# A numerical sink of axial angular momentum in CAM-FV

**Thomas Toniazzo, Peter Lauritzen, Christiane Jablonowski, Mats Bentsen, Helge Drange, Trond Iversen**

**AMWG meeting, Boulder 9 Februrary 2016**

# CAM-FV likes easterlies

Held and Suarez (1994) high-top simulations by Yao and Jablonowski (2015) with CAM and different dycores shows peculiarity of FV case.

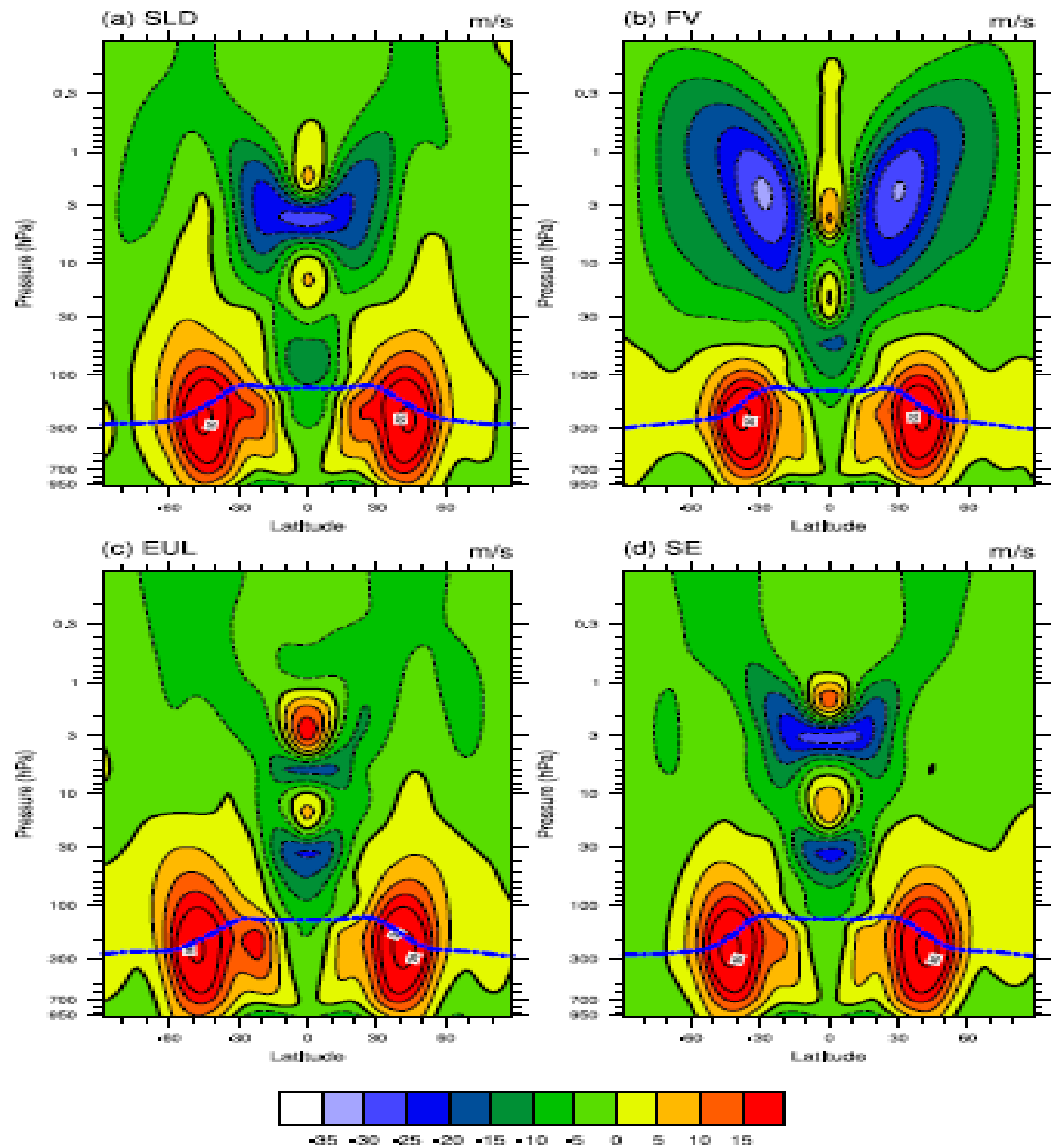
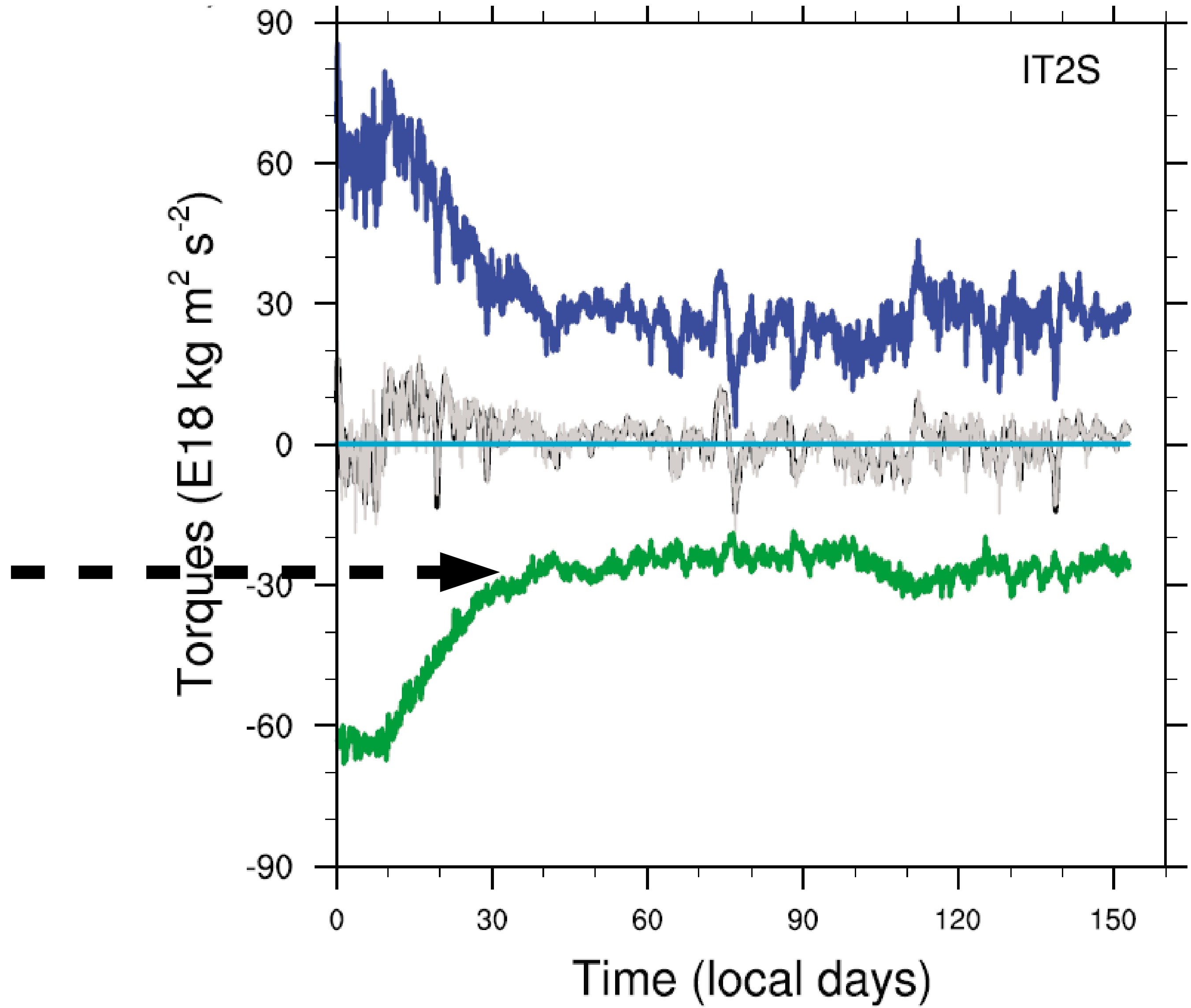



FIG. 3. Pressure–latitude cross sections of the monthly-mean zonal-mean zonal wind for (a) SLD, (b) FV, (c) EUL, and (d) SE. A single month is depicted. The blue line indicates the position of the tropopause; the zero wind line is enhanced.

# CAM, superrotation and Titan

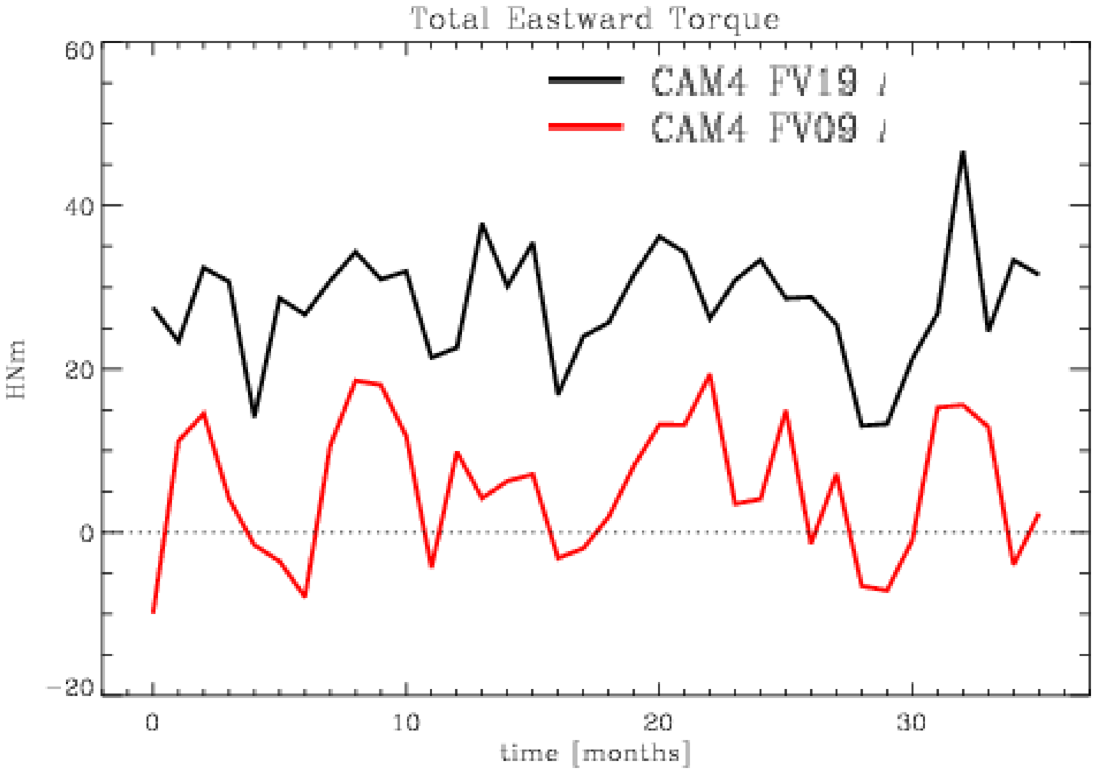
**Lebonnois et al. 2012, JGR 117/E12004**

**Lauritzen et al. 2014, J.Adv.Model.Earth Syst. 6/129**




residual sources and sinks [...] may be much larger than the AAM conservation errors, but their difference, which is crucial for circulation build-up, is not. In the case of

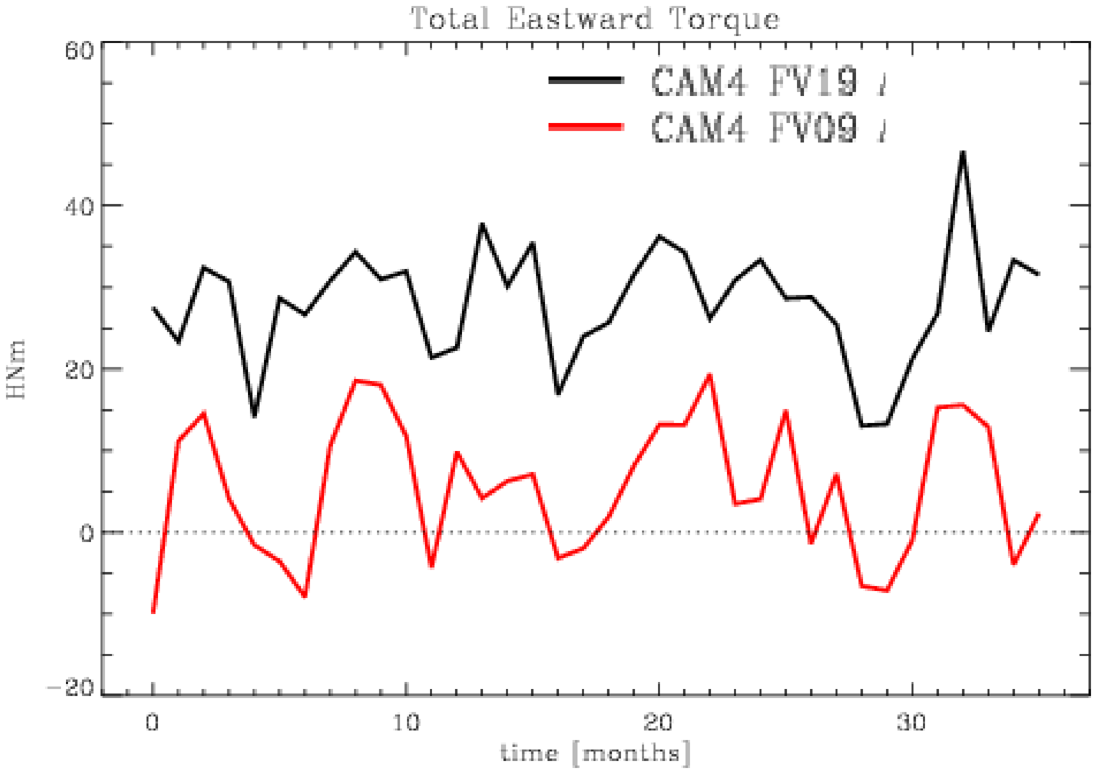
# CAM FV and angular momentum




**CAM (4/5) FV dycore appears not to conserve momentum at 1.9x2.5 degree resolution**

**Going to 0.9x1.25 degrees, the problem seems mitigated**

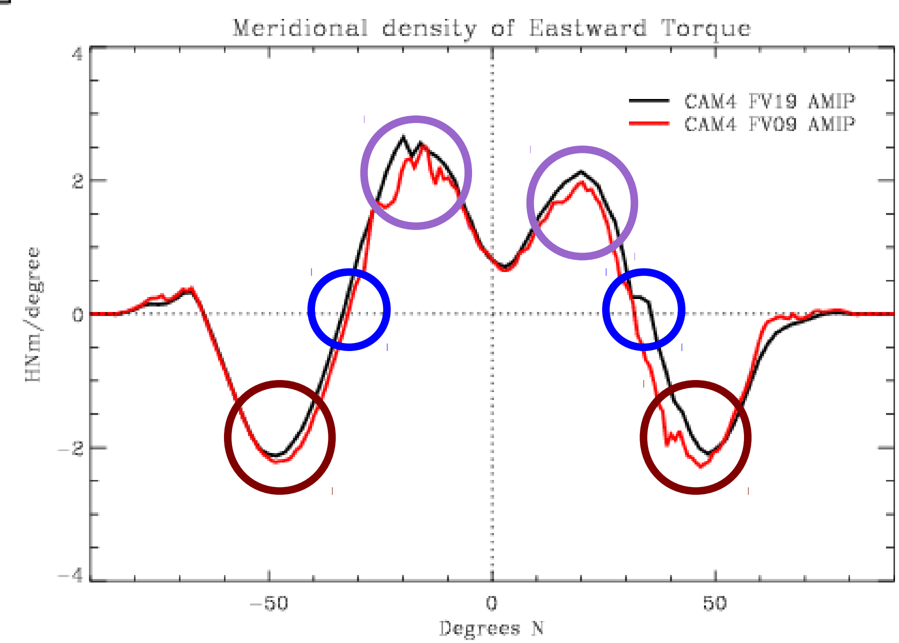
# CAM FV and angular momentum




CAM (4/5) FV dycore appears not to conserve momentum at 1.9x2.5 degree resolution

Going to 0.9x1.25 degrees, the problem seems mitigated

Increased net torque appears associated with stronger and wider easterlies, poleward and weaker Westerlies



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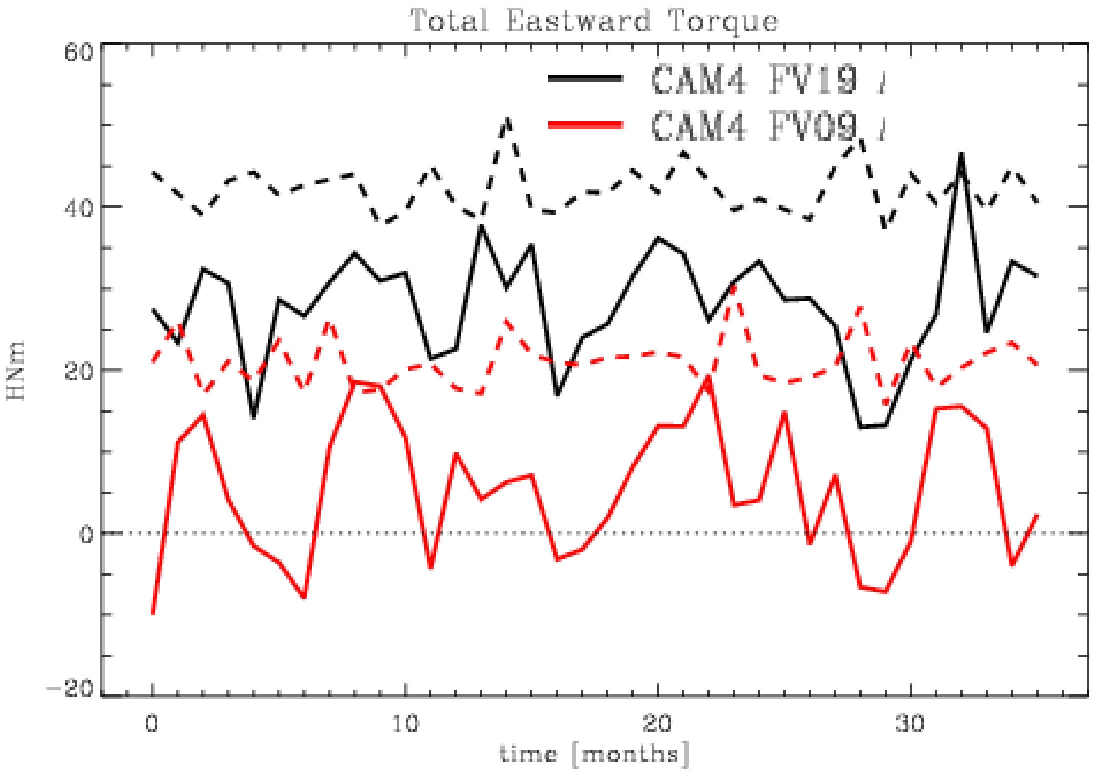


Imbalance is confirmed in AP mode

Doubling the resolution halves the error

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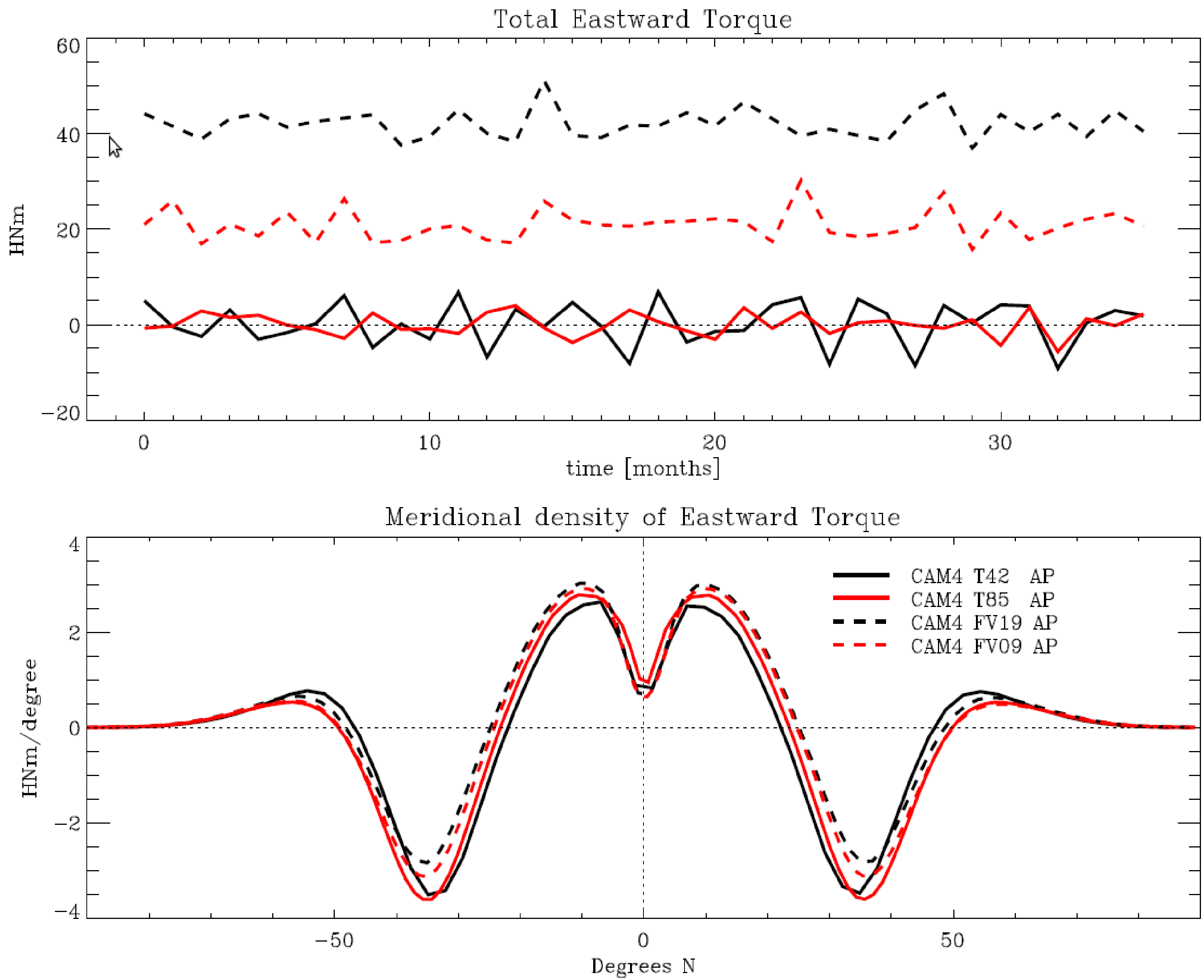

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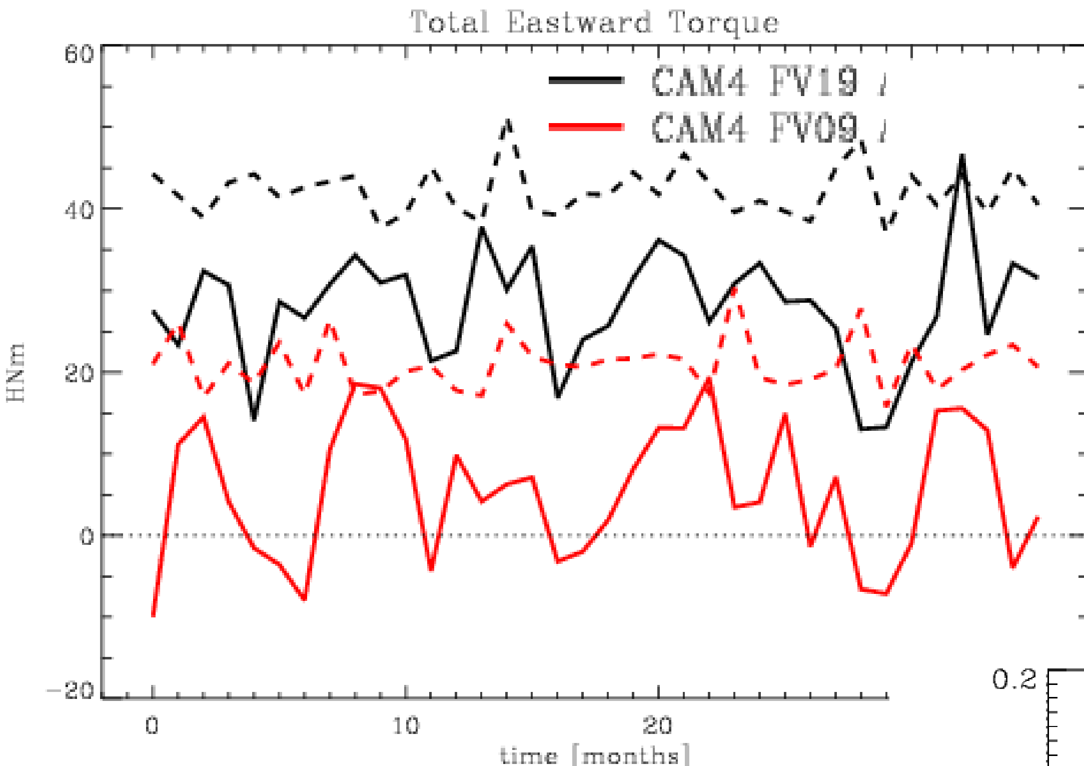


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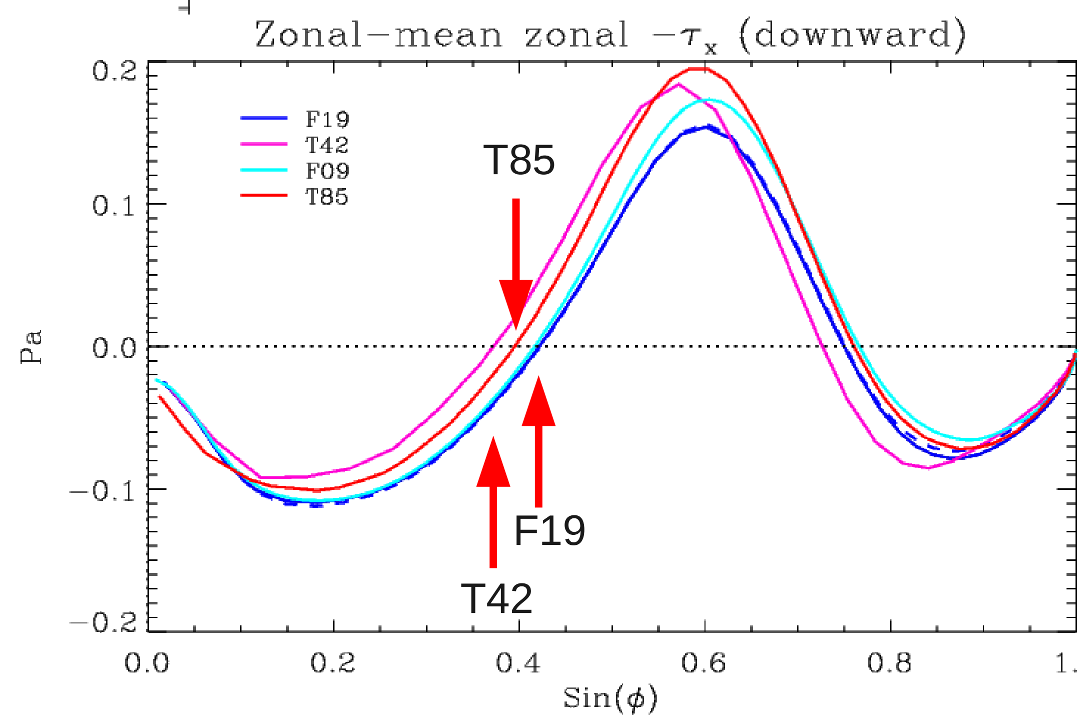
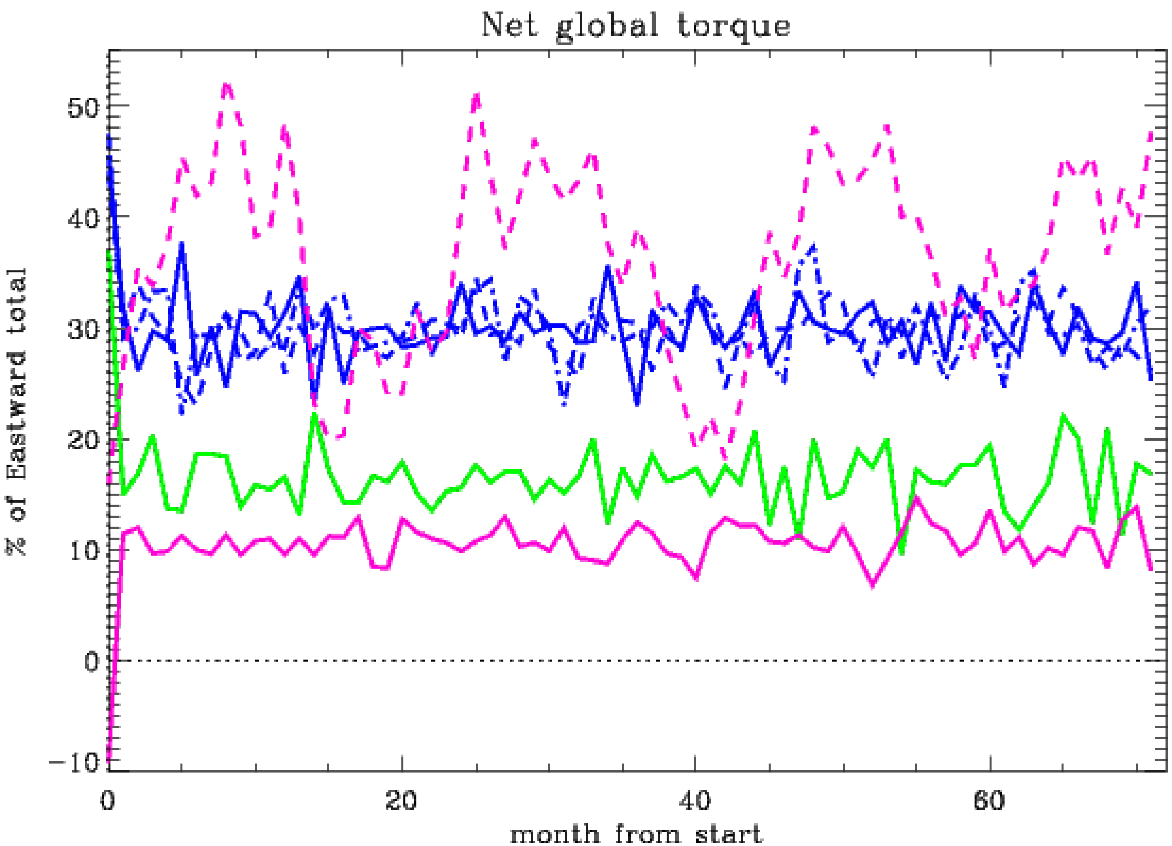
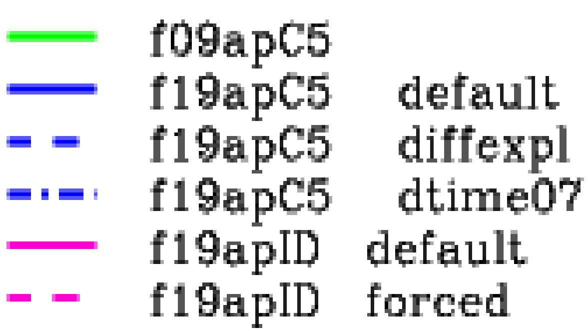



Comparison with spectral (EUL) dycore confirms weak westerlies & strong easterlies.

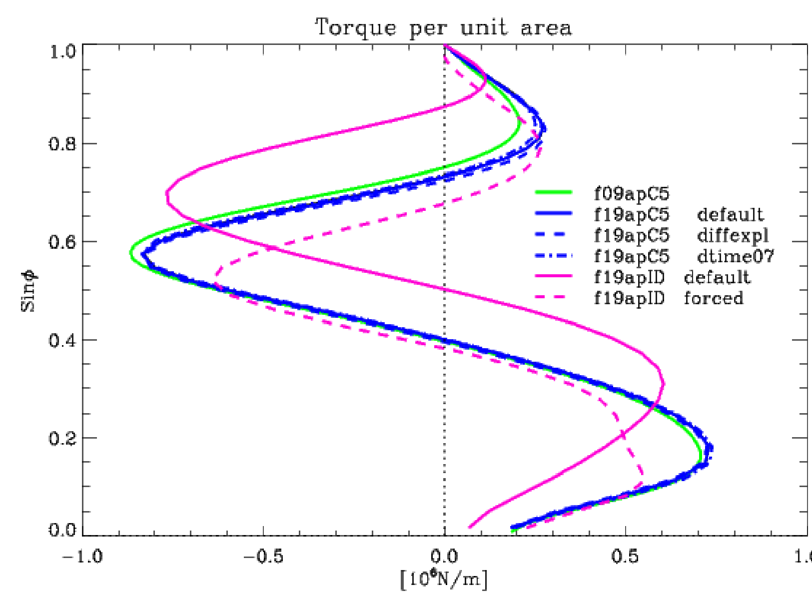
# CAM FV and angular momentum



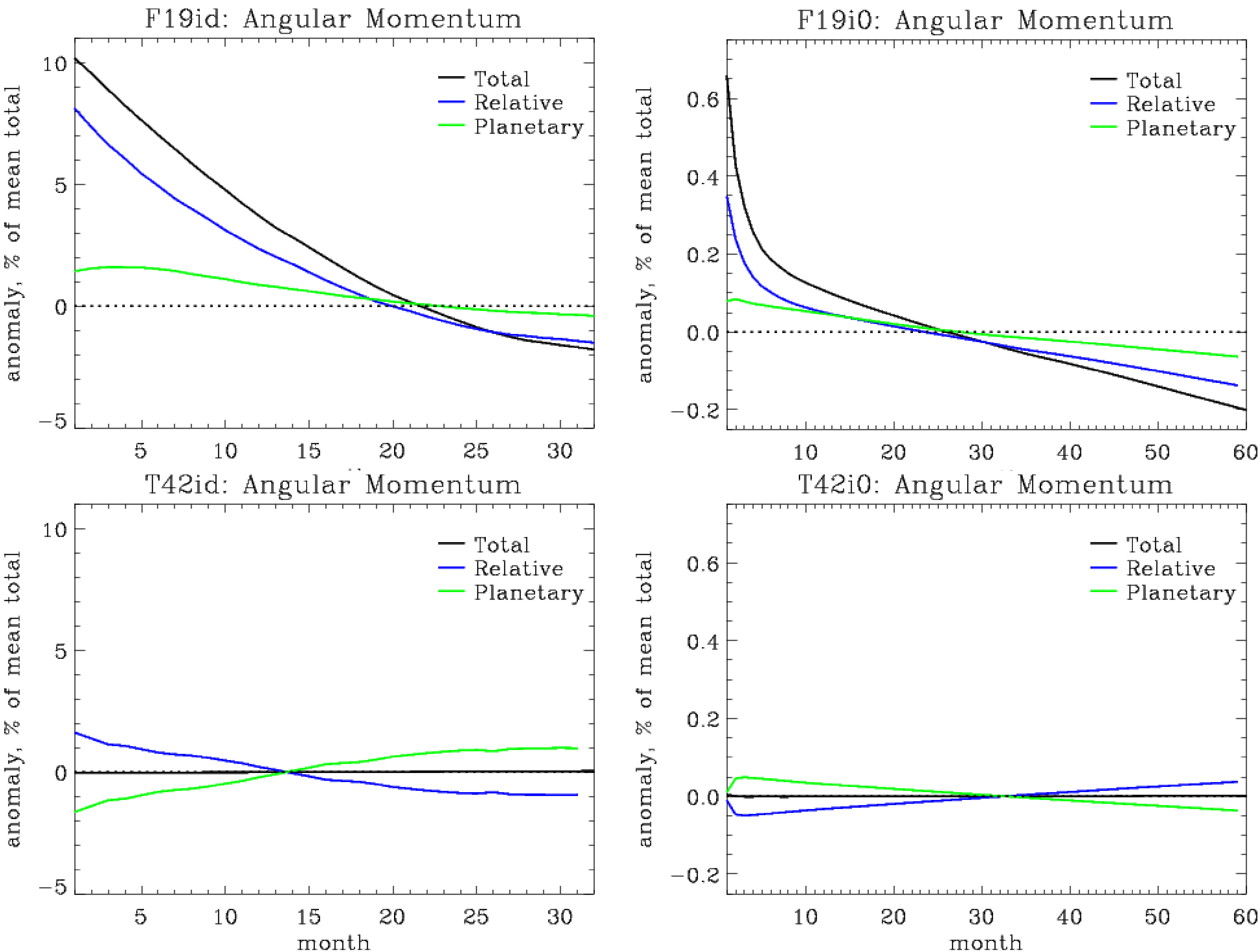




**Relative error is**

- **Proportional to grid-spacing (blue/green)**
- **Insensitive to time-step (blue)**
- **Insensitive to explicit diffusion or damping (blue)**
- **Circulation dependent (magenta, solid)**
- **Insensitive to physics (magenta, broken)**

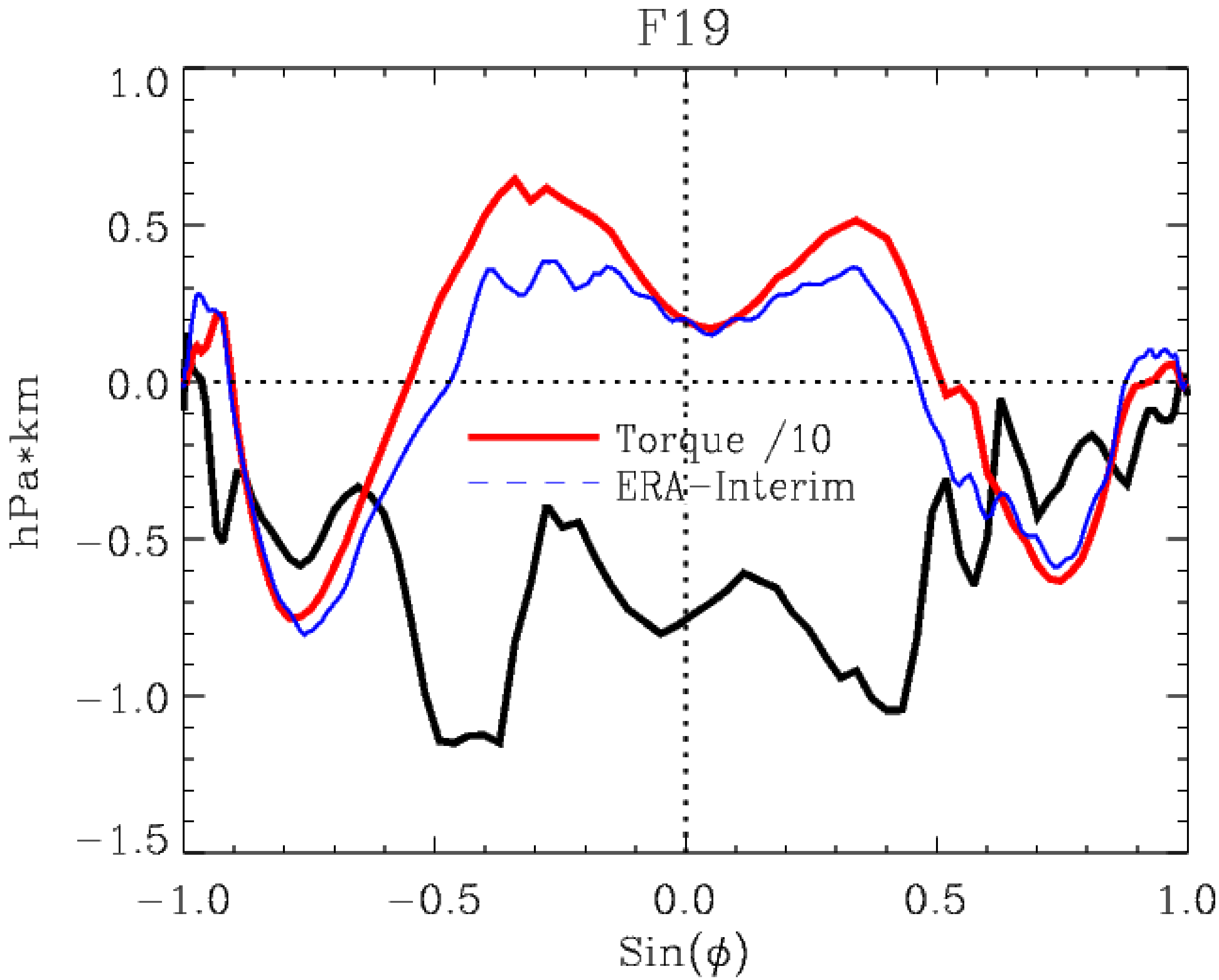


# Stress-free simulations



# CAM-FV biases

- Double ITCZ
- Hadley circulation too symmetric and too intense
- Trade winds too wide and strong



# An aside: systematic biases in CAM

# Einstein (1926), Schneider (1977), Held & Hou (1980)

**momentum conservation**

$$0 = -\nabla\cdot(\mathbf{v}M) + \frac{\partial}{\partial z}\left(\nu\frac{\partial M}{\partial z}\right), \quad (7)$$

$$M = \Omega a^2 \cos^2\theta + ua\cos\theta$$

$$fV_G \approx Cu(0) - \nu\frac{\partial u}{\partial z}\bigg|_\delta, \quad (20)$$

where $V_G \equiv \int_0^\delta v\,dz$, $\delta$ being the depth of this

**Dissipation of axial momentum and (resolved) overturning circulation are in balance with each other**

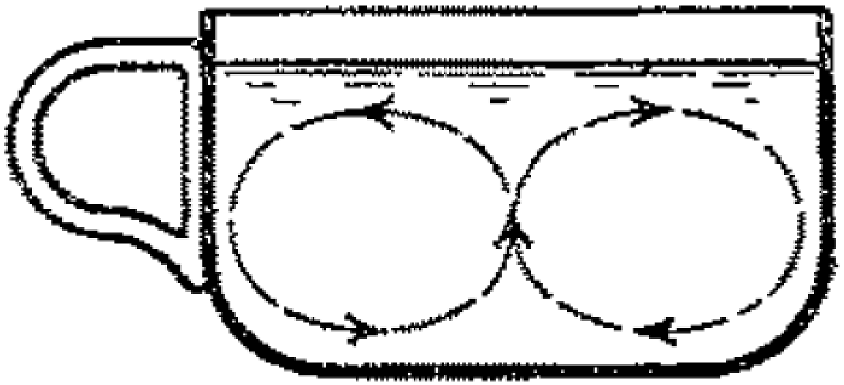
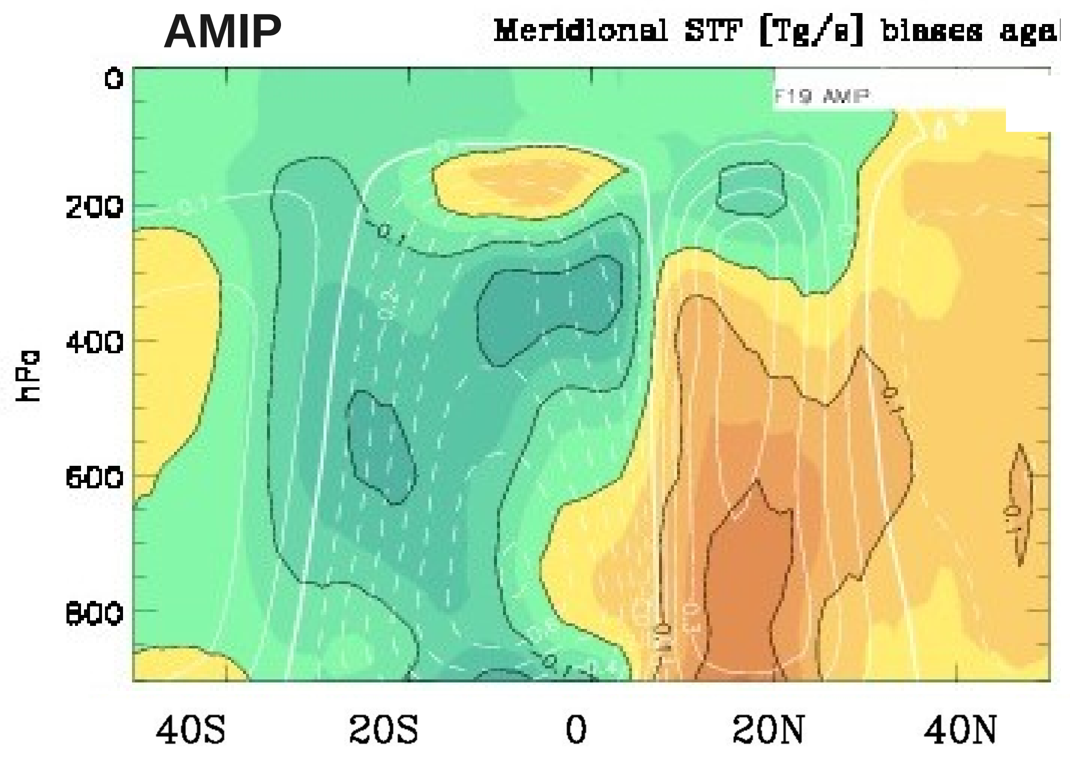


Fig. 1.

# CAM4-FV biases

- Hadley circulation too strong, symmetric
- Double ITCZ, amplified by coupling



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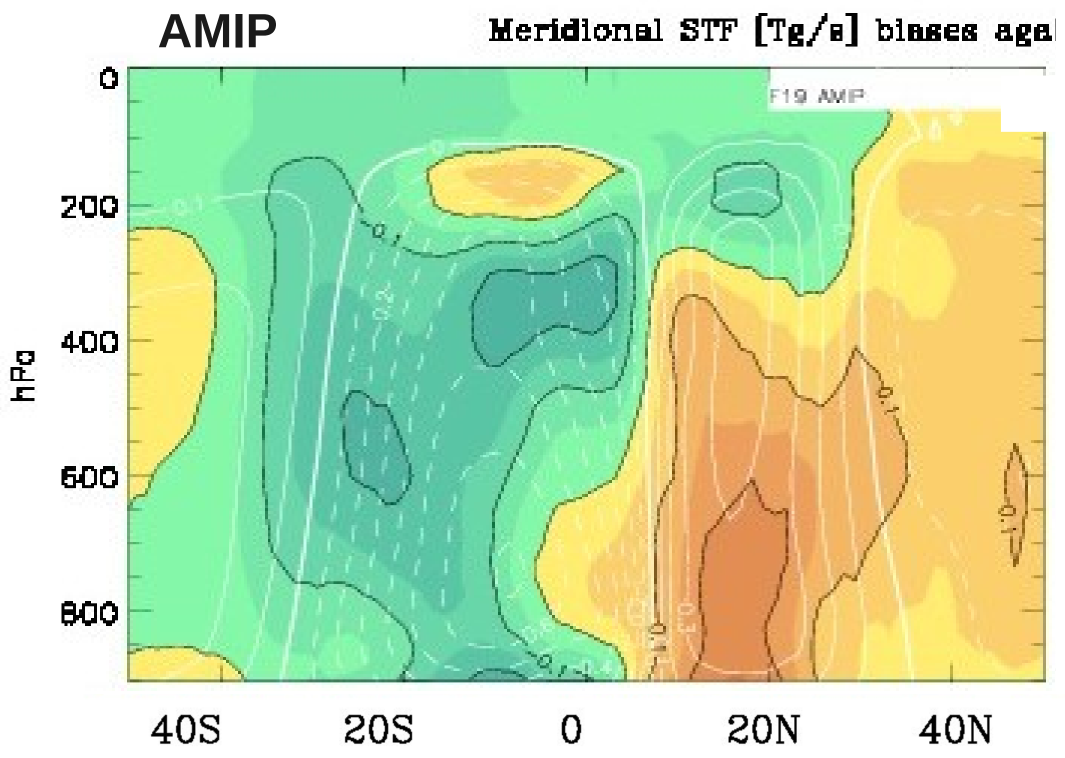


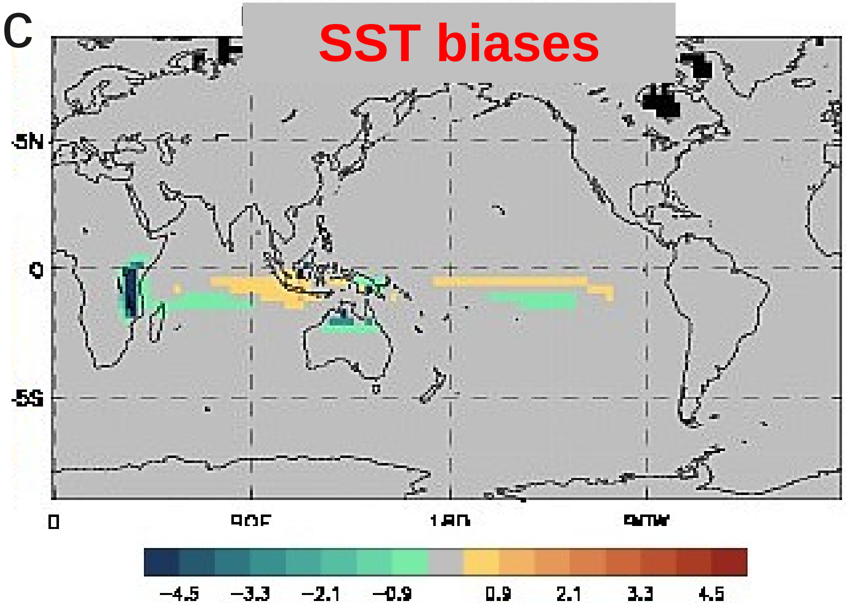

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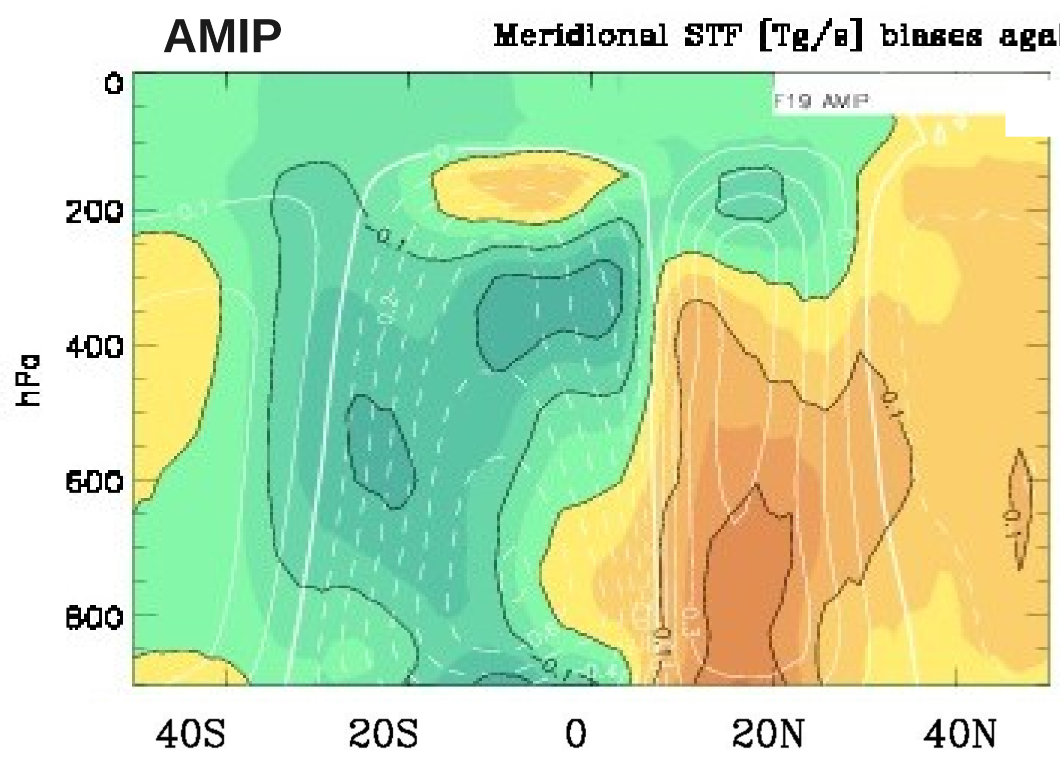


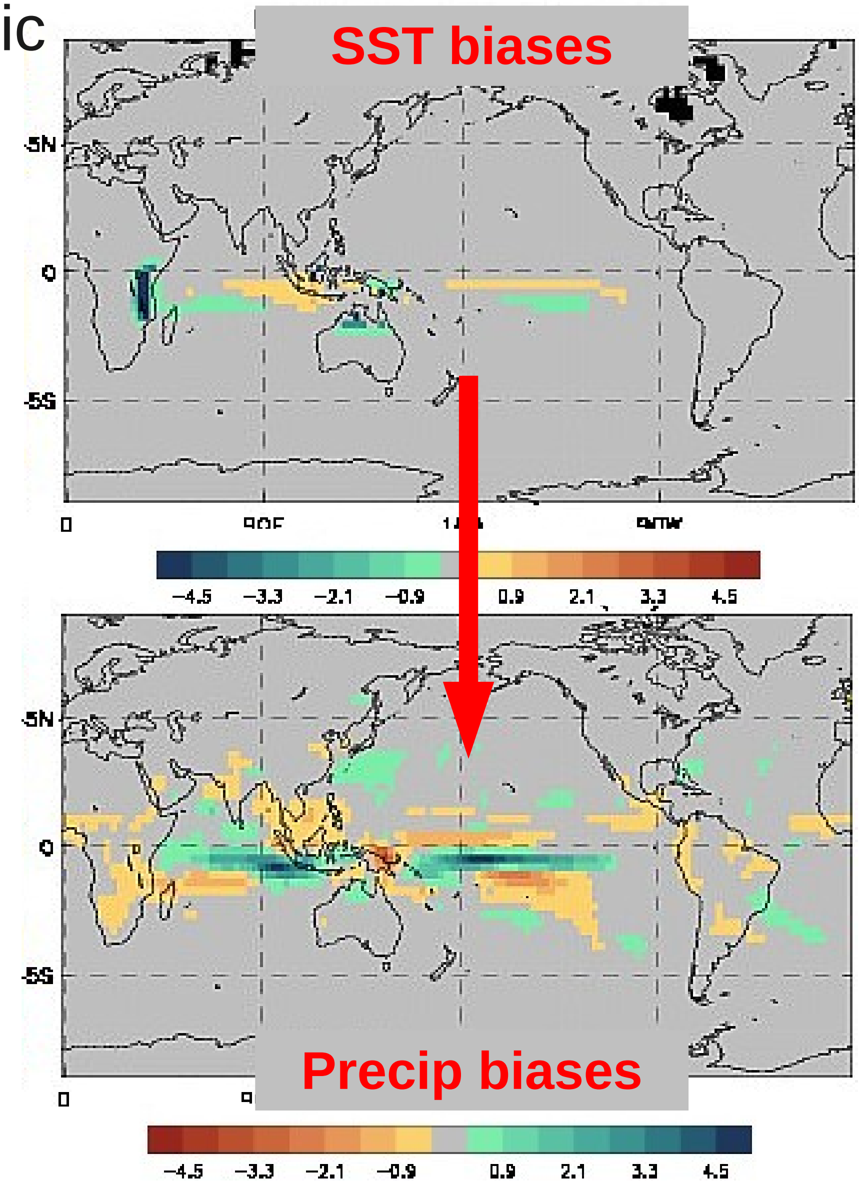

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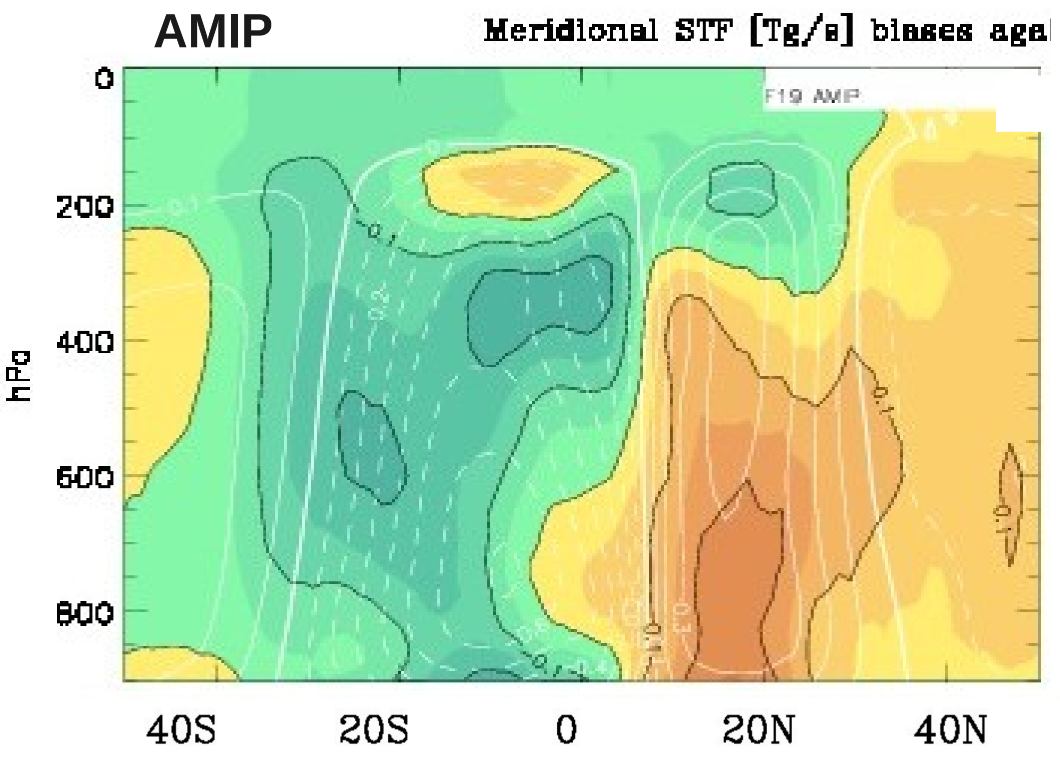
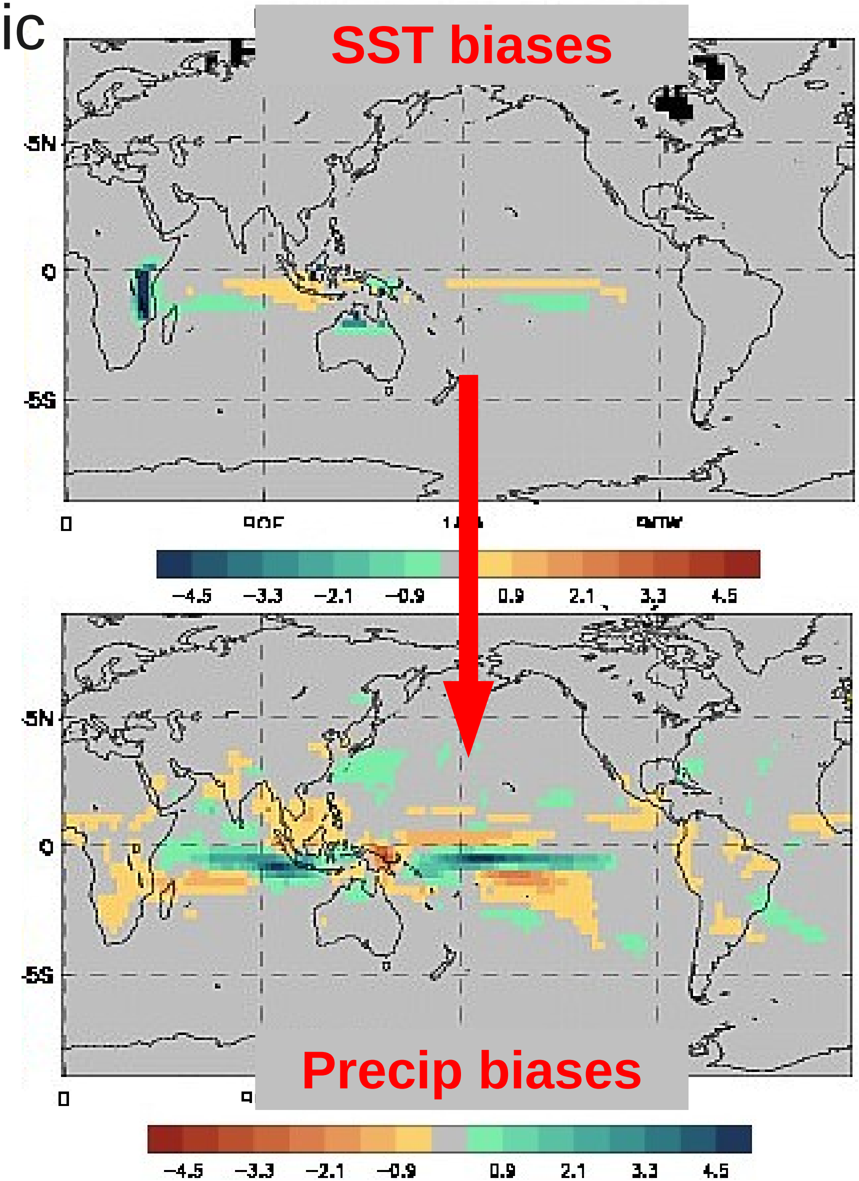



**How about the *width*?...**

# Schneider (1977), Held & Hou (1980) model

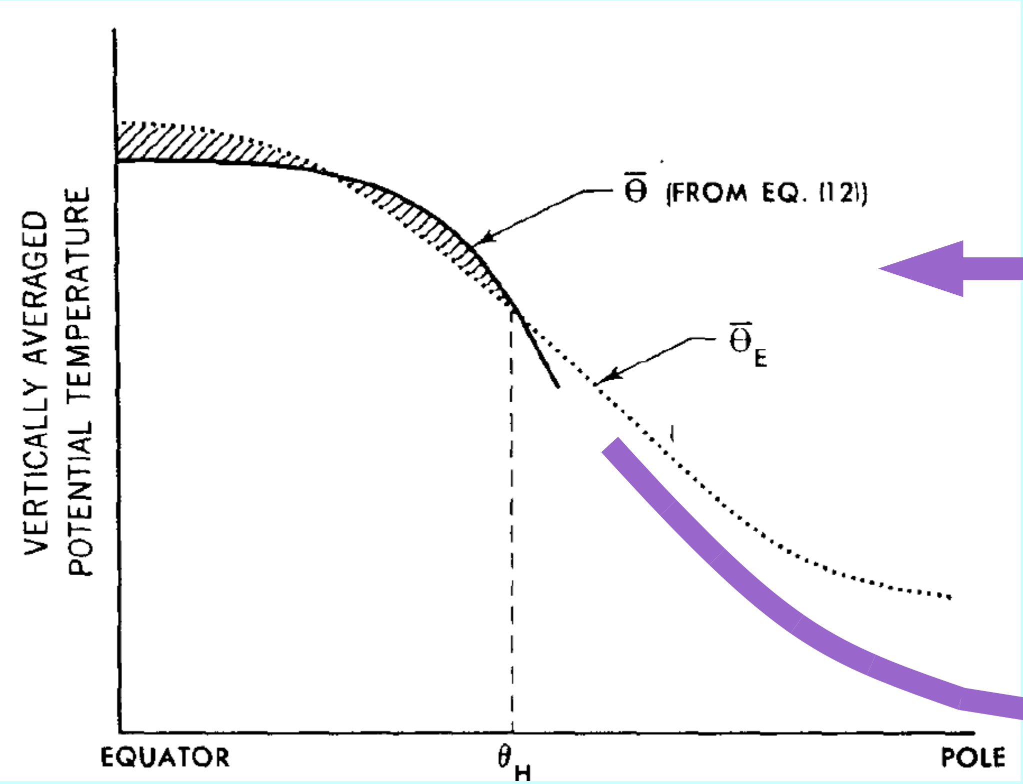
**a) momentum conservation**

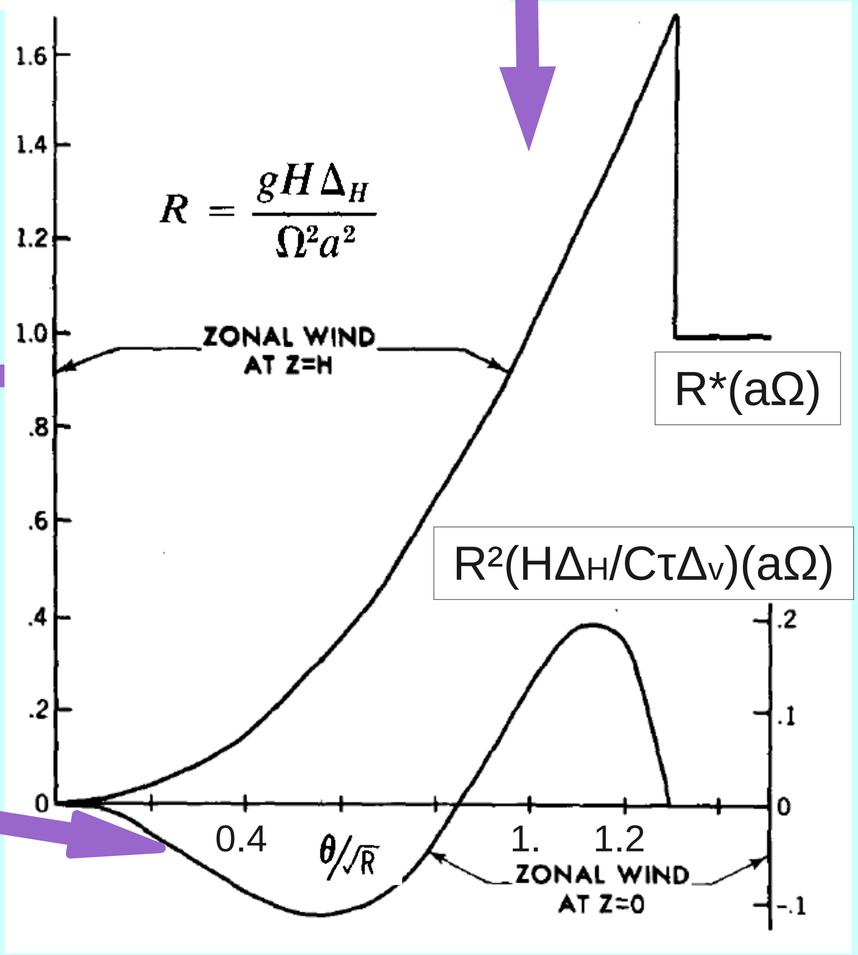
$$0 = -\nabla \cdot (\mathbf{v} M) + \frac{\partial}{\partial z}\left(\nu \frac{\partial M}{\partial z}\right) , \qquad (7)$$

$$M = \Omega a^2 \cos^2\theta + ua \cos\theta$$

**b) thermal wind balance**

$$fu + \frac{u^2 \tan\theta}{a} = -\frac{1}{a}\frac{\partial \Phi}{\partial \theta} .$$



# Effects of axial momentum loss on equilibrium solution

**Assume a loss or export of axial momentum near the edge of the Hadley Cell:**

$$D_t(m) = -2\Omega k_m \left(1 + \frac{\Delta_H}{2r}\right) .$$

Generally, if $k_m \neq 0$ export of angular momentum balances meridional advection resulting in a profile $m(z=H) \sim \left[1 - b\left(\frac{y_H}{y}\right)^\alpha\right]$ with $\alpha \sim av\cos\theta/k_m \gg 1$ and $b = \left(y_H^2 - \frac{\Delta_H}{2r}\right) \simeq \frac{\Delta_H}{3r}$ (if $\Delta_H \ll 1$).

The effect is to flatten the profile of $\overline{\Theta}$ compared to Equation (12) and to increase the value of the solution for $y_H = \sin\theta_H$, i.e. to broaden the Hadley cell.

**In other words:**
**the "drop off" of the thermal-wind T field occurs further poleward, thus expanding the Hadley Cell**

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# Interim summary

- CAMx-FV (x≥3) has a non-physical sink of axial momentum
- large: 40% of the physical fluxes in FV19 (but circulation dependent)
- requires compensation by unbalanced easterly surface stress
- results in excessively strong and wide trade winds
- physically linked with over-active overturning (Hadley) circulation, and may contribute to the “double ITCZ” problem
- insensitive to physics or to time-step, but proportional to horizontal grid spacing
- compares unfavourably with other non-conserving dycores, e.g. ~8% spurious source in non-mass-conserving HadGAM3
- to our knowledge, worst case in CMIP5 – but GFDL and GISS come close

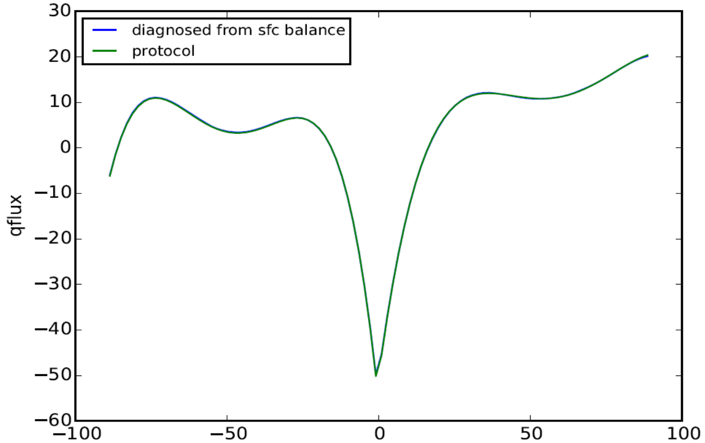
# Aside #2: risk of bad science with biased CAM (& possibly others?...)

# TRAC-MIP: a model intercomparison based on ML-AP integrations

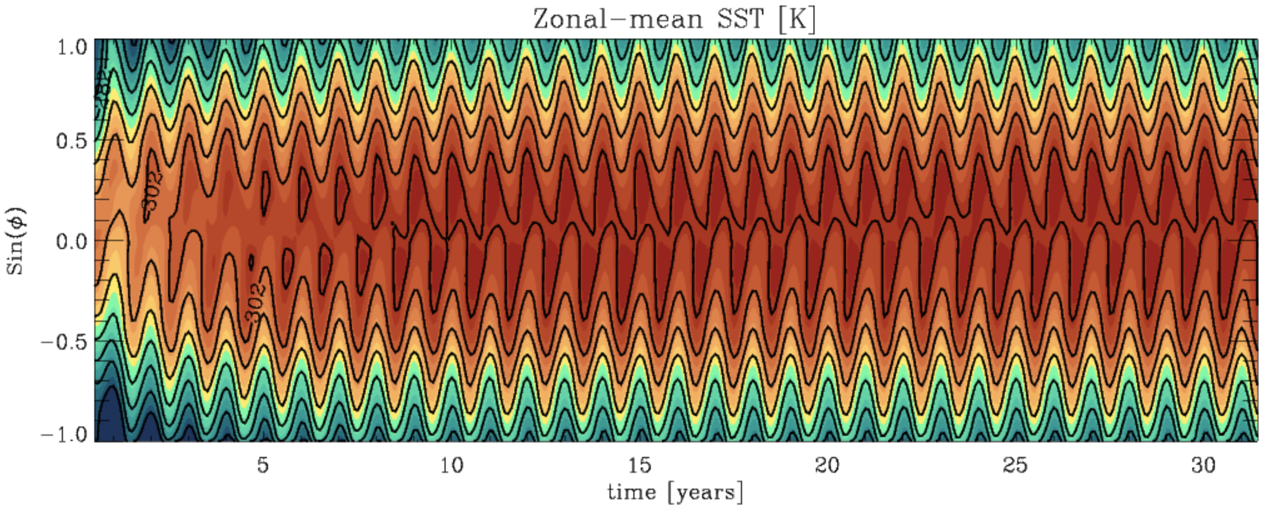
http://www.ldeo.columbia.edu/~biasutti/MonsoonITCZsWorkshop/sim_protocol.pdf

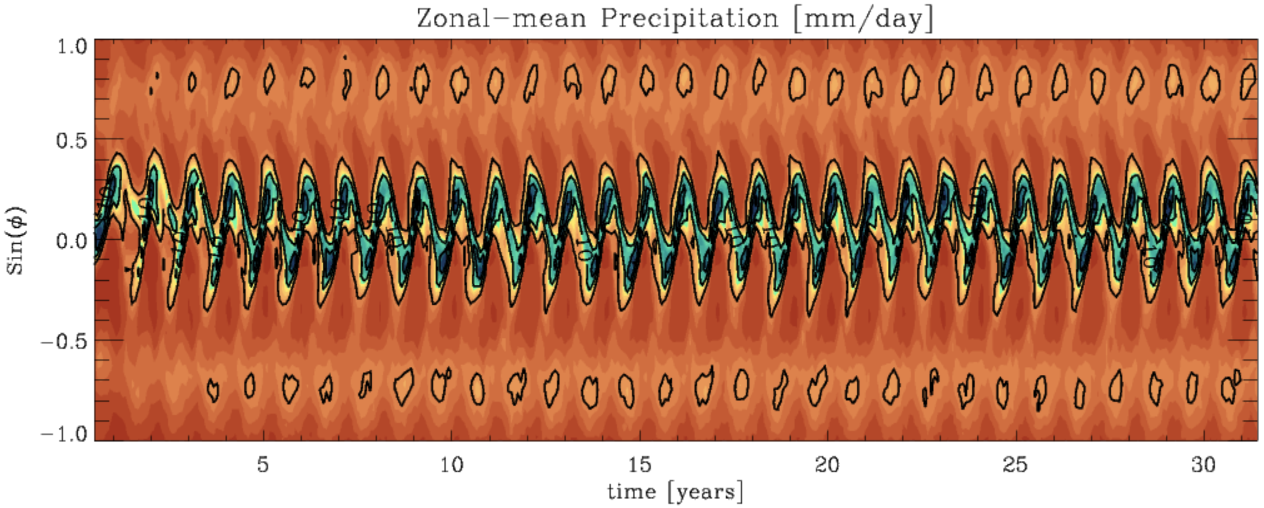
Voigt et al. 2015.

Bjerknes Centre (i.e. TT) participating with CAM5-Oslo (NorESM-2 set-up)




1. Energetically closed
2. Thermodynamically coupled



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http://www.ldeo.columbia.edu/~biasutti/MonsoonITCZsWorkshop/Workshop_on_Monsoons_and_ITCZs.html

***Groups and model currently participating:***

- Sarah Kang and Jeongbin Seo from UNIST (GFDL AM2)
- Elizabeth Maroon from UW (GFDL AM2)
- Juergen Bader and Jong-yeon Park from MPI (ECHAM6.3)
- Aiko Voigt from LDEO (ECHAM6.1)
- Nick Klingaman from University of Reading (MetUM GA6.0)
- Masakazu Yoshimori from Hokkaido (MIROC)
- Thomas Toniazzo from Uni Climate, Bergen (CAM5, FV19)
- Brian Rose from SUNY Albany (CAM4, FV19)
- Ross Dixon from U. Wisconsin (CAM3, T42)
- Simona Bordoni from CalTech (Moist Idealized GCM)
- Ruby Leung and Jian Lu from PNNL (MPAS with CAM5 physics)
- Francis Codron from UPMC (LMDZ)
- Joy Singarayer from University of Reading (HadCM3)
- Sonali McDermid from NASA GISS (ModelE)

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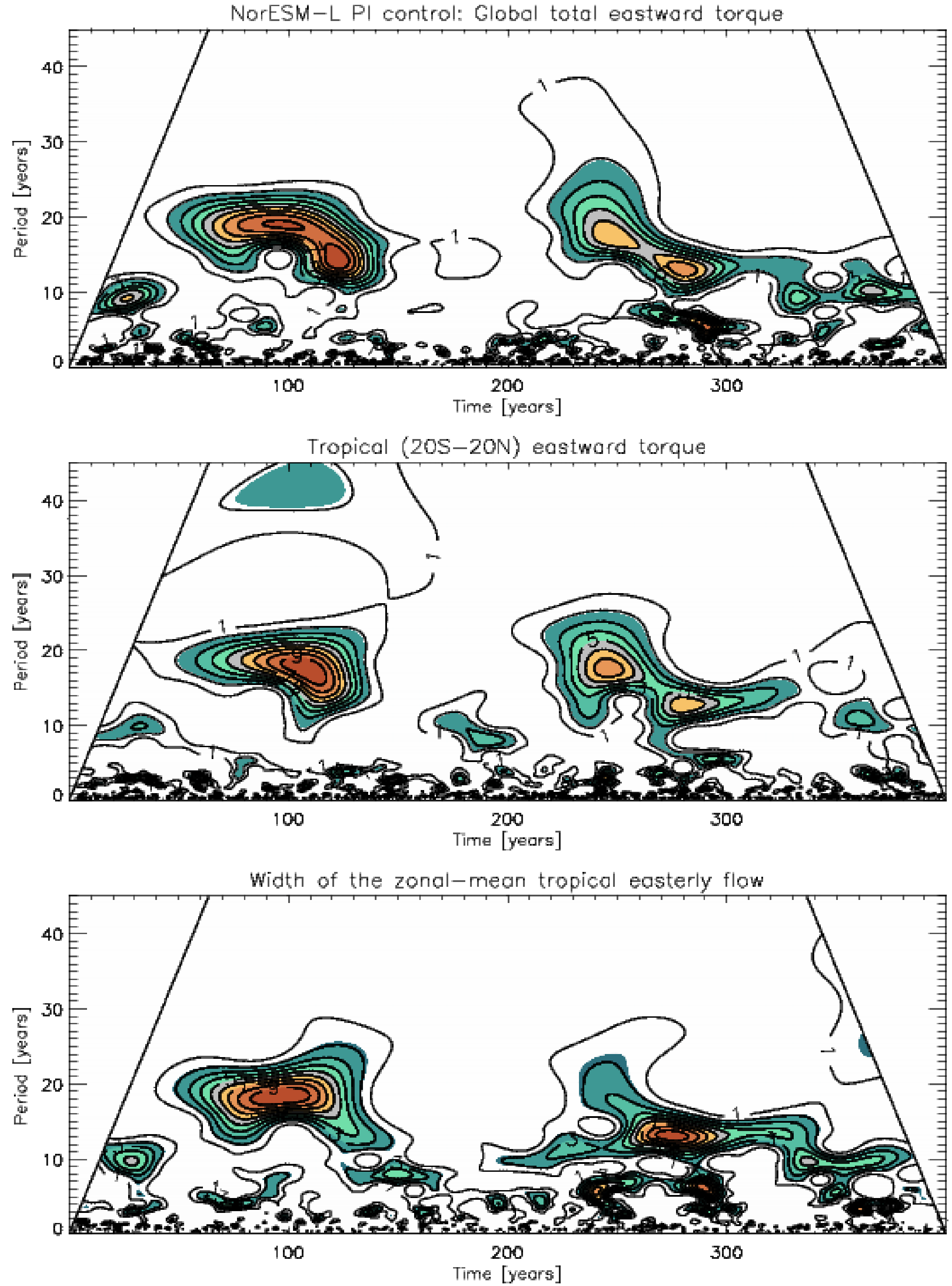
# Centennial-scale variability in NorESM

Long PI-control and LM integrations show centenntial-scale variability and is the subject of current studies.

It is coupled with anomalous surface torque and may be entirely spurious.



# Diagnostic assessment of AM source

$$S_M = \partial_t L_R + D_L - T_x - C_\lambda$$

$$L_R = \iint_{p_*}^{p_{top}} (u\, a \cos\phi) \frac{dp}{g} (a \cos\phi)\, d\lambda$$

$$D_L = \frac{1}{a} \frac{\partial}{\partial\phi} \iint_{p_*}^{p_{top}} (\overline{uv}\, a \cos\phi) \frac{dp}{g} (a \cos\phi)\, d\lambda$$

$$T_x = \int (\tau_x\, a \cos\phi) \ (a \cos\phi)\, d\lambda$$

$$C_\lambda = -a\,\Omega \sin(2\phi)\, \partial_t \int_0^\phi \int p_* a^2 \cos\phi' \, d\lambda\, d\phi'$$

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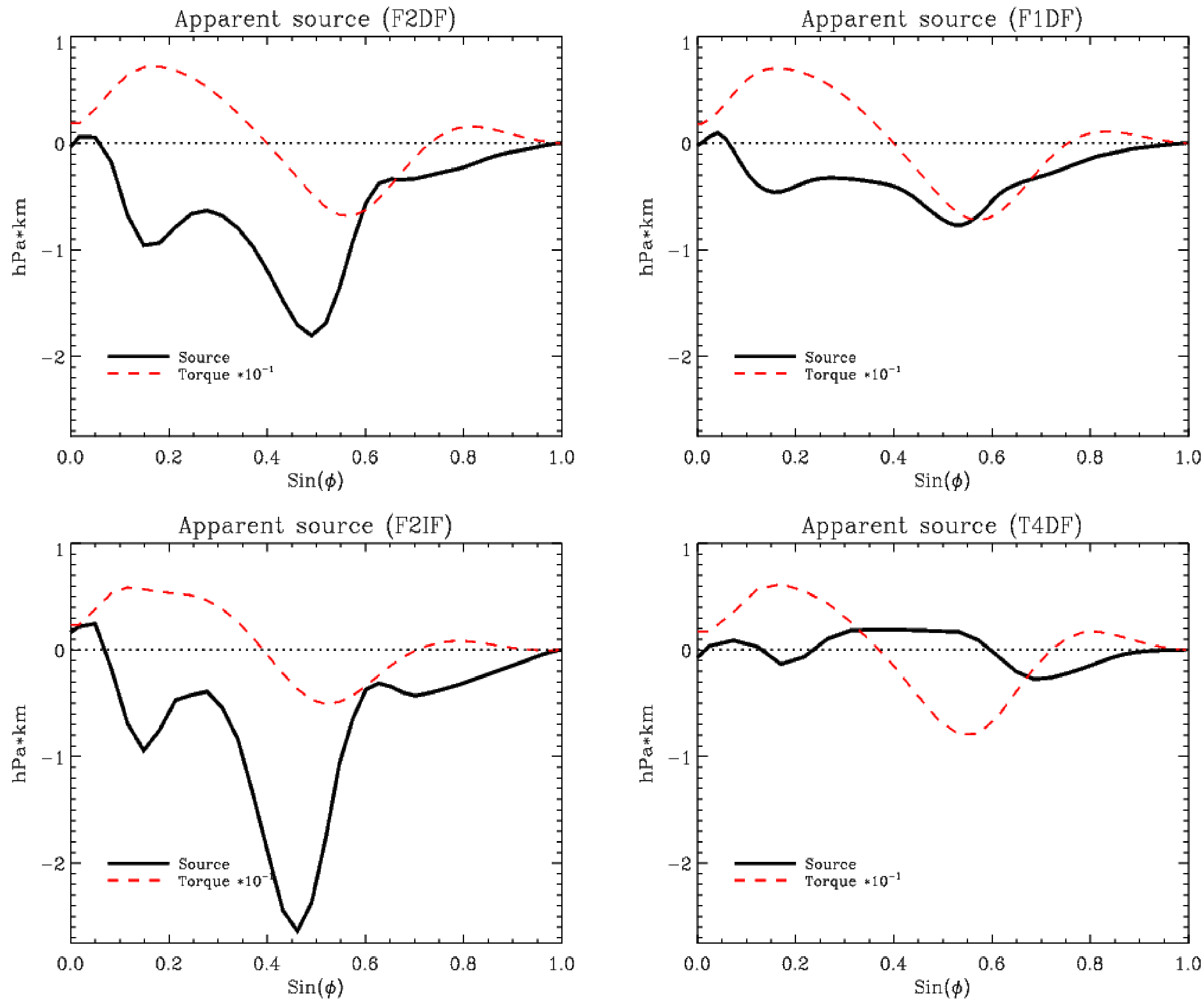
# $S_M$

- T42,85 show balanced apparent source consistent with diffusion

- F19,09 show M sink everywhere, esp. subtropics



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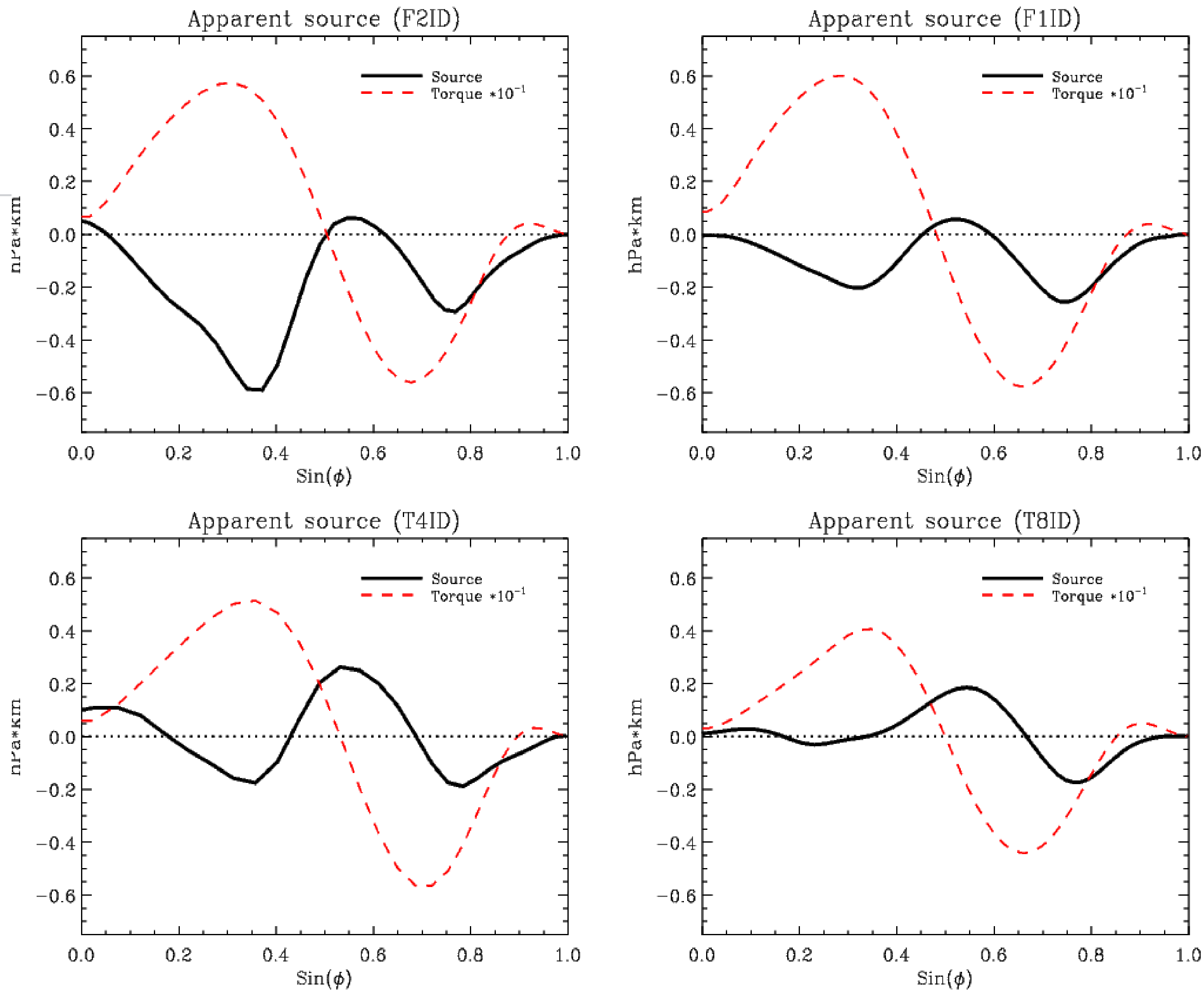

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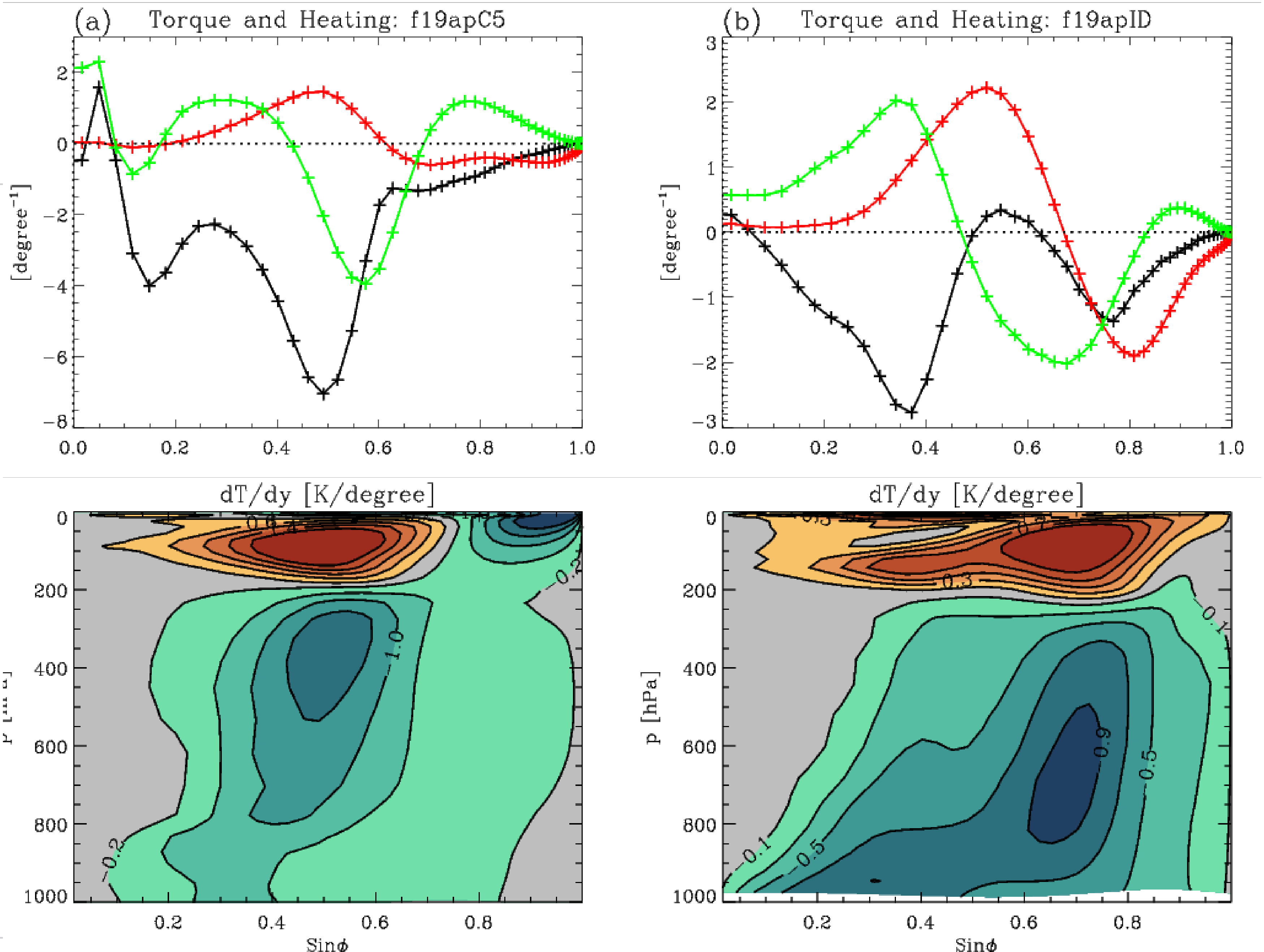

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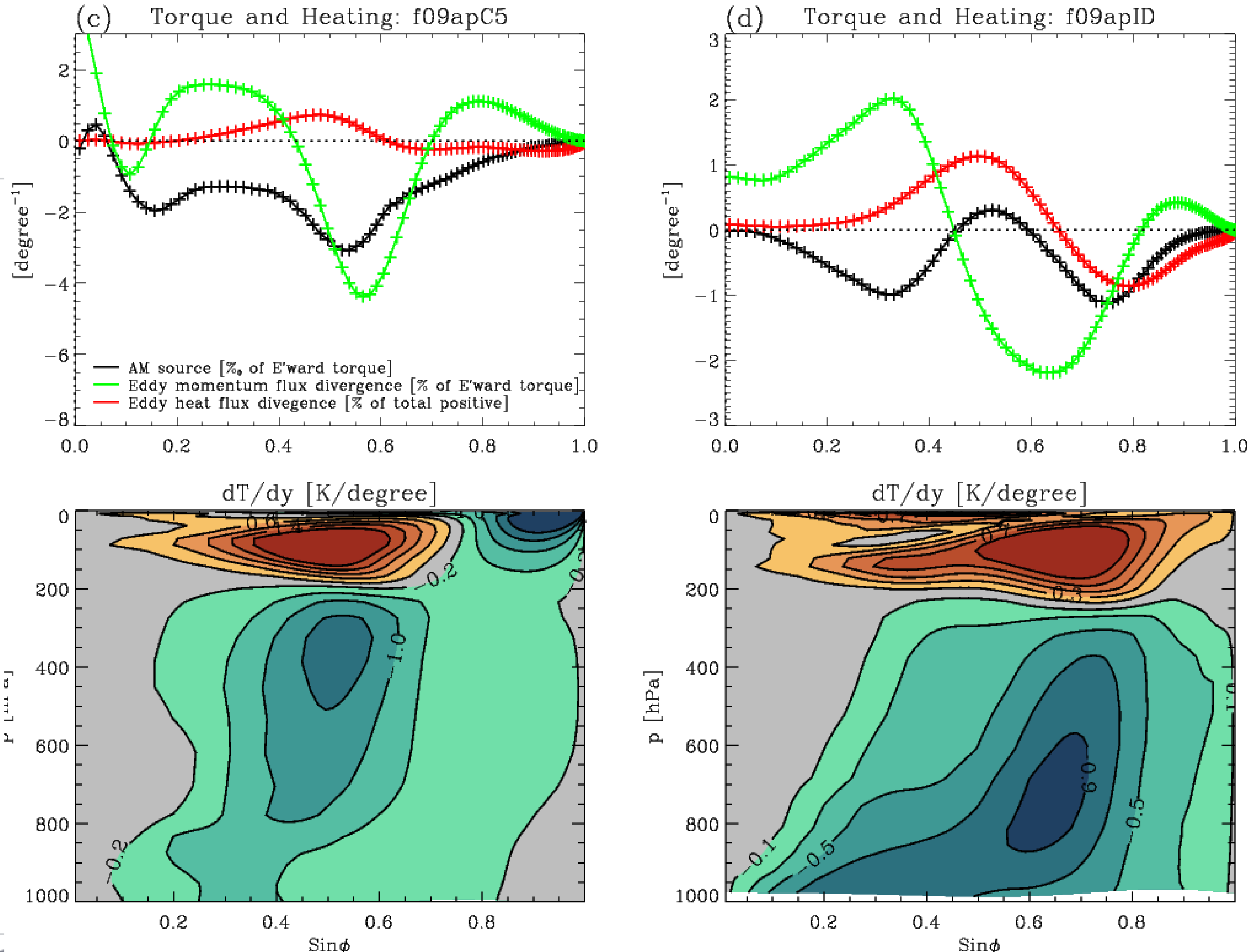
(c) Torque and Heating: f09apC5
(d) Torque and Heating: f09apID
[degree$^{-1}$]
AM source [%$_0$ of E'ward torque]
Eddy momentum flux divergence [% of E'ward torque]
Eddy heat flux divegence [% of total positive]
dT/dy [K/degree]
p [hPa]
Sin$\phi$
-0.2
-1.0
-0.1
-0.5
-0.9

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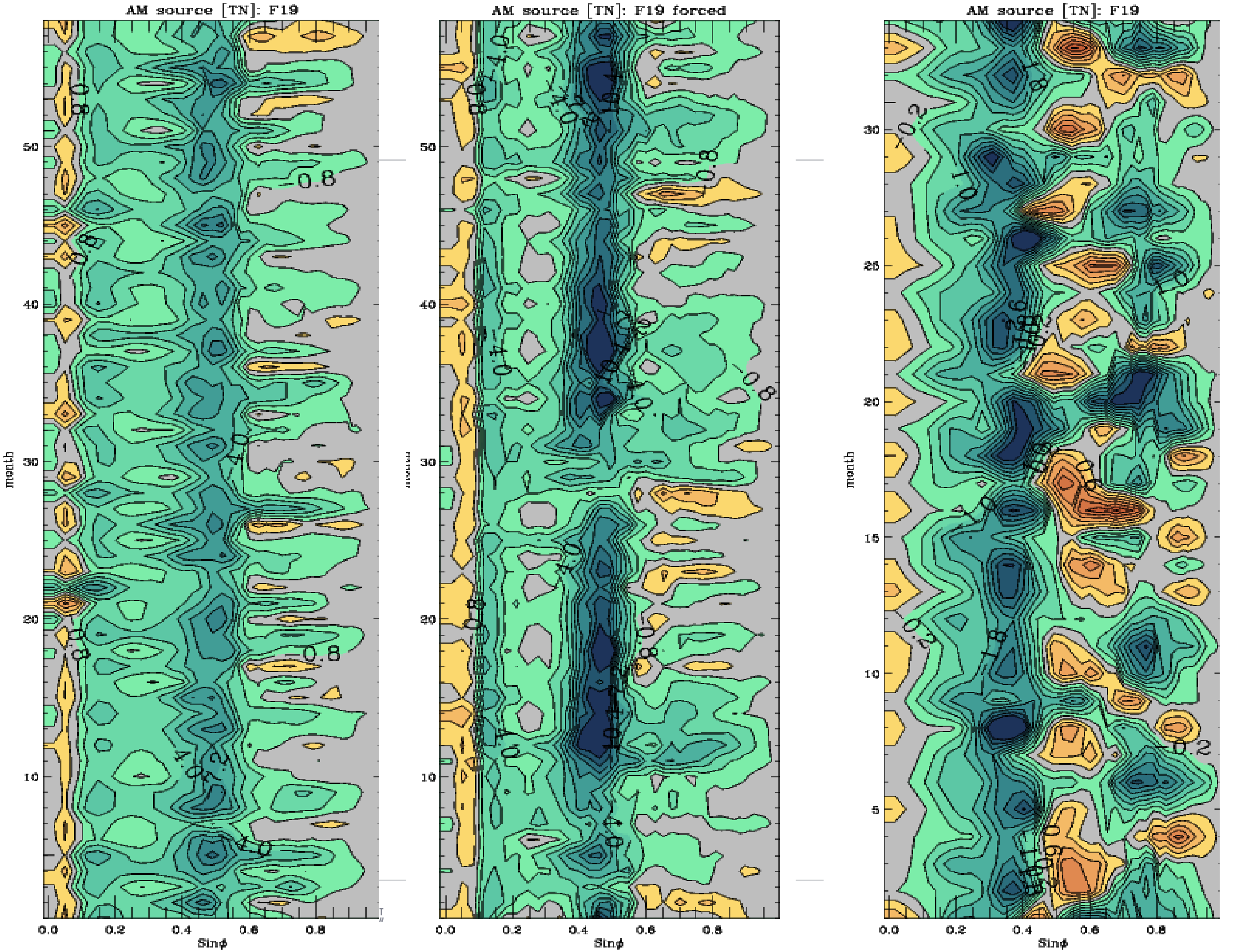
# $S_M$

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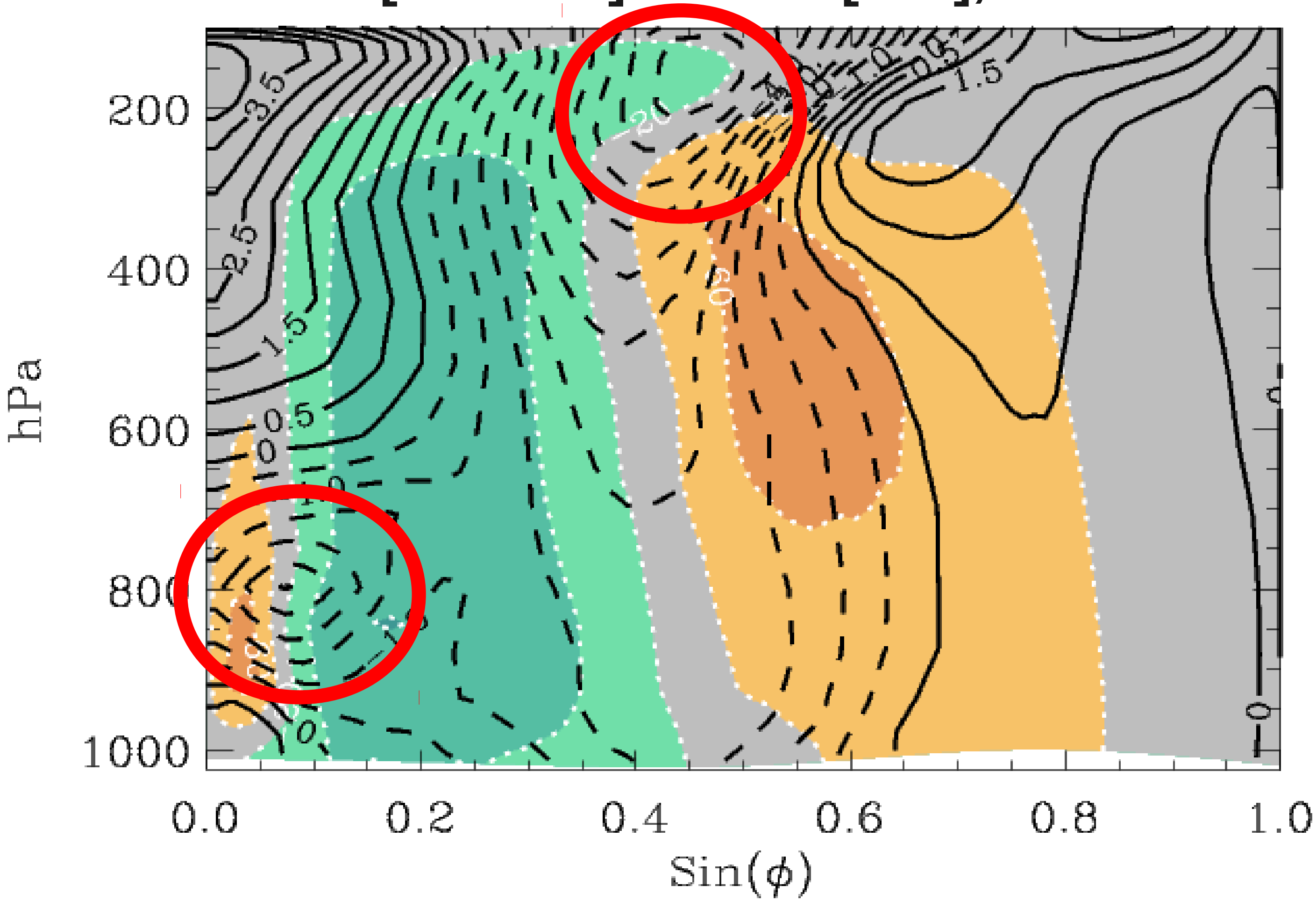
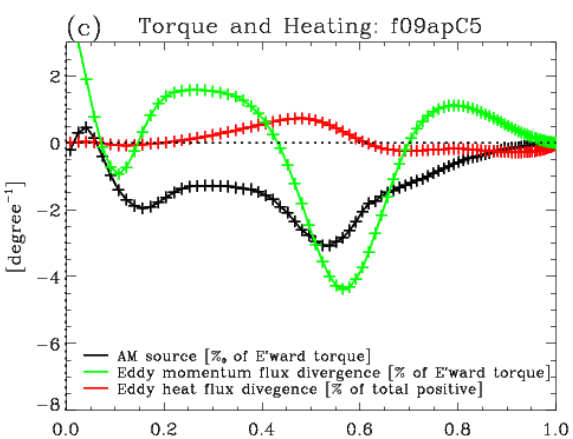
# Angular-momentum streamfunction $\Psi_M$

$$\Psi_M = \iint_{p}^{p_{top}} \left(\overline{uv}\, a\cos\phi + \bar{v}\, a^2 \Omega^2 \cos^2\phi\right) \frac{dp}{g}\, a\cos\phi\, d\lambda$$

**Differences between FV and spectral dycore simulations highlight M advection towards two areas of low M**

ΔΨM [kPa km²] and Δu [m/s], F09 - T85



# Interim Summary #2

- Localisation of spurious sink of axial momentum apparently governed by physics
- broadly colocated with baroclinic zones of momentum convergence
- Investigation proposed to find causes (NFR Frinatek submission) – got great marks, wonderful praise, and no money
- We keep at it anyway

# Speculations...

***Possible causes of numerical AM sink in the FV dycore:***

1. representation of the pressure gradient terms, especially its departure from Simmons and Burridge (1981);
2. C-D grid discretisation and related interpolations (Skamarock 2008);
3. Lin and Rood's (1996) FFSL extension of Colella and Woodward's (1984) PPM algorithm;
4. Arakawa-Lamb (1981) momentum source in discretisation of kinetic energy term;
5. Suarez-Takacs (1994) upwinding for Hollingworth-Kållberg instability.

# ...and next steps

Possible causes of numerical AM sink in the FV dycore:

1. Test a S&B-like implementation of pressure-gradient terms (a la UKMO UM);
2. Leave dummy C-D grid interpolations in H&S set-up, applying (T,u) tendencies on the dycore grid;
3. Test $FV^3$ for AM dissipation.