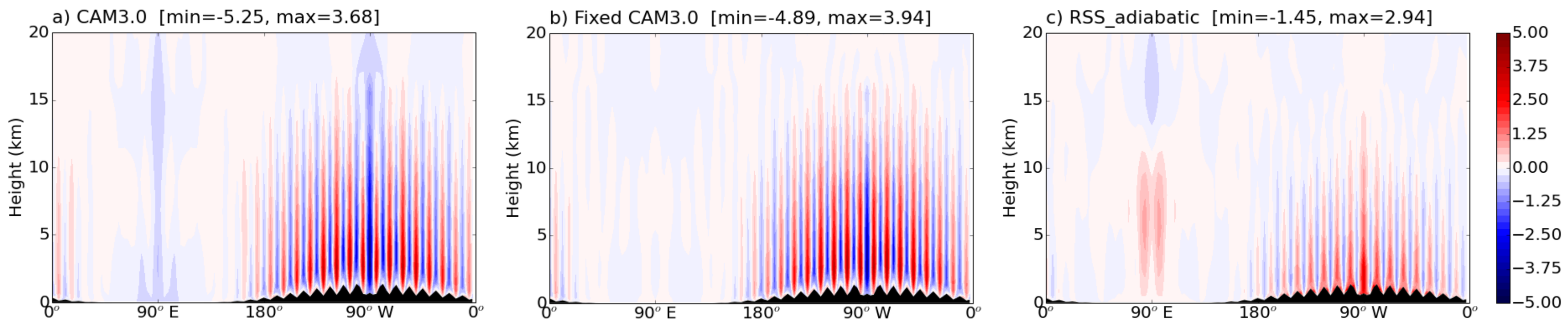


Figure 1. Height-longitudinal cross section of the vertical pressure velocity (shaded, unit: 10^{-2} Pa s^{-1}) along the equator at day 6, with the orography being masked with black color.

- RSS_adiabatic scheme is numerically stable, but the RSS_Wu08 is unstable for this test case;
- Fixing the bugs in CAM3.0 helps little, but the RSS can reduce the numerical errors effectively.

2) Propagation of pure internal gravity waves

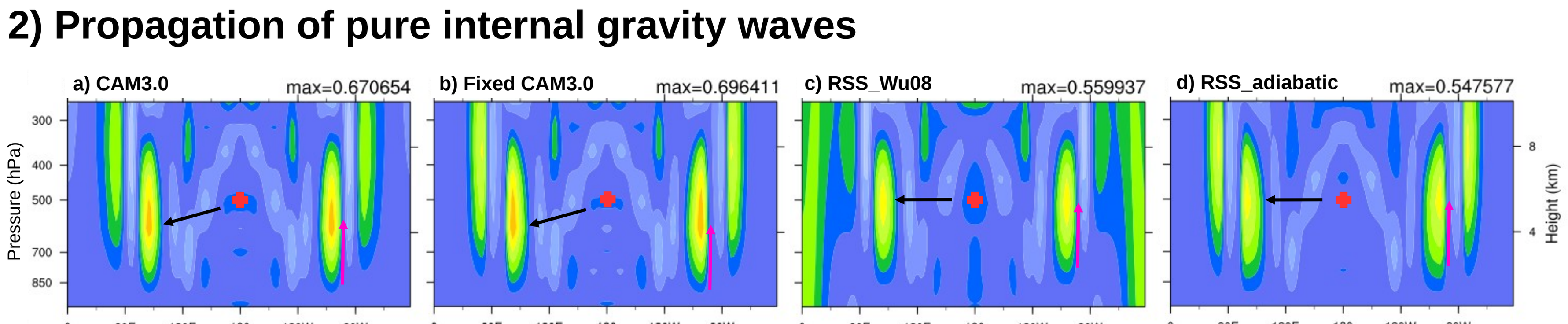


Figure 2. Pressure-longitudinal cross section of the perturbed potential temperature (unit: K) along the equator at day 4. Red crosses represent the initial heating centers.

- The RSS scheme produces a sharper pattern of leading gravity waves (wave dispersion);
- CAM3.0 simulates a slightly downward propagation of gravity waves, while introducing the RSS scheme causes the wave propagation to be more parallel with the ground.

3) Held-Suares forcing

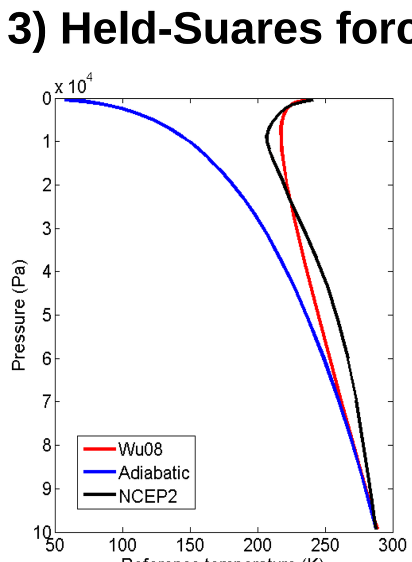


Figure 3. Profiles of the reference atmospheres

Stable:
- Wu08

Unstable:
- Adiabatic
- NCEP2

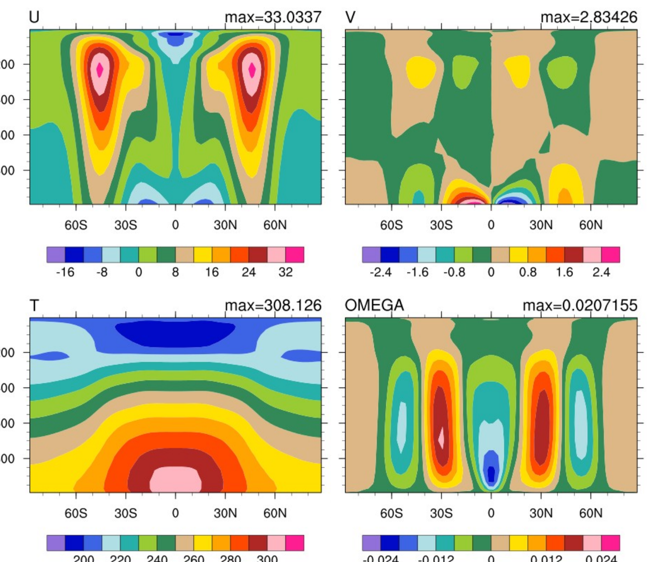
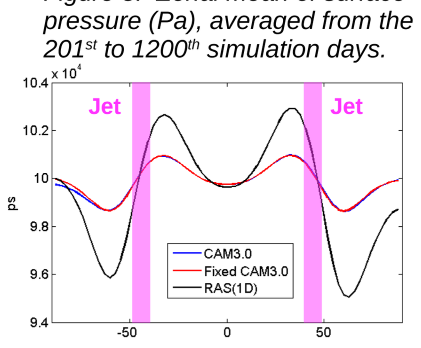


Figure 4. Zonal mean of zonal and meridional wind (m s^{-1}), temperature (K), and vertical velocity (Pa s^{-1}), averaged from 201^{st} to 1200^{th} simulation days of CAM3.

Figure 5. Zonal mean of surface pressure (Pa), averaged from the 201^{st} to 1200^{th} simulation days.



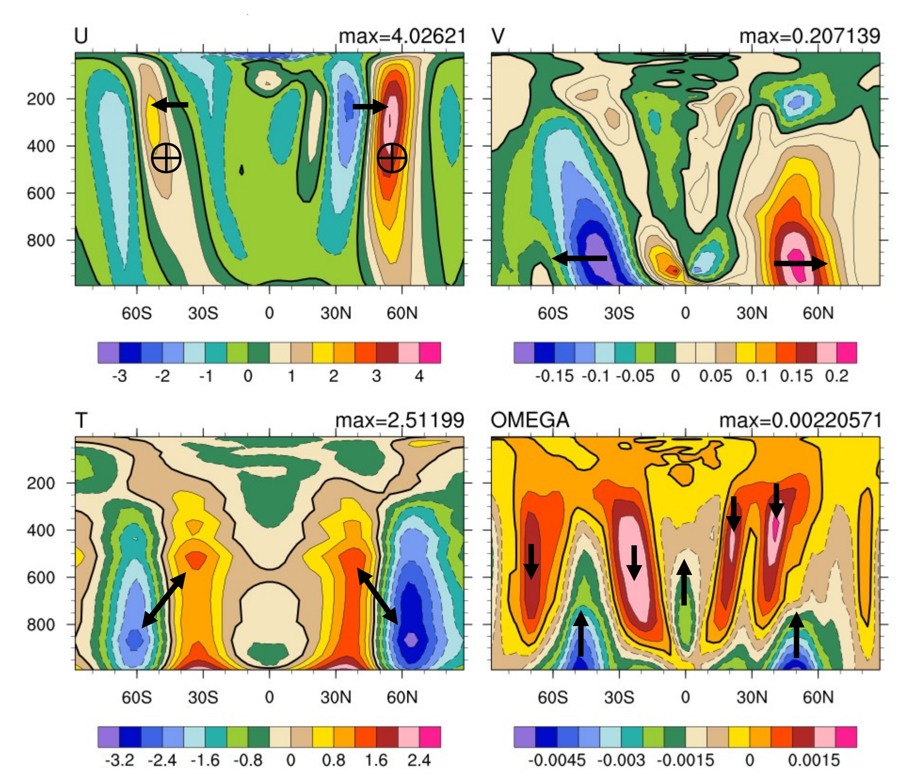


Figure 6. Differences between RSS_Wu08 and CAM3.0 on zonal mean zonal and meridional wind (m s^{-1}), tempera-ture (K), and vertical velocity (Pa s^{-1}).

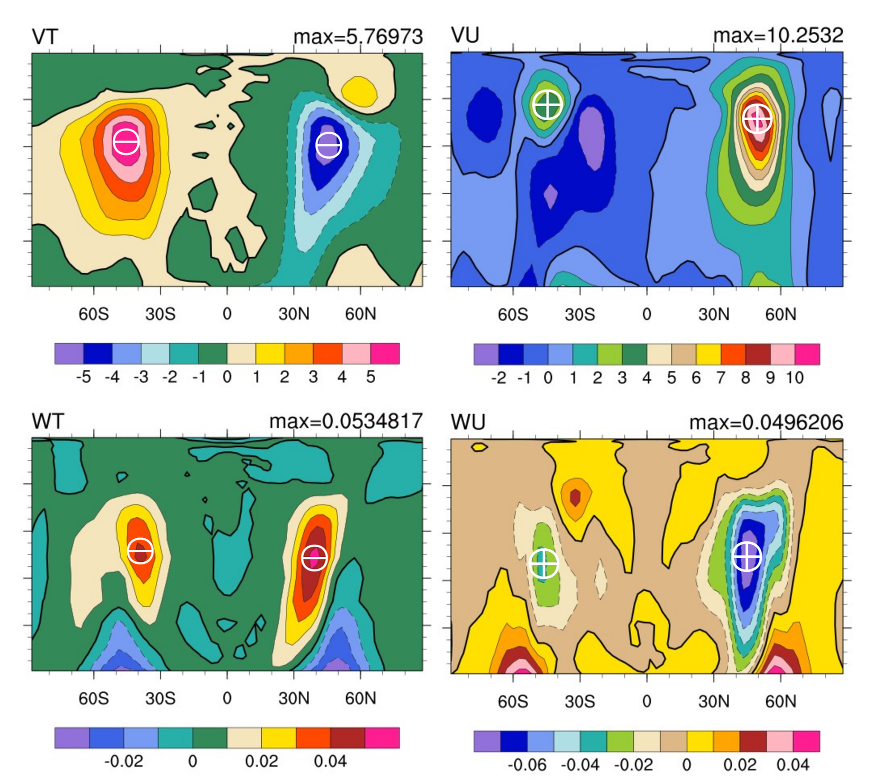


Figure 7. The same as Figure 6, but for meridional heat (K m s^{-1}) and momentum (m^2 s^{-2}) transport; vertical heat (K Pa s^{-1}) and moment (m Pa s^{-2}) transport.

4) Aqua-Planet Experiments (APEs)

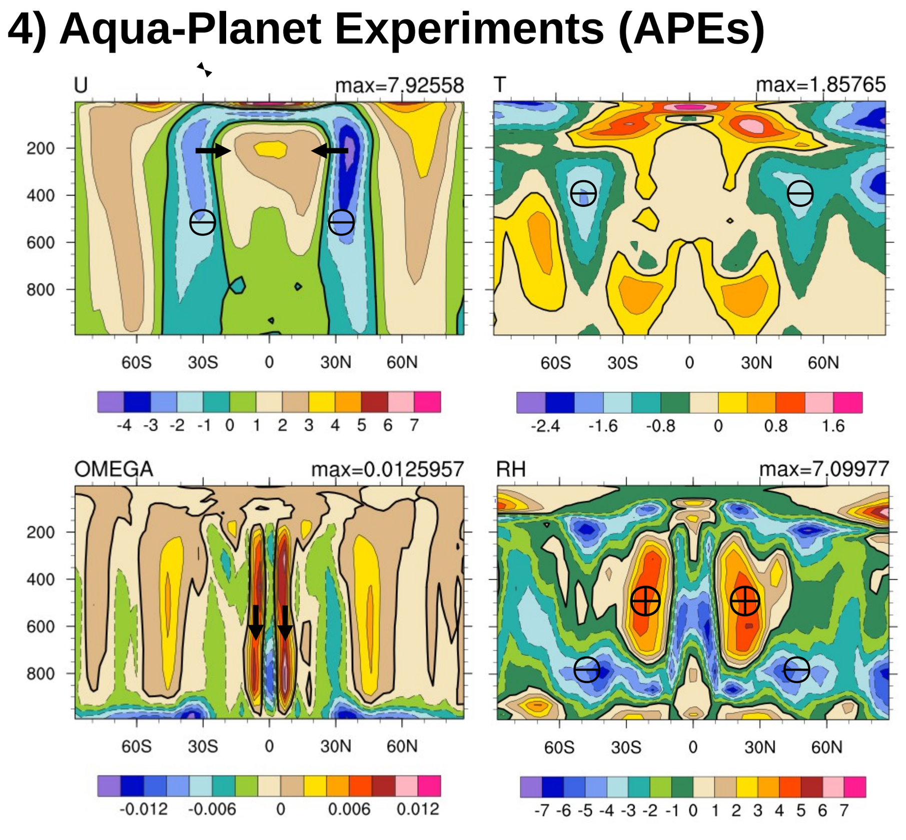


Figure 8. Differences between RSS_Wu08 and CAM3.0 on zonal mean zonal wind (m s^{-1}), vertical velocity (Pa s^{-1}), tempera-ture (K), and relative humidity (%).

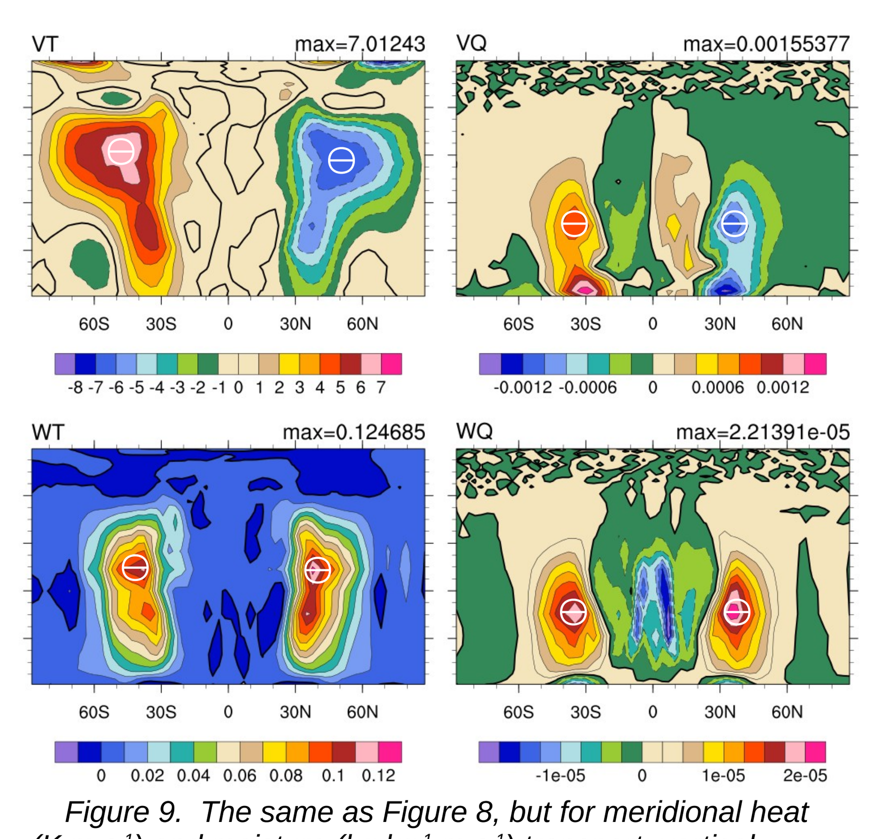


Figure 9. The same as Figure 8, but for meridional heat (K m s^{-1}) and moisture (kg kg^{-1} m s^{-1}) transport; vertical heat (K Pa s^{-1}) and moisture (kg kg^{-1} Pa s^{-1}) transport.

Dry dynamical core

- RSS causes stronger baroclinicity and mid-latitude jets (consistent with Zhang et al., 2013);
- The above changes are corresponding with weaker poleward eddy heat transport and stronger poleward eddy momentum transport, respectively.

Physics coupled dynamical core

- RSS causes weaker subtropical jets and equatorial shifts (consistent with Wu et al., 2008);
- RSS causes dryer atmosphere at middle/low level over tropics/subtropics;
- Being associated with weaker poleward eddy heat, momentum, and moisture transport.

Main References

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