Sources of CAM3 Arctic Surface Bias from Parsing the Temperature Equation

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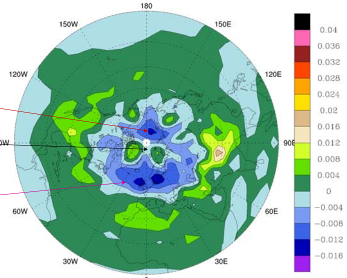
1. Background Information

Recent versions of NCAR climate models have consistent simulation errors in Arctic surface climate (e.g. sea level pressure and low-level wind). These errors have important consequences, such as unrealistic spatial distribution and thickness of Arctic sea ice.

We have been studying the simulation errors by examining the remote mechanisms that affect the Arctic sea level pressure (SLP) in both observation and model output. We use uncoupled (CAM 3.0) model output, since the coupled runs introduce additional error brought by ocean model climate drift. Our primary focus is upon the SLP bias, and that bias is similar in both CCSM and CAM3.0.

Figure 1: bias of q = ln(Ps) where PS is surface pressure. q and SLP bias show the model simulates:

- Beaufort High too low and offset towards Europe.
- positive bias often near Novaya Zemlya.
- Icelandic low is much stronger
- Atlantic storm track extends further into northern Europe.



Previously we showed 3-D structure of the CAM3 model bias in the Arctic and surrounding region.

A model of the linearized CAM3 dynamics (Branstator, 1990) with friction and heating to control nonlinear instability is used to deduce the forcing that creates the model bias as a stationary 'solution'.

The forcing needed to produce the structures and nearly all the amplitude of the Arctic region bias are either localized to the Arctic region or in the midlatitude storm tracks.

2. Data Used

Linear Stationary Wave (LSW) Model

A model used by Branstator (1990) is adapted to this problem. It is run on the UCD cluster 'keas'. The model linearizes the CAM primitive equations about the seasonal time mean. The model is used here two ways:

1. in normal configuration: bias-like stationary solutions are found from a specified forcing.
2. In **reverse configuration**: model bias is input and the requisite forcing to create that bias is found.

This model is run at various resolutions. Results here use R12 and 10 'sigma' levels.

Observational data

We use ERA-40 reanalysis ("**ERA data**") 4x daily data from 1979 to 2002. This data is imported at full resolution then regridded to match the LSW model resolution when constructing the bias. P_s from NCEP.

CAM data

On the UCD cluster we ran a 20 year AMIP T42, 23 level, simulation from 1979-1998 of **CAM3**.0.

3. Parsing the Temperature Equation

The instantaneous temperature equation (P coord.):

$$\frac{\partial T}{\partial t}+\vec{V}\bullet\nabla T+\omega\frac{\partial T}{\partial p}-\frac{\omega\alpha}{C_V}=Q \qquad (*)$$

The diabatic heating is a residual from this equation:

$$\overline{Q}=\Delta T/\Delta t+\overline{\vec{V}}\bullet\nabla\overline{T}+(P/P_0)^{\frac{R}{C_p}}\,\overline{\omega}\partial\overline{\theta}/\partial p+(p/p_o)[\nabla\bullet\overline{\vec{V}\theta'}+\partial(\overline{\omega'\theta'})/\partial p] \qquad (0)$$

Define time average with overbar and use a prime for the deviation from that average. Subscript "C" denotes CAM3 data; subscript "E" denotes ERA-40 data. The time mean of the CAM3 model data is:

$$\overline{V}_C\bullet\nabla\overline{T}_C+\overline{\omega}_C\left(\frac{\partial\overline{T}_C}{\partial P}-\frac{\alpha}{C_V}\right)=-\overline{V_C'\bullet\nabla T_C'}-\overline{\omega_C'\frac{\partial T_C'}{\partial P}}+\overline{Q}_C \qquad (1)$$

For the time mean of the ERA-40 observational data we have:

$$\overline{V}_E\bullet\nabla\overline{T}_E+\overline{\omega}_E\left(\frac{\partial\overline{T}_E}{\partial P}-\frac{\alpha}{C_V}\right)=-\overline{V_E'\bullet\nabla T_E'}-\overline{\omega_E'\frac{\partial T_E'}{\partial P}}+\overline{Q}_E \qquad (2)$$

Define a ^ notation for the bias, for example: . Subtract (1) – (2):

$$\hat{V}\bullet\nabla\overline{T}_E+\overline{V}_E\bullet\nabla\hat{T}+\hat{\omega}\left(\frac{\partial\overline{T}_E}{\partial P}-\frac{\alpha}{C_V}\right)+\overline{\omega}_E\left(\frac{\partial\hat{T}}{\partial P}-\frac{\alpha}{C_V}\right)=-\hat{V}\bullet\nabla\hat{T}-\hat{\omega}\frac{\partial\hat{T}}{\partial P}\underbrace{-\overline{V_C'\bullet\nabla T_C'}+\overline{V_E'\bullet\nabla T_E'}-\overline{\omega_C'\frac{\partial T_C'}{\partial P}}+\overline{\omega_E'\frac{\partial T_E'}{\partial P}}}_{=THF}+\hat{Q} \qquad (3)$$

The first 2 terms on the RHS are nonlinear terms in the bias. The group labeled THF are transient heat advection bias. Q^ is the bias in diabatic heating.

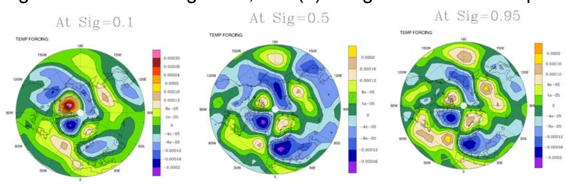
The time mean temperature equation in the reverse configuration of the Branstator LSW looks like:

$$\hat{V}\bullet\nabla\overline{T}_E+\overline{V}_E\bullet\nabla\hat{T}+\hat{\dot{\sigma}}\frac{\partial\overline{T}_E}{\partial\sigma}+\hat{\omega}\frac{\kappa\overline{T}_E}{P}+\overline{\dot{\sigma}}_E\frac{\partial\hat{T}}{\partial\sigma}+\overline{\omega}_E\frac{\kappa\hat{T}}{P}=\underbrace{-\alpha_T\hat{T}+K_T\nabla^2\hat{T}+K_v\frac{\partial^2}{\partial\sigma^2}\left(\hat{T}\sigma^{-\kappa}\right)}_{diffusion\,\&\,friction}+F \qquad (4)$$

F is for nonlinear bias, quadratic transient advection and diabatic processes. When run in reverse, the LSW model finds F (for all 4 governing equations: T, D, ζ, and q=lnPs.)

4. Forcing Fields from LSW Model (reverse config.)

Fig. 2: Thermal forcing fields, F in (4) using CAM-Obs bias input.



5. Groups of Terms in (3)

Terms in (3) at illustrative levels; σ= 0.1, 0.5, and 0.95; σ=1 is the Earth's surface. Calculated in T42 plotted at R12. **Contour ranges vary to show detail!**

Term 1 refers to the linear advection terms by the stationary bias and climatological fields; it is all terms on the LHS of (3).

Term 2 refers to the nonlinear advection of the bias by the bias; it is the first 2 terms on the RHS of (3).

Term 3 refers to the time mean advection by the transients; it is labeled THF in (3).

Term 4 is the diabatic heating bias, $\hat{Q}$. We also compute this term using only high frequency (2-8 days) for the transient parts of (0).

Figure 3: Term 1 (top), term 2, and term 3 (bottom)

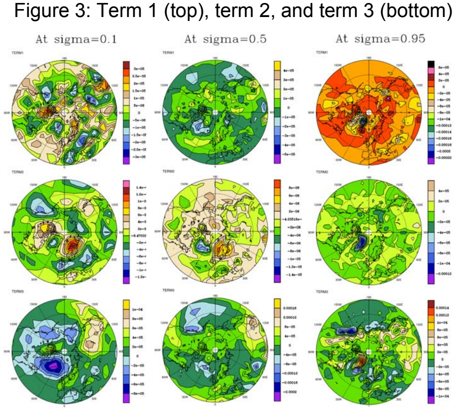


Figure 4: term 4 (diabatic heating)

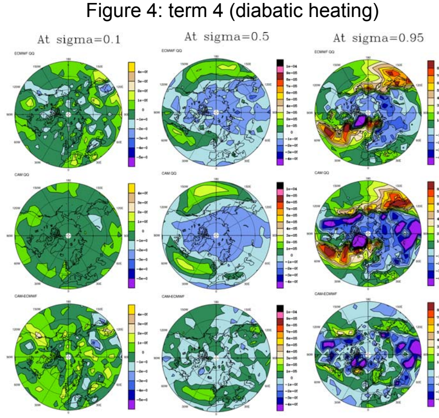
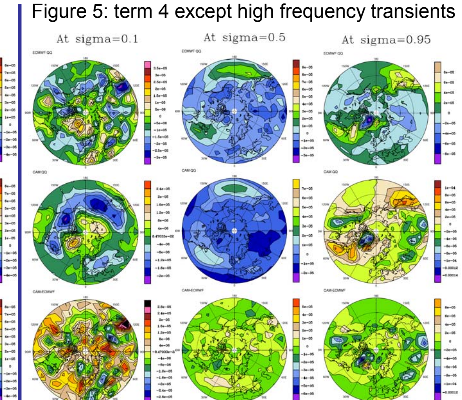


Figure 5: term 4 except high frequency transients



6. Discussion & Conclusions

A. LSW model thermal bias forcing, F, eqn (4)

- Bias forcing mainly local to the Arctic; exception is N. Atlantic
- Dipole forcing is associated with monopole bias.
- Dipole N Atlantic bias has quadrupole forcing F.
- Caution: F magnitude seems too large; max heating rates >12K/day.

B. Forcing from model output and observations, eqn (3)

- Linear stationary wave advection (term 1) dipolar in Atlantic (negative NW of positive); opposite but weak dipole over Europe.
- The nonlinear term (term 2) has 3 of the 4 poles found in F but is smaller than other terms (and F).
- The transient advection (term 3) comparable to F at Denmark Strait (negative sign and size) not so similar elsewhere.
- Diabatic fields from ERA-40 and CAM3 consistent with each other and with other researchers (e.g. DeWeaver, 2004 CCSM Workshop)
- Diabatic bias (term 4) larger & positive in Atlantic storm track
- Transient and diabatic forcing (terms 3 & 4) imply model storm track is a key source of the Atlantic bias, consistent with LSW forcing.

7. Ongoing and Future work

- Fix F magnitude. Find & remove large eigenvalue modes from bias?
- Further parse the forcing by region, frequency range, and level
- Examine vorticity and q forcing from their respective equations