Sources of CAM Arctic Surface Climate Bias Deduced from the Vorticity and Temperature Equations -- DJF

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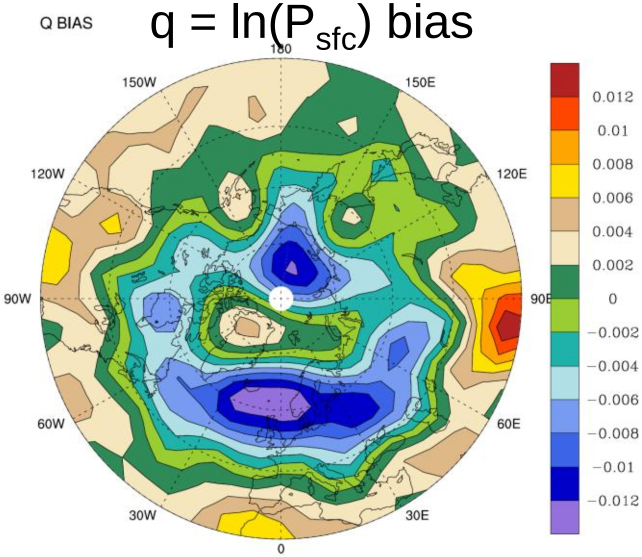
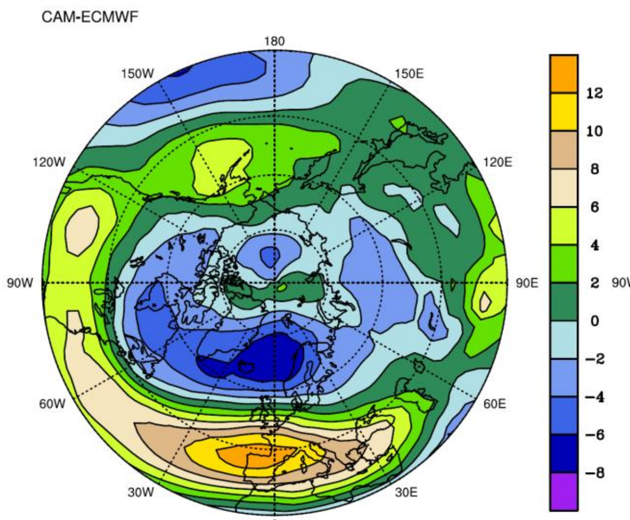
Snapshot of CAM3 DJF Bias

- T42 bias (CAM3 AMIP minus ERA-40) shown for U, V, T. (NCEP RAI used for q)
- Bias has prominent values in NE Atlantic.
  - Over N Europe: SLP & T too low, ζ too high
  - Over Barents Sea/NW Russia region: opposite
  - Over Beaufort Sea: SLP too low
- Representative level shown for U, V, & T

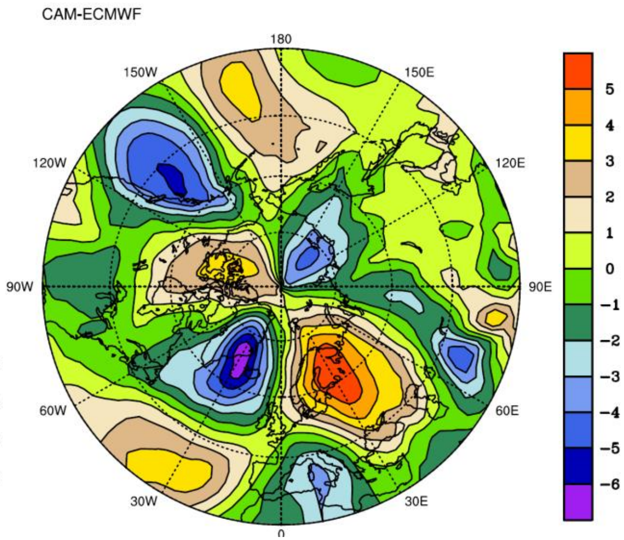
$q = \ln(P_{sfc})$ bias



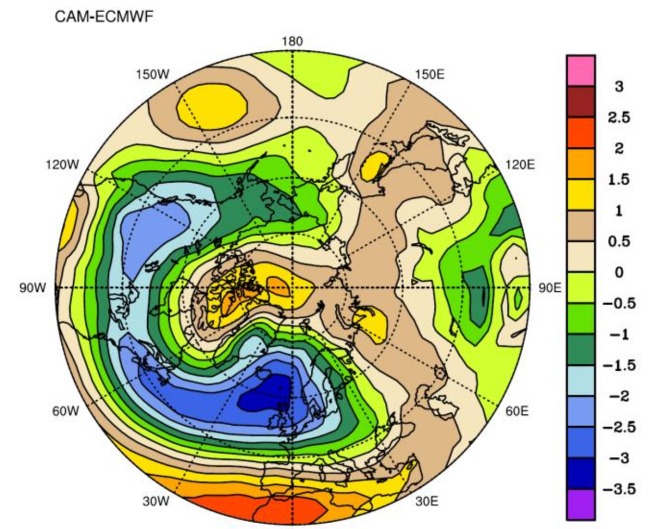
U bias @ σ =0.5



V bias @ σ =0.5



T bias @ σ =0.5



Contributors to the Temperature *bias* equation:

$$\underbrace{\hat{\vec{V}} \bullet \nabla \overline{T}_E + \vec{\overline{V}}_E \bullet \nabla \hat{T} + \hat{\omega}\left(\frac{\partial \overline{T}_E}{\partial p} - \frac{\alpha_E}{C_p}\right) + \overline{\omega}_E\left(\frac{\partial \hat{T}}{\partial p} - \frac{\hat{\alpha}}{C_p}\right)}_{\text{TERM 1}} = \underbrace{-\hat{\vec{V}} \bullet \nabla \hat{T} - \hat{\omega}\left(\frac{\partial \hat{T}}{\partial p} - \frac{\hat{\alpha}}{C_p}\right)}_{\text{TERM 2}}$$

$$\underbrace{-\overline{\vec{V}_C' \bullet \nabla T_C'} + \overline{\vec{V}_E' \bullet \nabla T_E'} - \overline{\omega_C' \frac{\partial T_C'}{\partial p}} + \overline{\omega_E' \frac{\partial T_E'}{\partial p}}}_{\text{TERM 3}} + \hat{Q}\,.$$

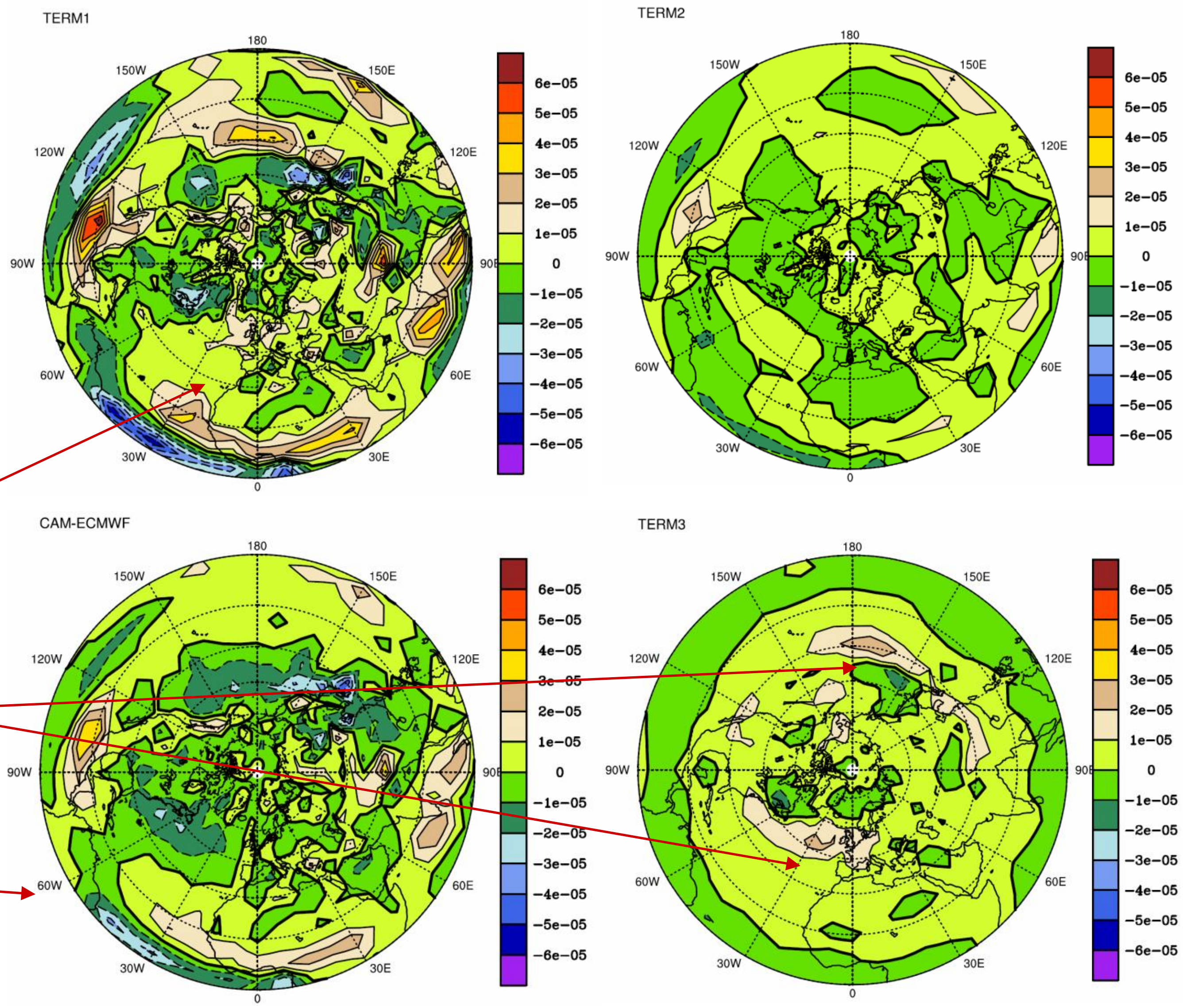
- T bias equation is CAM T equation minus ERA-40 T eqn.
  - $\hat{T}$ = $T_C - T_E$. Where T_C is CAM3, T_E is era-40 DJF temperature
  - Term 1 has CAM bias and ERA-40 combinations found in a linear stationary wave (LSW) model such as Branstator (1990)
  - Term 2 (nonlinear bias terms)
  - Term 3 (all transient terms)
  - $\hat{Q} = Q_C - Q_E$ diabatic heating bias. Q_C & Q_E use independent $\overline{Q}$ eqn
- T equation in a LSW model is Term 1 + forcing term

$$\overline{Q} = \overline{\Delta T / \Delta t} + \overline{\vec{V}} \bullet \nabla \overline{T} + (p / p_0)^{\frac{R}{C_p}} \overline{\omega} \partial \overline{\theta} / \partial p + (p / p_o)[\nabla \bullet \overline{\vec{V}\theta'} + \partial(\overline{\omega'\theta'}) / \partial p]$$

T bias eqn terms upper troposphere σ=0.3, DJF

LSW terms

Nonlinear terms



Diabatic from θ eqn residual

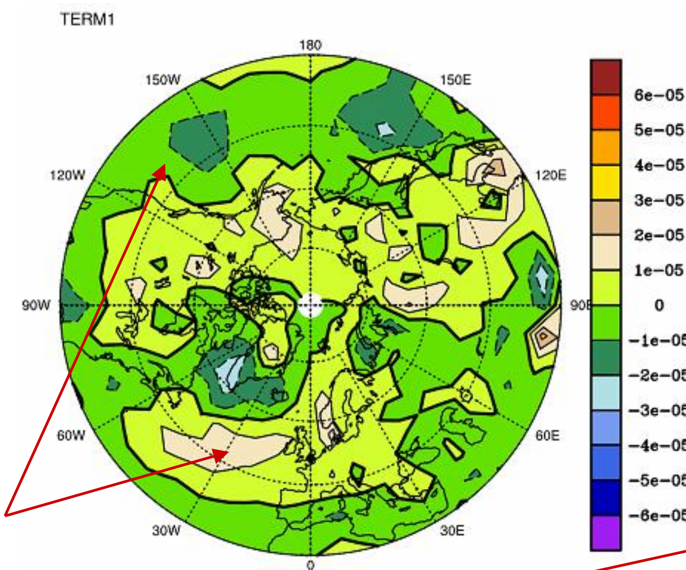
Transient terms

- For upper troposphere along each midlatitude storm track:
- LSW terms mainly
  - balanced by transient fluxes (lower right) &
  - diabatic heating (lower left)
- Nonlinear terms NOT as important in T bias equation

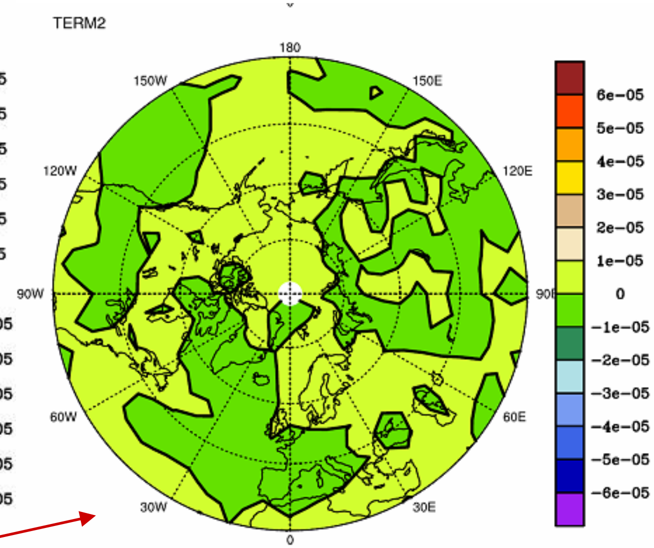
T bias eqn terms mid-troposphere σ=0.5, DJF

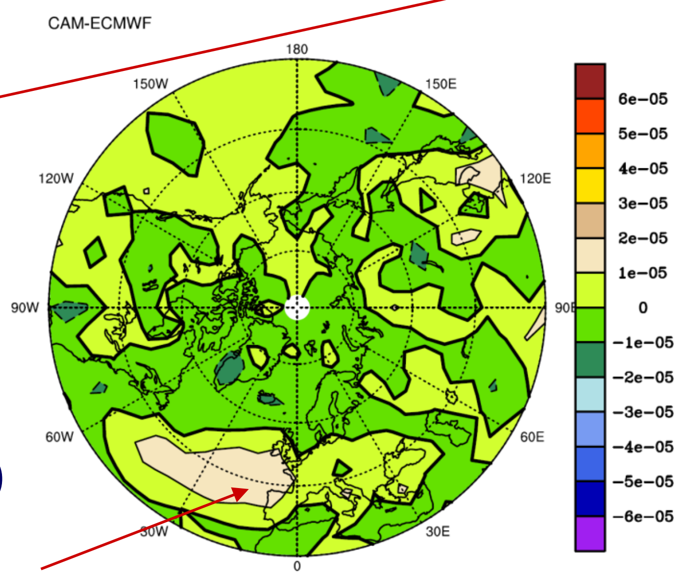
- LSW terms large:
  - along midlatitude storm tracks
  - Arctic land areas
- Nonlinear terms NOT important
- LSW terms mainly balanced by:
  - transient bias (<0 then >0 along track)
  - diabatic bias (at Atl track end >0 reverse of σ=0.3 level)

LSW terms

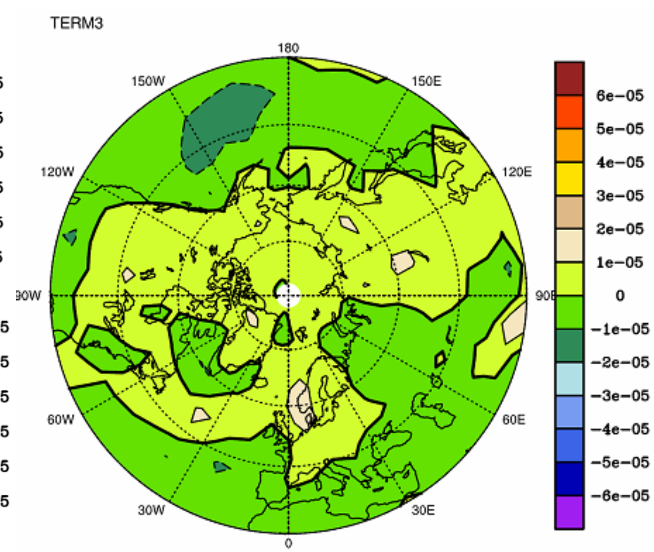


Nonlinear terms





Diabatic from θ eqn residual



Transient terms

T bias eqn terms near Earth surface σ=0.95, DJF

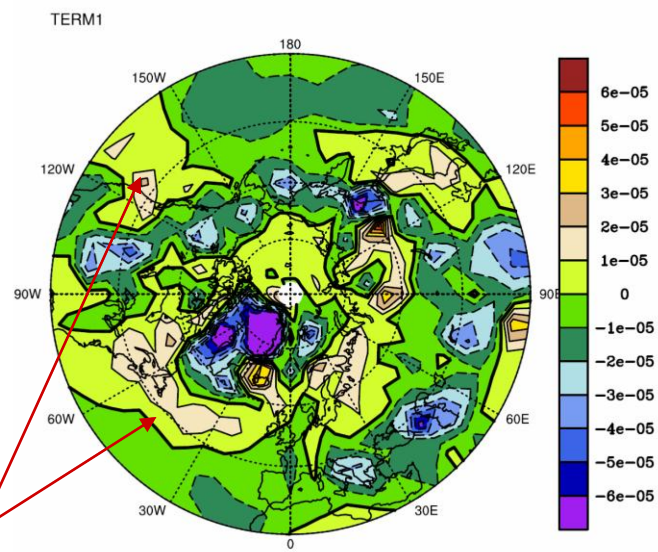
- LSW terms large:
  - along midlatitude storm tracks
  - Arctic land areas
  - Barents Sea

- Nonlinear terms have import over Arctic lands

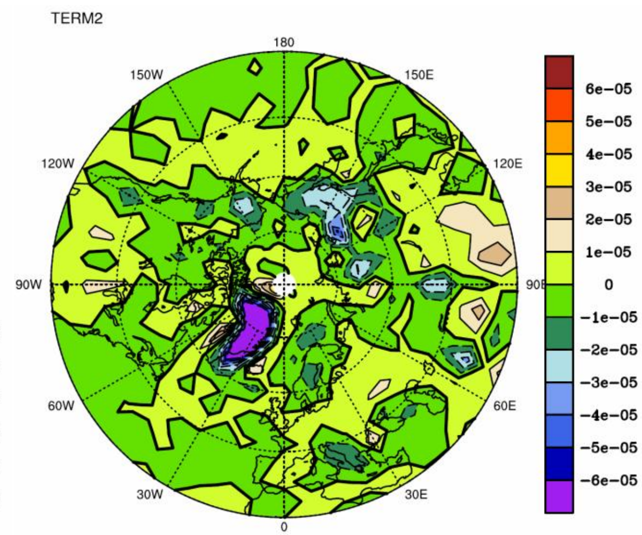
- Transient bias:
  - Dipolar Pac coast
  - >0 Arctic lands

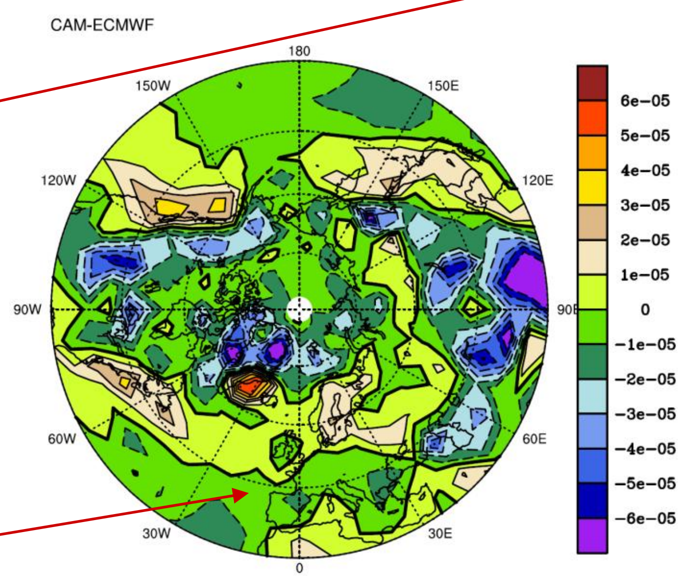
- Diabatic bias:
  - < 0 N of 65N
  - >0 Pac, Scand.

LSW terms

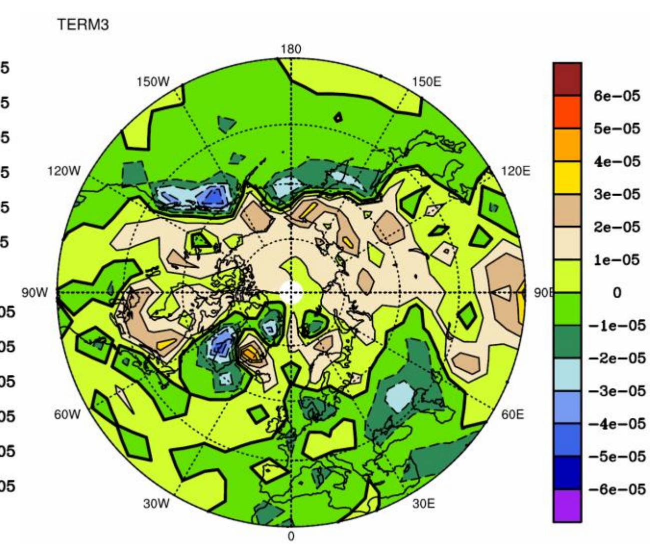


Nonlinear terms





Diabatic from θ eqn residual



Transient terms

T-bias Eqn. Conclusions

- In most of troposphere, LSW bias (term 1) is larger term.
- Nonlinear (term 2) is comparable to term1 only near surface, mainly Arctic lands.
- Transients (term 3) comparable to term 1 at upper troposphere, mainly storm tracks
- Diabatic (term 4) large at troposphere and surface levels;
- Transient & diabatic forcing key at surface & Atlantic storm track.

Contributors to the Vorticity *bias* equation:

$$\overline{\vec{V}}_E \bullet \nabla \hat{\xi} + \hat{\vec{V}} \bullet \nabla(\overline{\xi}_E + f) + \overline{\omega}_E \frac{\partial \hat{\xi}}{\partial p} + \hat{\omega} \frac{\partial \overline{\xi}_E}{\partial p} + (\overline{\xi}_E + f)\nabla \bullet \hat{\vec{V}} + \hat{\xi}\nabla \bullet \overline{\vec{V}}_E - \vec{k} \bullet \left(\frac{\partial \overline{\vec{V}}_E}{\partial p} \times \nabla \hat{\omega}\right) - \vec{k} \bullet \left(\frac{\partial \vec{V}}{\partial p} \times \nabla \overline{\omega}_E\right) =$$

$$-\hat{\vec{V}} \bullet \nabla \hat{\xi} - \hat{\omega}\frac{\partial \hat{\xi}}{\partial p} + \hat{\xi}\nabla \bullet \hat{\vec{V}} + \vec{k} \bullet \left(\frac{\partial \hat{\vec{V}}}{\partial p} \times \nabla \hat{\omega}\right)$$

$$-\overline{\vec{V}'_c \bullet \nabla \xi'_c} - \overline{\omega'_c \frac{\partial \xi'_c}{\partial p}} - \overline{\xi'_c \nabla \bullet \vec{V}'_c} + \overline{\vec{k} \bullet \left(\frac{\partial \vec{V}'_c}{\partial p} \times \nabla \omega'_c\right)} - \overline{\vec{V}'_c \bullet \nabla \xi'_c} + \overline{\omega'_E \frac{\partial \xi'_E}{\partial p}} + \overline{\xi'_E \nabla \bullet \vec{V}'_E} - \overline{\vec{k} \bullet \left(\frac{\partial \vec{V}'_E}{\partial p} \times \nabla \omega'_E\right)}$$

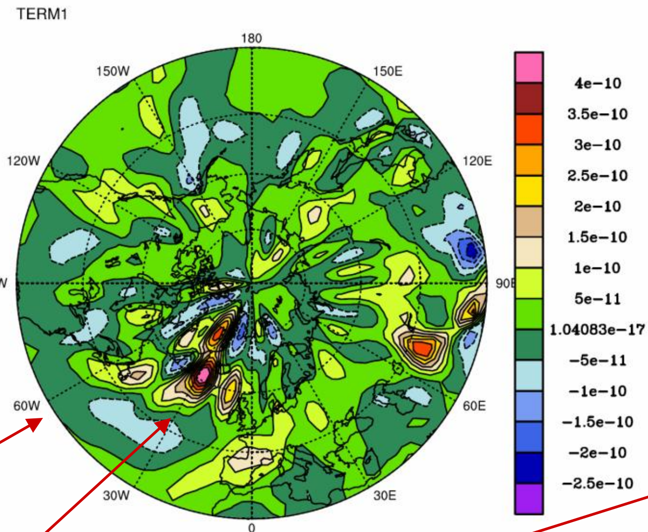
$$+ \hat{F}_r$$

Term 1 = Term 2 + Term 3 + Term 4

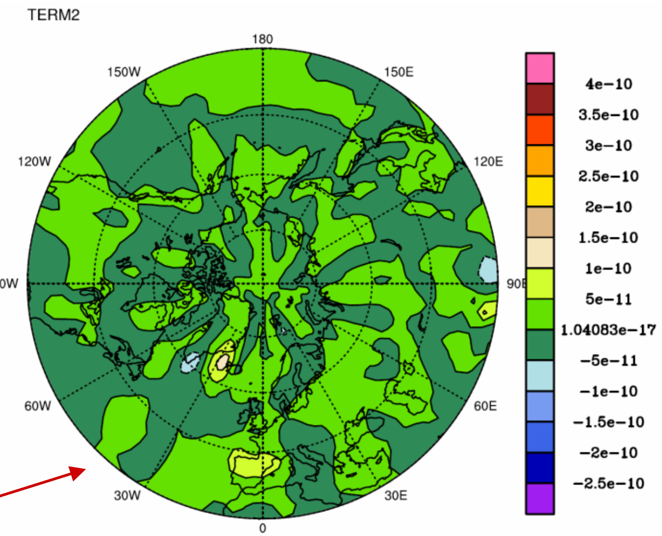
- ζ bias equation is CAM ζ equation minus ERA-40 ζ eqn.
  - $\zeta\hat{} = \zeta_C - \zeta_E$. Where ζ_C is CAM3, ζ_E is era-40 DJF temperature
  - Term 1 has CAM bias and ERA-40 combinations found in a linear stationary wave (LSW) model such as Branstator (1990)
  - Term 2 (nonlinear bias terms)
  - Term 3 (all transient terms)
  - Term 4 (diffusion/friction) $F\hat{} = F_C - F_E$
- ζ equation in LSW is Term 1 + forcing terms on RHS

ζ bias eqn terms mid-troposphere σ=0.5, DJF

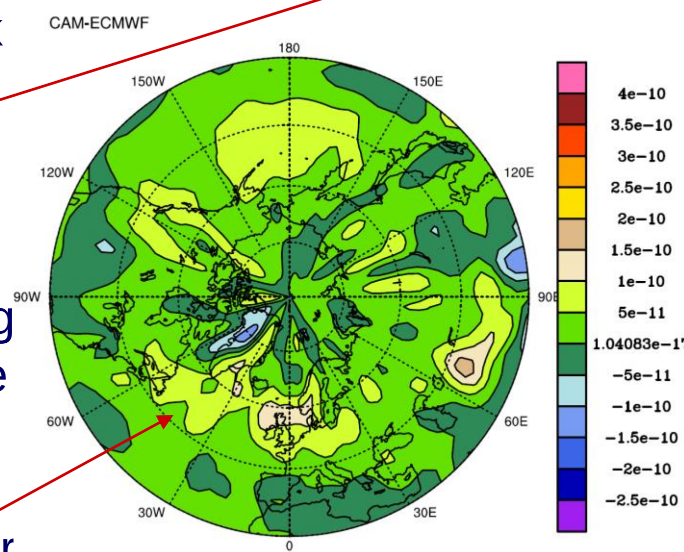
LSW terms



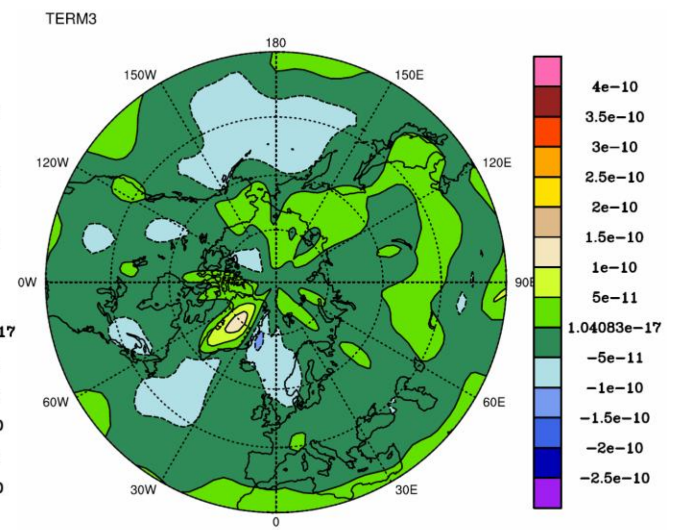
Nonlinear terms



- LSW pattern noisy:
  - Multiple poles N Atlantic & Greenland
  - >0 N side, <0 S side Atl. storm track



Diabatic from ζ eqn residual



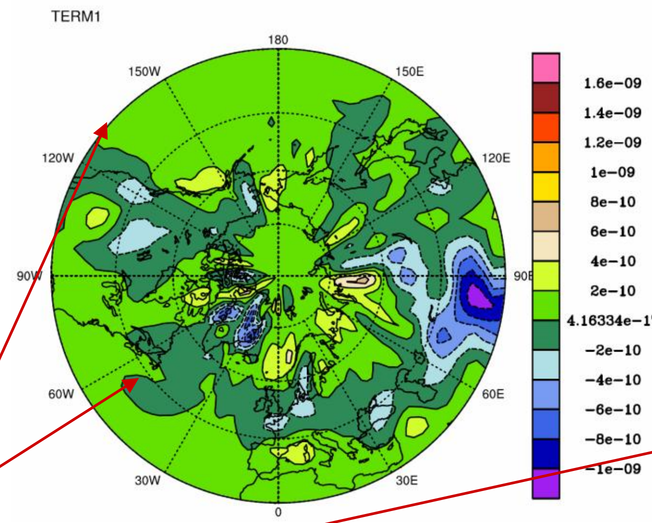
Transient terms

- Nonlinear term large near: Iceland, Spain.
- Transient bias <0 along tracks; Greenland dipole
- Diffusion/Friction bias:
  - Reinforce nonlinear
  - Oppose transients

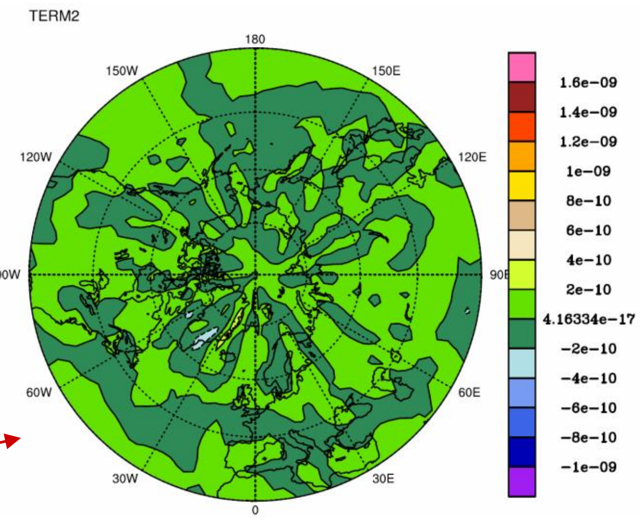
ζ bias eqn terms near Earth surface σ=0.95, DJF

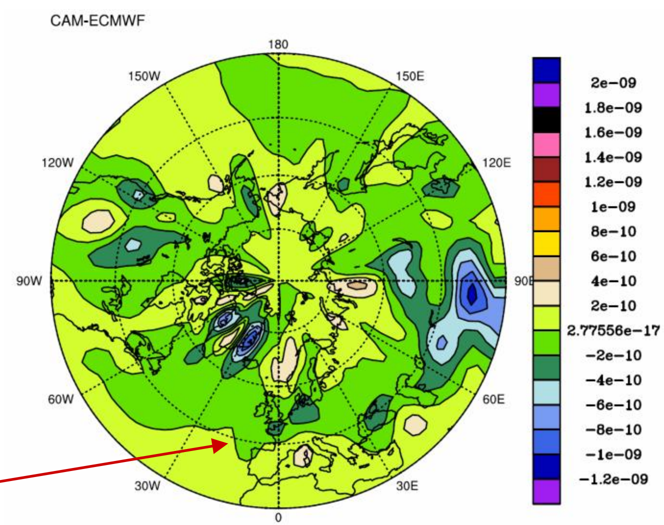
- LSW terms dipoles:
  - Scand., Siberia, Bering St., Greenl'd
- Nonlinear terms small
- Transient bias small
- Diffusion/Friction bias main balance to LSW:
  - Scand. dipole
  - Greenland poles
  - Bering strait dipole

LSW terms

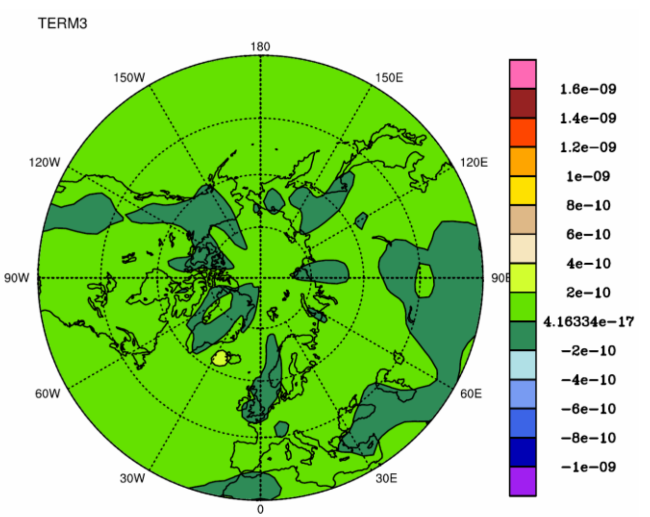


Nonlinear terms





Diabatic from ζ eqn residual
CONTOUR RANGE CHG.



Transient terms

ζ-bias Eqn. Conclusions

- Linear (term 1) very noisy, dominates at upper levels and surface.
- Nonlinear (term 2) important in spots
- Transients (term 3) <0 along northern end of storm tracks (where CAM biases: $U>0$, $\zeta<0$)
- Friction term dominates at surface, downstream parts of storm tracks

Contributors to vertically-integrated diabatic *bias*:

- T bias equation has large contribution from diabatic terms. But calculation as residual of θ equation is uncertain.
- Trenberth & Smith (2008) recommend vertical integrals of the residual in T and moisture equations. Residual for T eqn is:

$$C_p \int_0^{p_s} \{\Delta \overline{T} / \Delta t + \overline{\vec{V}} \bullet \Delta \overline{T} + (p / p_0)^{\frac{R}{C_p}} \overline{\omega} \partial \overline{\theta} / \partial p + (p / p_o)[\nabla \bullet \overline{\vec{V}'\theta'} + \partial(\overline{\omega'\theta'}) / \partial p]\} \frac{dp}{g} = \overline{Q}_1$$

- Calculate this for CAM & ERA-40.
- Note that the vertical integrals also equal sums of boundary fluxes: TOA net radiation, surface sensible heat flux, L*Precipitation:

$$\overline{Q}_1 = R + SH + LP$$

- Compare bias calculated each way.
- Bias from direct evaluation is:

$$\hat{Q}_1 = R_c + SH_c + LP_c - (R_E + SH_E + LP_E)$$

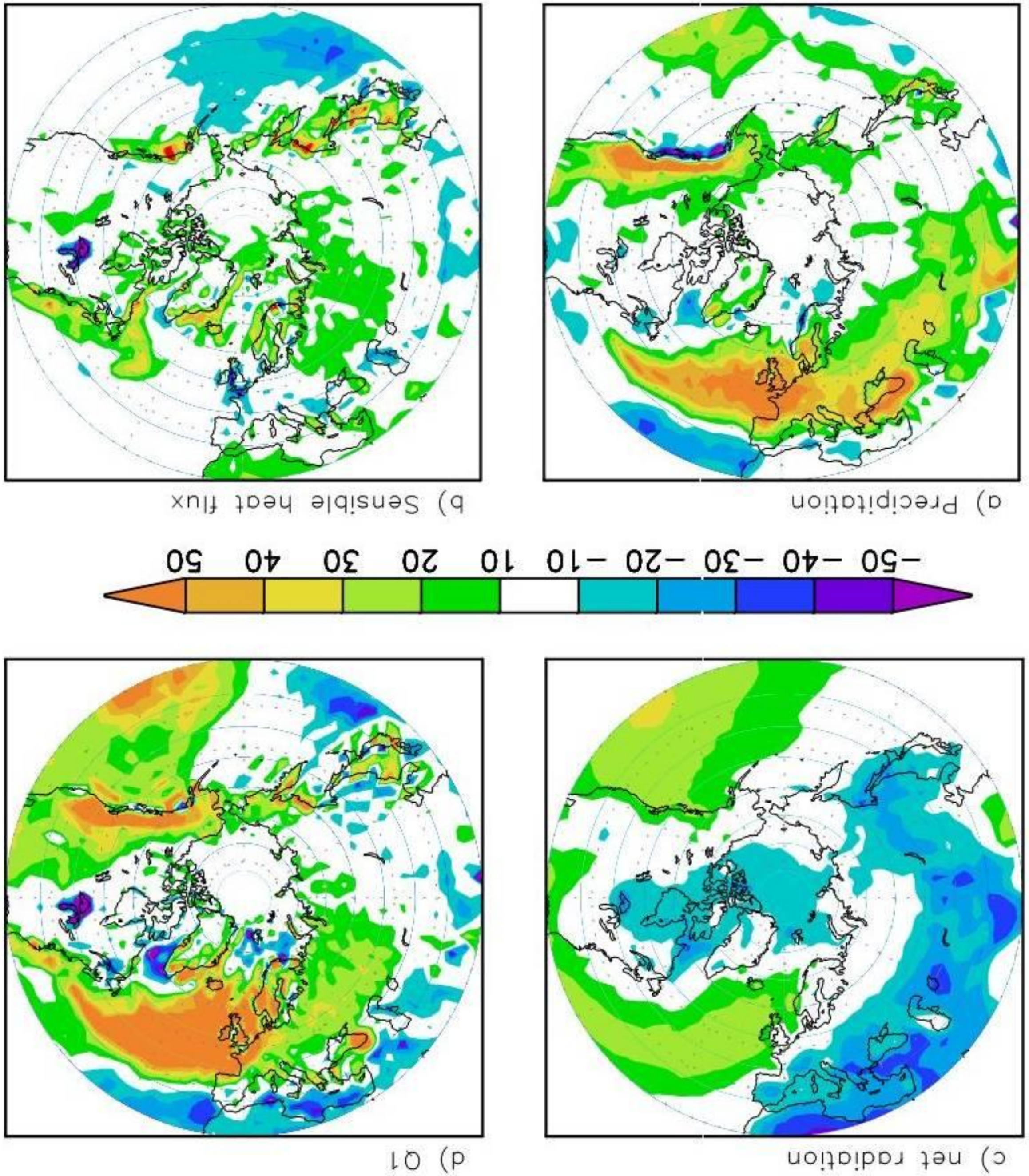
- Compare individual parts of the Q_1 bias.
- Compare to ‘apparent’ heating of moisture eqn: Q_2 = L*(Precip.– Evap.)
- Compare to heating in Total energy eqn: $Q_1 - Q_2$

DJF vertically-integrated diabatic bias

- Q1 bias dominated by heating bias (>0) over Atlantic, Pacific, W. coast (W/m^2)

•Net radiation bias (R) cooling (<0) over Arctic Ocean & Russia. While >0 over Atlantic storm track mainly Precip., also Rad.

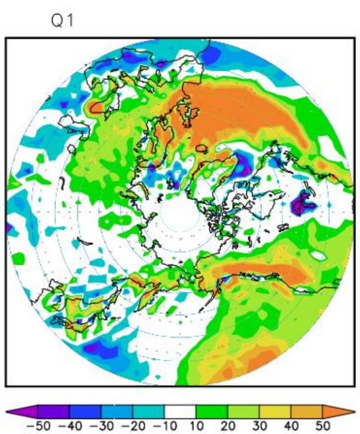
•Pacific storm track <0 at start from SHF, >0 at end from P & R.

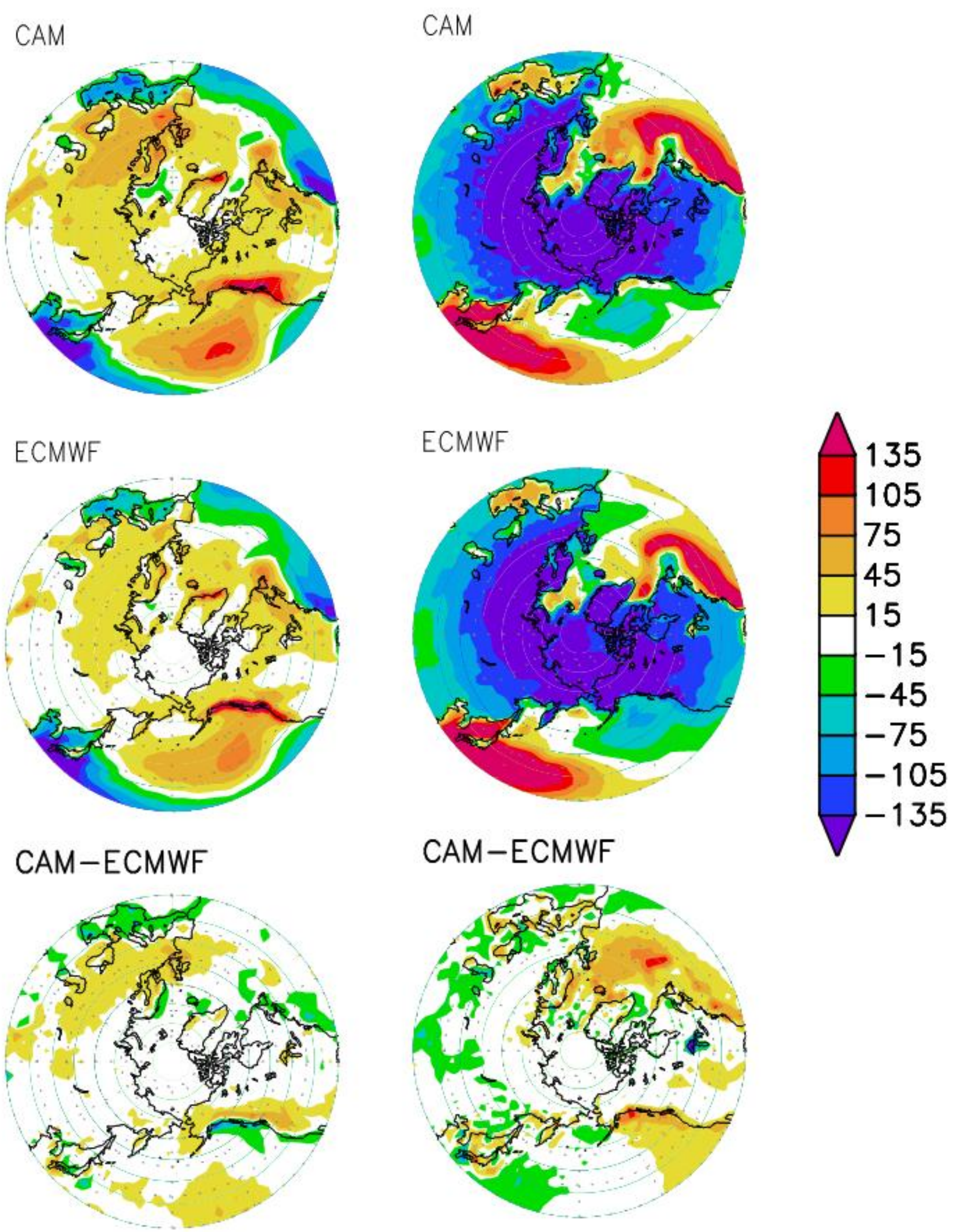


DJF vertically-integrated bias in ‘apparent’ heating & total energy

- Q_2 is heating deduced in a moisture eqn. Q_2 is stronger in CAM over western Russia and part of N. Pacific.

- $Q_1 - Q_2$ total energy eqn heating bias
    - N Atlantic track >0
    - Pacific track <0 @ start, >0 downstream
- Bias →





Vertically-integrated heating Conclusions

- In T eqn heating bias, Q_1: the part from precip (P) > net radiation (R) and both >0 over the N. Atlantic storm track.
- R & P somewhat oppose over Europe and western former Soviet Union.
- R <0 over much of Arctic Ocean, opposed by SHF
- N. Atlantic storm track dominates bias in diabatic heating for T bias and total energy bias, (N. Pacific track different bias at start, not enough SHF in model)

Overall Conclusions

- Analyses of the T bias equation and the ζ bias eqn support using a LSW model to study the forcing responsible for the bias. (Though nonlinear terms a bit larger in ζ bias eqn. and near Earth's surface)
- Analysis of T & ζ bias equations:
  - Finds different behavior in Atlantic and Pacific storm tracks
  - Finds larger forcing of Arctic bias in Atlantic storm track,
    - especially in T eqn.
    - from diabatic and transient processes
  - Finds some forcing of Arctic bias locally
  - Diabatic bias has large contribution by precipitation differences, but also net radiation, especially on downstream end of storm tracks.
  - Most terms have large contributions near surface (unclear if is resolution issue)
- Recommendations:
  - Need to fix >0 bias in: precipitation, net radiation, and heat flux in Atlantic storm track (including downstream over Europe)
  - Need to fix track error of the Atlantic storm track (creates dipolar forcing that results in single-pole bias)
  - Revisit low level diabatic processes over the Arctic?

The End

- Thanks for your patience!

Storage below

- Slides below may be useful if there are questions.

Snapshot of CAM3 DJF Bias

- T42 bias (CAM3 AMIP minus ERA-40) shown for U, V, T. (NCEP RAI used for q)
- Bias has prominent values in NE Atlantic.
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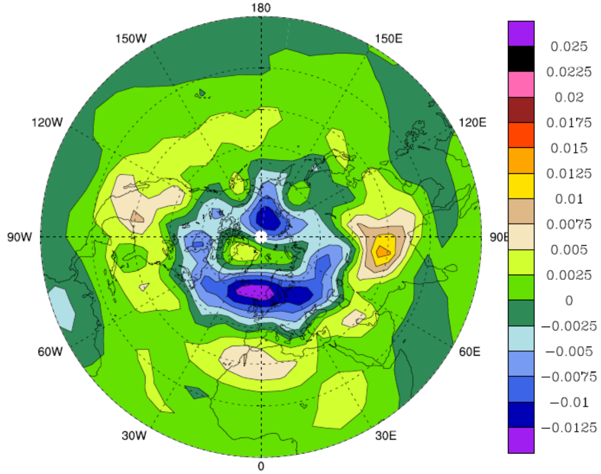

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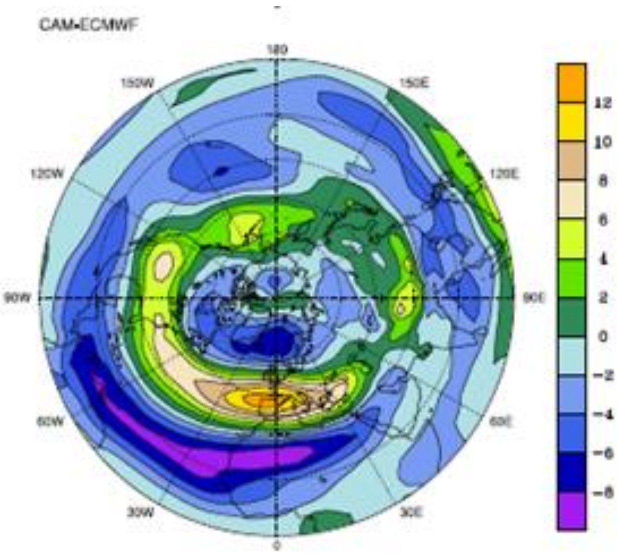
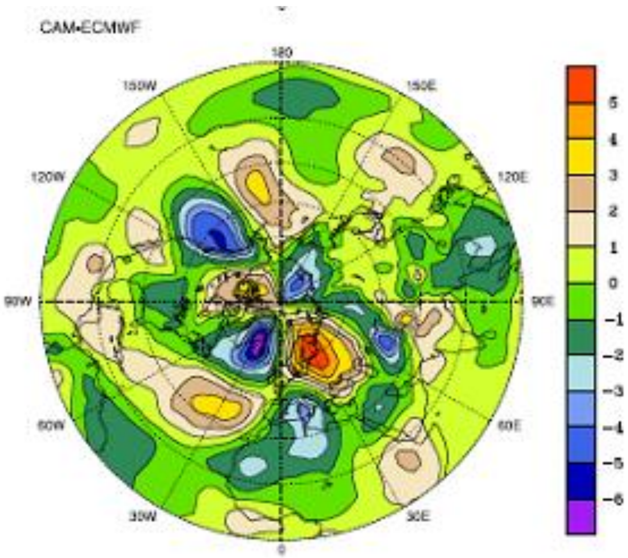
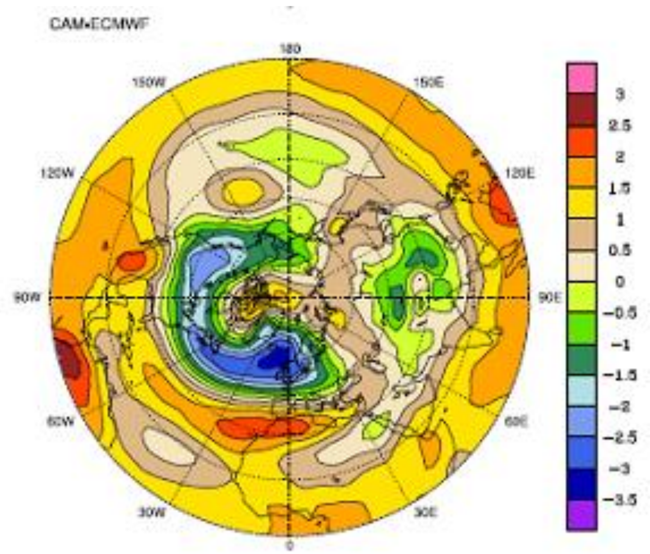


V bias @ σ =0.5



T bias @ σ =0.5



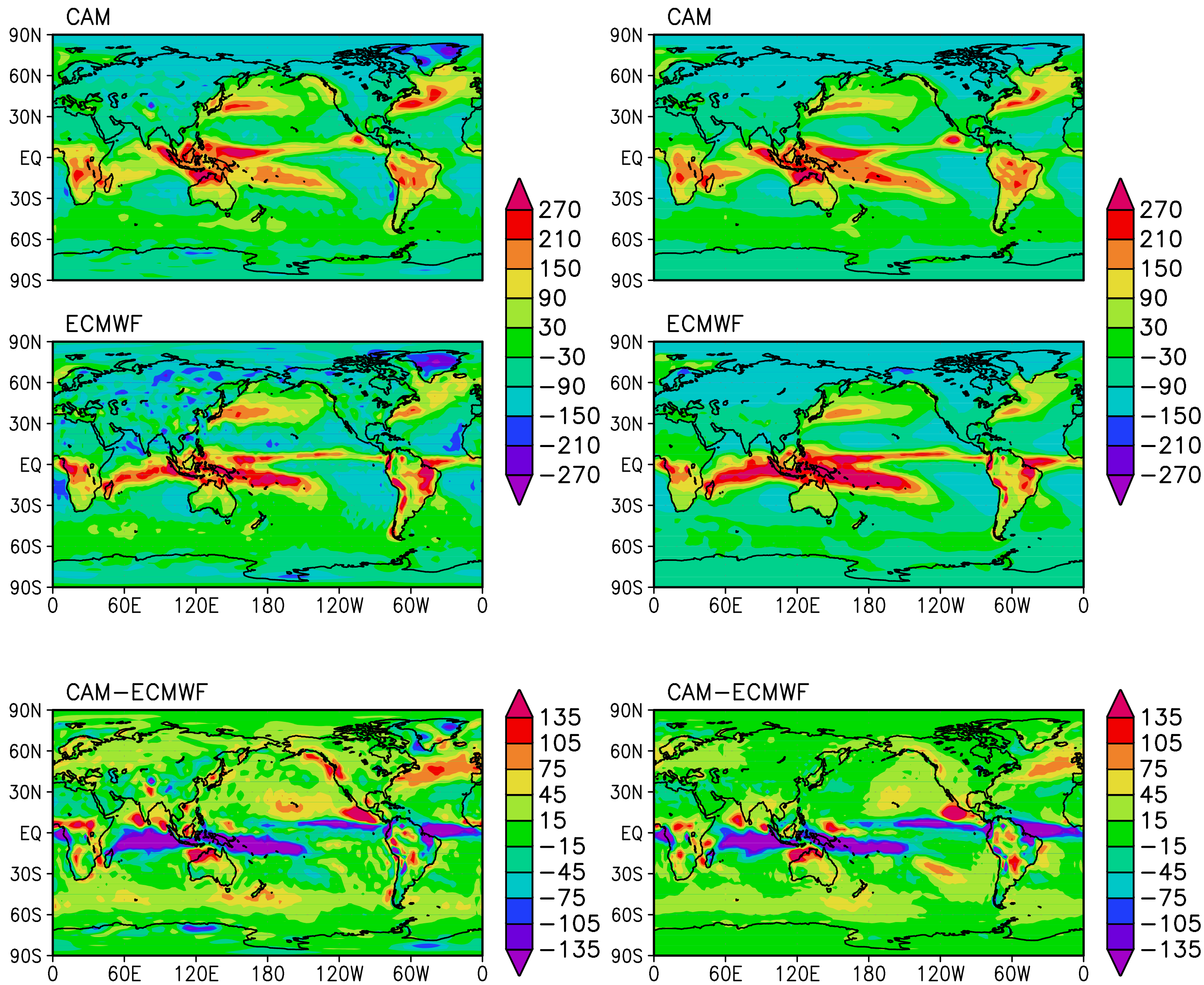
DJF vertically-integrated diabatic Q_1 & bias

- Left panels: diabatic heating from vertical integral of the residual in T eqn.

- Right panels: diabatic heating from direct measures of P, R, SHF.

- Bottom is bias.

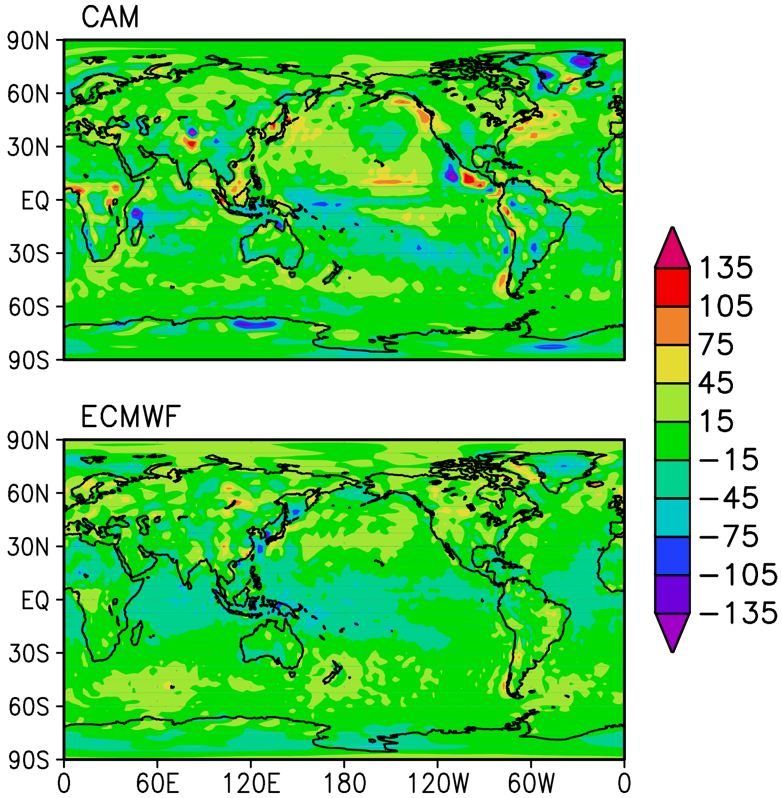
- So essentially same bias for either calculation of Q_1



DJF vertically-integrated diabatic Q_1 & bias

- Difference between calculating Q_1 from vertical integral of the residual in T eqn. versus diabatic heating from direct measures of P, R, SHF.

- So essentially same Q_1 bias for either calculation



DJF vertically-integrated diabatic Q_1 & bias

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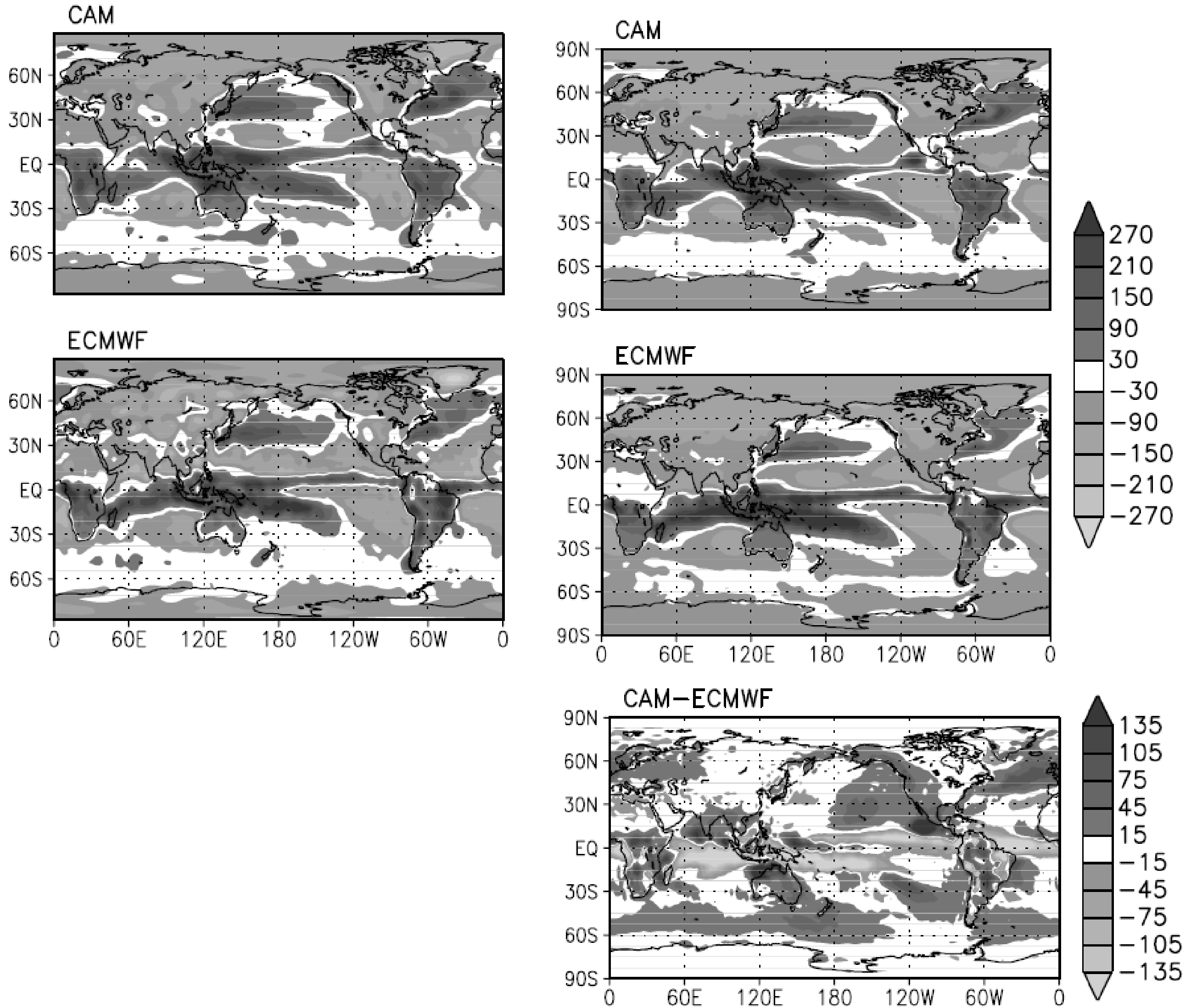

Conclusions

- A temperature bias equation has been examined.
- T bias eqn terms comprise 4 groups:
  - linear combinations of the T bias,
  - diabatic heating bias,
  - transient heat fluxes bias,
  - nonlinear (bias x bias) terms.
- The diabatic heating and and transient eddy groups are prominent at latitudes higher than 30N (mainly in the midlatitude storm tracks) Nonlinear bias terms are small
- The diabatic heating and transient heat fluxes are consistent with the well know storm track error in the N Atlantic.
- The linear terms are included in a linear stationary wave (LSW) model, so such a model can be used to study the bias as if the bias were a stationary wave pattern. (The LSW model also includes divergence, vorticity, and log of surface pressure equations.)
- LSW model severely limited by low resolution but previously we showed:
  - Bias in Arctic can be reproduced from forcing in Arctic and the N Atlantic.
  - Vorticity & T forcing have larger contribution than divergence and ln(Ps) forcing.
- Future work may include testing the forcing in CAM from this T eqn analysis and from a corresponding vorticity eqn analysis.