Annual Report for Period: 05/2007 - 04/2008
Submitted on: 03/17/2008
Principal Investigator: Grotjahn, Richard .
Award ID: 0354545
Organization: U of Cal Davis
Title:
Understanding Arctic Surface Climate Simulation Errors

Project Participants

Senior Personnel

Name: Grotjahn, Richard
Worked for more than 160 Hours: Yes
Contribution to Project:
Richard coordinates all the research tasks and activity by the personnel. He has nearly daily meetings with his Post-doc and had held weekly meetings with any graduate students employed by this grant. In these meetings results are reviewed and he develops the next steps to be taken. His research tasks include facilitating data transfers from NCAR and ECMWF. Richard also advises on coding issues including: subroutine procedures, debugging code created by others, writing subroutines for others. He has communicated SWM (stationary wave model) programming queries by his students and postdoc to NCAR collaborators. During this period, he has traveled to present results and solicit feedback at: the annual CCSM Workshop (June, 06), a separate NCAR visit (October 06), and the AMWG meeting (January 07). He has also been doing independent companion research related to the project (e.g. statistical analyses of remote forcing of Arctic SLP, comparisons of ERA-40 and NCEP/DOE reanalysis II datasets)

Name: Branstator, Grant
Worked for more than 160 Hours: No
Contribution to Project:
Grant provided a copy of his stationary model (spherical geometry) code. He has helped us by providing testing datasets, evaluating whether the updated model is working properly and coding issues with our use of his model. Grant has also been advising us as to developing a nonlinear iterative application of this model and a storm track model to sort out nonlinear forcing of the stationary wave error pattern. Grant has also been advising us as to developing a procedure to separate the forcing of the bias pattern into transient eddy, diabatic, nonlinear, and other sources. Grant has been very active this year in discussing ideas and approaches.

Name: Briegleb, Bruce
Worked for more than 160 Hours: No
Contribution to Project:
Bruce has assisted us in identifying appropriate current model datasets. We needed data run at high resolution (T85) and using observed forcing in order to compare and contrast what model and atmosphere do differently. These 'AMIP' datasets were not publicized, but know to Bruce through his other work at NCAR. Bruce also gave some advice on how to read the data.

Name: Tribbia, Joseph
Worked for more than 160 Hours: No
Contribution to Project:
During the first year Joe has provided a valuable role of someone with whom the PI can discuss ideas and approaches.

Post-doc

Name: Pan, Lin Lin
Worked for more than 160 Hours: Yes
Contribution to Project:
Dr. Pan was hired in August 2006; all his salary and benefits are paid by this grant. The project is very challenging and beyond the capabilities of any graduate student available to the PI. During his first 7 months he has developed and successfully tested a 'backwards' version of Grant's SWM. He has run numerous tests and calculations. Examples: NCEP vs ERA-40 verifications; resolved issues with differing topographies in reanalysis, CAM, and SWM; implemented and tested higher vertical resolution (maxing out addressable storage); established the SWM forcing of all the bias fields and various parts and regions of the bias fields. He successfully ported CAM3.1 and is developing a scheme to separate transient from diabatic from other causes of the bias.

Graduate Student

Name: Osman, Muhtarjan

Worked for more than 160 Hours: No

Contribution to Project:

Muhtar has been charged with a variety of tasks. He rapidly learned NCL and netcdf commands to develop and test some statistical analysis programs. The statistical programs do such tasks as: 1-point correlations (with significance tests), power spectra, Lanzcos filtering, and composite analysis (with significance). He needed much time to modernize and make portable on our computer system Branstator's stationary wave model. This last task proved more difficult than expected. Muhtarjan probably worked roughly 1000 hours the past year on this project.

Name: Hanrahan, Elena

Worked for more than 160 Hours: No

Contribution to Project:

Elena is a new MS-level who commenced working on tasks related to this project in September 2005. She was supported during the academic year: half by this grant and half by other fund sources.

Name: Tan, Elcin

Worked for more than 160 Hours: No

Contribution to Project:

Elcin worked on data gathering and simple statistical analysis tasks during Fall 2006. She is no longer funded by this grant and expects to finish her Masters degree in Spring 2007.

Undergraduate Student

Technician, Programmer

Name: Jacobsen, Richard

Worked for more than 160 Hours: Yes

Contribution to Project:

Richard developed a new cluster computer dedicated to this project that will finally allow us to have the data we need to separate the sources of the bias in a timely manner. He is paid from departmental funds and not from the grant.

Other Participant

Research Experience for Undergraduates

Organizational Partners

National Center For Atmospheric Research

NCAR staff member (Andy Mai) ran some initial tests of a modified version of CAM3.0 to include T and vorticity forcing provided by us. He needed to collaborate with other staff at NCAR. He used computing resources from a small grant the PI obtained.

Other Collaborators or Contacts

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)

(See PDF version submitted by PI at the end of the report)
Please see attached file for list of activities since the last annual report. (Period: April 2007 through March 2008). This report is cumulative over the entire grant.

Findings: (See PDF version submitted by PI at the end of the report)

Please see attached ACTIVITIES file for list of major findings since the last annual report. (Period: April 2007 through March 2008). This report is cumulative over the entire grant

Training and Development:

During the 12 months (April 2006-March 2007):
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Muhtar completed his assigned tasks in regridding, statistical analyses (mainly 1-point correlations), SWM studies, and documenting the programs and scripts he wrote. Muhtar completed his MS degree and graduated in June 2006.
Elcin learned plotting and data handling uses of NCL. She also learned about 1-pt correlation statistical procedure.
Lin Lin picked up where Muhtar had left off, completing implementation of the 'backwards SWM': where the forcing is deduced from the bias field. He had to learn the details of the SWM in order to change the resolution and improve and include new output variables and plotting. He learned NCL. He obtained a copy of the currently released CAM and has made test runs on 'aske' the computer purchased on this grant in year 1. With our departmental linux manager, he is testing CAM on multi-processor computers. He gave a presentation using his own SWM (which includes transient forcing) at the AMS annual meeting (January, 2007).
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During the 12 months (April 2007-March 2008):
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Lin Lin continued his training by installing and running a version of CAM on a local computer cluster. He also prepared a proposal to NSF to continue work he did on his dissertation; it was his first try at writing a proposal (with assistance from the PI) but the inital decision is puzzling. Lin Lin also learned some new (to him) statistical procedures that the PI has used in other publications and theses. Lin Lin is assisting the PI in the preparation of another proposal (different subject).

Outreach Activities:

Nothing much yet for the general public. Of course, we have been informing those people most directly interested in the work via CCSM and AMWG meetings.

Journal Publications

Richard Grotjahn, "On type B cyclogenesis in a quasi-geostrophic model", Quarterly Journal of the Royal Meteorological Society, p. 109, vol. 131, (2005). Published,

Richard Grotjahn and Muhtarjan Osman, "Remote weather associated with North Pacific subtropical sea-level high properties", International Journal of Climatology, p. 587, vol. 27, (2007). Published, 10.1002/joc.1423

Richard Grotjahn, "Deducing the General Circulation from Basic Concepts and a Few Empirical Facts", Dynamics of Atmospheres and Oceans, p. 3, vol. 43, (2007). Published, 10.1016/j.dynatmoce.2006.05.002

Richard Grotjahn, "Preface to Part 1", Dynamics of Atmospheres and Oceans, p. 1, vol. 43, (2007). Published, 10.1016/j.dynatmoce.2006.10.001

Richard Grotjahn, "Different data, different general circulations? A comparison of selected fields in NCEP/DOE AMIP-II and ECMWF ERA-40 reanalyses", Dynamics of Atmospheres and Oceans, p. , vol. , (2008). Accepted, 10.1016/j.dynatmoce.2007.08.001

Richard Grotjahn, "Preface to Part 2", Dynamics of Atmospheres and Oceans, p. , vol. , (2008). Accepted, 10.1016/j.dynatmoce.2007.10.001

Richard Grotjahn and Ghislain Faure, "Composite Predictor Maps of Extraordinary Weather Events in the Sacramento, California, Region", Weather Analysis and Forecasting, p. , vol. , (2008). Accepted, 10.1175/2007/WAF2006055.1

Books or Other One-time Publications

Web/Internet Site

URL(s):

http://atm.ucdavis.edu/~grotjahn/Arctic/

Description:

This site is intended to accumulate materials that foster communications about our study between the participants in the research. We have also found it useful for communicating our in-progress results to others in the NCAR CCSM community.

Other Specific Products

Contributions

Contributions within Discipline:

The QJRMS paper acknowledges partial support from this NSF grant (the new computer purchased to complete a research project started before this grant). The paper's significance to dynamics is to clarify the 'type B' mechanism of cyclogenesis in a nonlinear framework using realistic initial conditions. In the process it also proposes a mechanism to explain observed propagating, but non-amplifying short waves.

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The IJC paper also finishes up a research project started before this grant. The significance lies in sorting out what forcing maintains the subtropical north Pacific subtropical high (NP high). Several theories for the maintenance of the NP high have been proposed by others using dynamical reasoning or model simulations. We are the first to look in depth at observed associations and find too little support for two of the theories and some support for two others. One theory seems to have the connection backwards; instead of low level thermal structure forcing the high, the high creates that low level thermal structure. We find the NP high to be much more less tropical forcing than was the south Pacific high.

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The two papers in DAO are part of a special issue.

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The shorter DAO paper shows how one can deduce the general circulation from first principles, but only to a point. Some theoretical dynamics along with the observed precipitation distribution are also needed.

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The second DAO paper has been extensively revised to highlight large scale circulation features that indeed differ between the ERA-40 and NCEP/DOE reanalysis II datasets. Some differences are not well known and have not appeared in the literature previously. This work led us to switch from the NCEP reanalysis II data we had been using for our Arctic bias calculations to the ERA-40 data. This is the first uniform comparison of the datasets on a global domain. Some prior works compared a limited set of variables and only certain limited regions. The datasets have different surface energy balance, and interhemispheric communication. The Hadley cells are quite different: stronger circulation but lower moisture content in ERA-40 but these compensate to give similar zonal mean precipitation. NCEP data is missing an Atlantic ICZ during DJF.

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The WAF paper finds large scale patterns associated with 4 different types of extreme weather events. This extensive study forms the basis for a new proposal that applies the knowledge from this current weather forecasting application to understanding key aspects of future climatic change.

Contributions to Other Disciplines:

Contributions to Human Resource Development:

A variety of skills were learned by the PI, the post-doc Lin Lin and graduate students Elena, Muhtar and Elcin that are listed above under 'Training and Development' heading. Successful MS student Brooke Bachmann also learned several statistical skills.

Contributions to Resources for Research and Education:

Contributions Beyond Science and Engineering:

Special Requirements

Special reporting requirements: None

Change in Objectives or Scope: None
Animal, Human Subjects, Biohazards: None

Categories for which nothing is reported:

Any Book
Any Product
Contributions: To Any Other Disciplines
Contributions: To Any Resources for Research and Education
Contributions: To Any Beyond Science and Engineering

Cumulative Research Activities:
NSF Grant: ATM0354545
PI: Richard Grotjahn

I. May 2004 – April 2005 (Year 1)
In the past 12 months (May 2004 – April 2005) we can report the following activities:

A. successfully completed initial sequence of observational studies with lagged correlation and composite statistical analyses of daily data. (had to low-pass filter data)
B. tested additional diaganostic tests as suggested by Brian Hoskins and by John (Mike) Wallace (however, results were inconclusive)
C. Implemented FORTRAN 95 version of stationary wave model (SWM) provided by Grant Branstator. (Code provided used: obsolete Fortran, a NCAR-specific unsupported iftran preprocessor, obsolete NCAR library routines, and double precision in a way that would not work on our Linux system.)
D. attended 8th CCSM workshop: presented results & met with collaborators
E. attended CLIVAR 2004: presented results and held discussions

II. May 2005 – March 2006 (Year 2)
In the past 11 months (May 2005 – March 2006) we can report the following activities:

A. completed our initial 1-point correlation studies using filtered data with lags and leads.
B. investigated a possible link between the SLP bias and the Arctic Oscillation (AO)
C. continued work to implement Branstator's stationary wave model (SWM)
D. developed code to interpolate model and observational fields to SWM sigma levels
E. have nearly completed development of scheme to derive forcing from bias fields
F. made extensive tests with temperature (T) forcing of the SWM, based on the T bias
G. evaluated whether ERA-40 or NCEP RA2 fields were better for bias & verification
H. attended 9th CCSM workshop: presented results & met with collaborators
I. attended IAMAS 2005: presented results and held discussions
J. 1 paper published, submitted 2 papers, revised and resubmitted a 3rd.

III. April 2006 – March 2007 (Year 3)
In the past 12 months (April 2006 – March 2007) we can report the following activities:

A. Student Muhtar Osman completed his MS degree (June 2006)
B. Postdoctoral scholar Lin lin Pan was hired (August 2006)
C. completed testing and implementation of Branstator's stationary wave model (SWM); including solving vexing problems with: divergence forcing, friction and diffusion testing, and topographic differences between CAM, SWM, and verification data.
D. used highest resolution of SWM (R12, 10L; limited by 2GB addressable storage on a 32-bit machine) so we began creating 64-bit computer to allow higher resolution
E. completed all initial 'forward calculation' (given the forcing, find the parts of the bias) runs of SWM

F. completed all initial ‘backwards calculation’ (given the bias, find the forcing that creates it) runs of SWM.
G. created a project website (http://atm.ucdavis.edu/~grotjahn/Arctic/) to facilitate communication between team members.
H. displayed the bias in 3-dimensional structure (see http://atm.ucdavis.edu/~lpan/doc/ or the project website)
I. identified the forcing structures in 3-dimensions for the 4 prognostic variables.
J. identified which parts of the Arctic region bias could be isolated (Beaufort high region) and which were linked (North Atlantic, Barents dipole).
K. began development of study to separate diabatic from transient forcing of the bias
L. attended 10th CCSM workshop: presented results & met with collaborators
M. attended AMWG meeting (January, 2007): presented results & met with collaborators
N. imported CAM3.1p and began running it locally (the TB of data with necessary time, space resolution not available elsewhere) for separating diabatic and transient forcing.
O. purchased new cluster computer to facilitate multi-year AMIP runs of CAM3.1 (goal: increase rate of annual simulations by factor of 10.)
P. revised 3 papers, two have been published.

IV. April 2007 – March 2008 (Year 4)
In the past 12 months (April 2007 – March 2008) we can report the following activities:

A. Student Brooke Bachmann completed her MS degree (March 2008)
B. attended 11th CCSM workshop (June 2007): presented results & met with collaborators
C. PI made 3 presentations (one invited) at IUGG in Perugia, Italy (July, 2007). Was co-convenor of 1 session.
D. AMWG meeting (January, 2008): presented results & obtained useful feedback
E. Completed analysis by linear stationary wave model (LSWM) of the forcing that is associated with parts of the CAM bias and vice-versa. A publication is in preparation.
F. Completed analysis of temperature bias (T-bias) equation using daily data from CAM & ERA-40. A publication is in final preparation. One result justifies use of LSWM.
G. Obtained NCAR computing account to make initial CAM tests.
H. Made some preliminary calculations using a modified version of CAM. NCAR staff assisted with the modifications and running of the code for 9 preliminary tests (5-year ensembles).
I. Revised 3 papers, 3 have been published or accepted.
J. 2 papers are in preparation.

Cumulative Research Findings:
NSF Grant: ATM0354545
PI: Richard Grotjahn

In this document the research findings from each year are appended and separated.

I. May 2004 – April 2005 (Year 1)
In the past 12 months (May 2004 – April 2005) we can report the following findings:

A. To see strong behaviors found in monthly mean data it was necessary to low pass filter the data; a10 days cut-off was long enough to recover correlations similar to monthly mean data but short enough to evaluate what precedes what.
B. One surprise was that stronger SLP in the Barents and GIN seas leads (not follows) a storm track shift into the Iberian Peninsula.
C. Eric deWeaver reported at the July 2004 CCSM workshop somewhat related linear calculations, his work spurred us to focus on developing a nonlinear iterative calculation in addition to the linear model calculations already planned.
D. CAM has stronger tropical connection (SLP autocorrelation) than does the NCEP/NCAR reanalysis data. See Fig. 1-1.

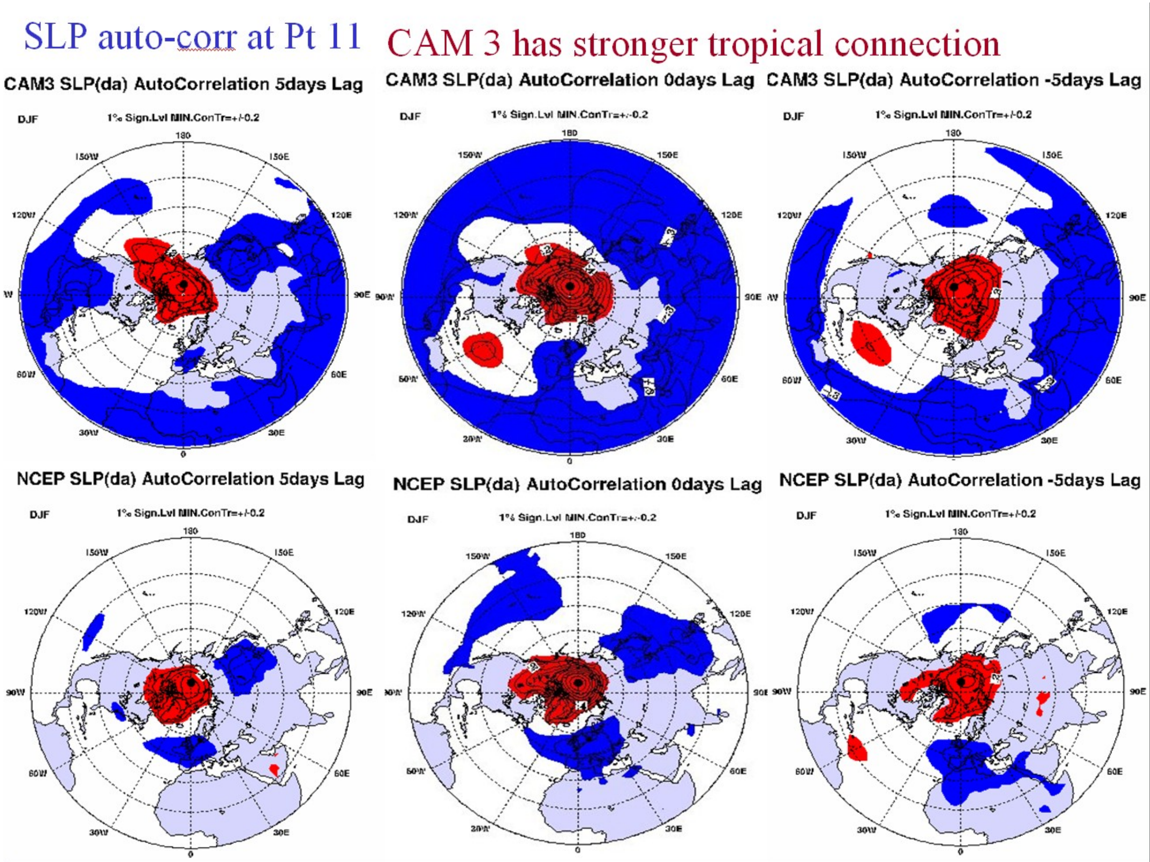

Figure 1-1. 1 point autocorrelations of CAM3 SLP and NCEP RA1 SLP for a point near center of Beaufort high (where CAM3 bias <0). The model has stronger tropical connection than observational data. Points on the Pacific side of the Beaufort high have stronger North Pacific connection in CAM3 than NCEP RA1. The figure shows a weak preference for above normal SLP over China and Mexico and below normal SLP in Alaska and adjacent Gulf to precede weaker Beaufort high. Positive correlation more easily spreads over Alaska in the model then in NCEP data, perhaps consistent with topography and surface drag hypotheses.

II. May 2005 – March 2006 (Year 2)

In the past 11 months (May 2005 – March 2006) we can report the following findings:

A. The SLP bias field has ring-like structure roughly centered near Barents Sea; to some people it looks like the AO. Since the AO is a strong internal mode of variability in the model, the AO could be stimulated by various means and therefore it would be difficult to identify primary cause(s) for the bias pattern. From CAM3 data we obtained the leading EOF of SLP (the model's form of the AO) and after interpolating to matching Gaussian grids projected that EOF onto the model SLP bias. We found that the bias was NOT like the AO. (Figure 2-1) The EOF was a small part of the bias, so internal variability cannot explain much of the bias field. Further, when the EOF was removed from the bias the resultant field looked more similar to the bias found in earlier model versions, recovering a positive maximum bias near Novaya Zemlya. This result is important because it means that it is reasonable to seek local and remote causes of the Arctic surface bias.

B. The 1-point correlation studies, both with model output and in NCEP/NCAR RA1 observations find a significant lagged correlation with Indian Ocean Precipitation (P) and outgoing longwave radiation (OLR). Filtered daily data find correlation between high SLP near Novaya Zemlya ~5 days before P (or OLR) in the NE Indian Ocean. The correlation flips sign as the location of P (or OLR) is moved latitudinally. (Figure 2-2) The P bias field has a dipole pattern in the NW Indian Ocean consistent with the SLP bias in the Novaya Zemlya region.

C. Tests with very simple idealized heating anomalies in the SWM reproduce various parts of the SLP bias. (Figure 2-3) Cold and warm anomalies can be generated by anomalous cooling and heating forcing in the SWM. Nine such cooling/heating anomalies can match prominent cold and warm anomalies in the lower free troposphere and generate wavetrains in SWM fields, including surface pressure (our conversion to SLP is shown). Tests of the 9 anomalies singly and in combination find that anomalous cooling over Saharan and Arabian deserts has the strongest link to positive SLP near the Barents Sea maximum SLP bias. Other major cooling/heating forcing (biases) have lesser effect on the Barents region. Anomalous warming (to match a warm bias) in eastern Siberia has a prominent secondary effect on Arctic Ocean region: contributing to the Barents SLP bias max and lower SLP over the Beaufort Sea (where the model has negative bias).

D. We compared numerous large scale variables in the ERA-40 and NCEP/DOE reanalysis II datasets. The ERA-40 data seem to allow more interhemispheric transfer of information than the NCEP data. The ERA-40 data has more vigorous Hadley cells but evaporates less water in the subtropics so that both datasets have quite similar precipitation(!) The tropical Atlantic was largely missing the ICZ during DJF in NCEP data(!) However, the northern Indian Ocean seemed more reasonable in NCEP data. This study suggests that we make comparisons (and bias calculations) with ERA-40 data as well as (or in place of) NCEP data.

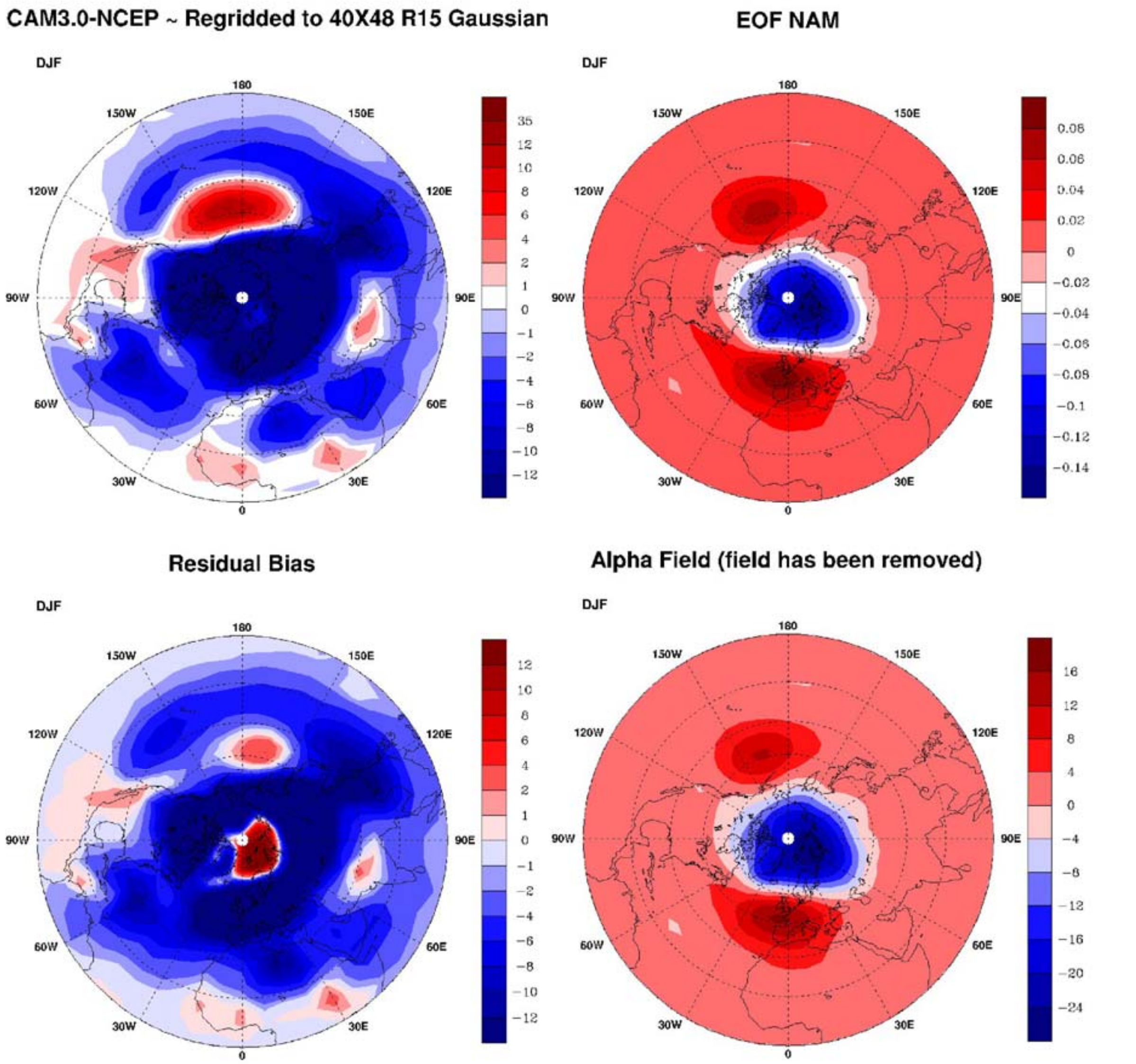

Figure 2-1. The SLP bias in CAM3 (and CCSM3) does ***not*** have a significant amount of the model's Arctic Oscillation (AO). Top left panel is CAM3 SLP bias (CAM3 minus NCEP RA I). Top right is leading EOF in CAM3, the model's form of the AO. Lower right panel is the projection of the bias onto the EOF. Lower left is the residual after removing that projection from the bias. Clearly the EOF is not a primary contributor to the SLP bias in the model. Removing the EOF produces a bias in CAM3 that more closely resembles the Arctic bias in earlier models (e.g. CCM3.6). This result is important because if the EOF was the main contributor then the SLP bias would be a natural mode of variability that could be excited by many different phenomena rather than a standing wave pattern that might be understood by distinct forcing, such as in a stationary wave model.

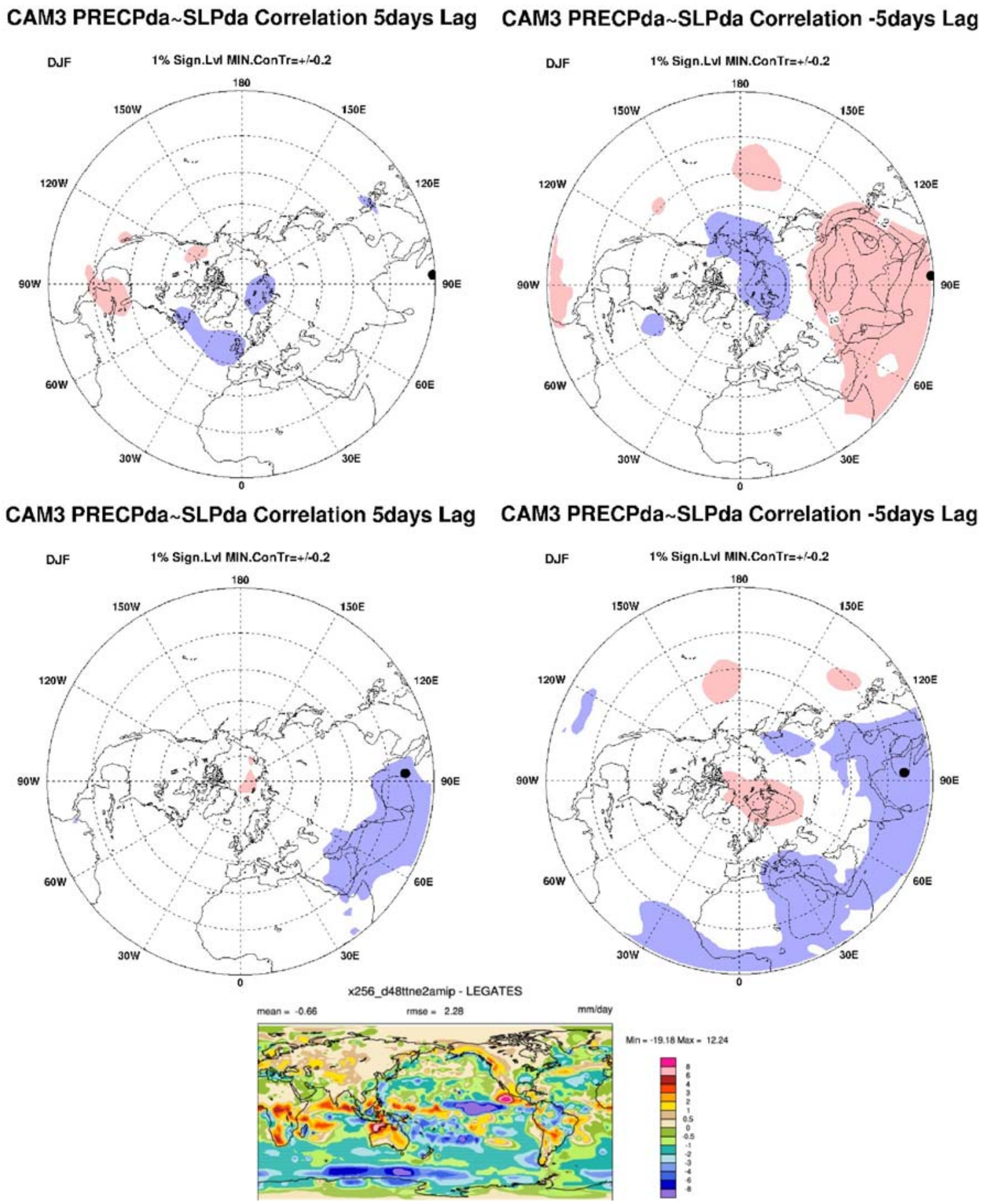

Figure 2-2. 1 point correlations of CAM3 precipitation (P at the black dot) and CAM3 SLP (2-Dimensional field). Left column, SLP correlation 5 days before value of P at black dot. Right column, SLP correlation 5 days after P at black dot. Data low pass filtered with 10d cut-off. Shaded areas pass a significance test at the 99% level. Bottom inset: CAM3 AMIP run (posted at NCAR-CGD website) which shows P bias dipole pattern in NE Indian Ocean: negative at equator (reverse sign of top row of plots) and positive at 10 N (middle row of plots). The dipoles in P bias both give SLP bias >0 near Novaya Zemlya. A similar connection is found in observed OLR and SLP.

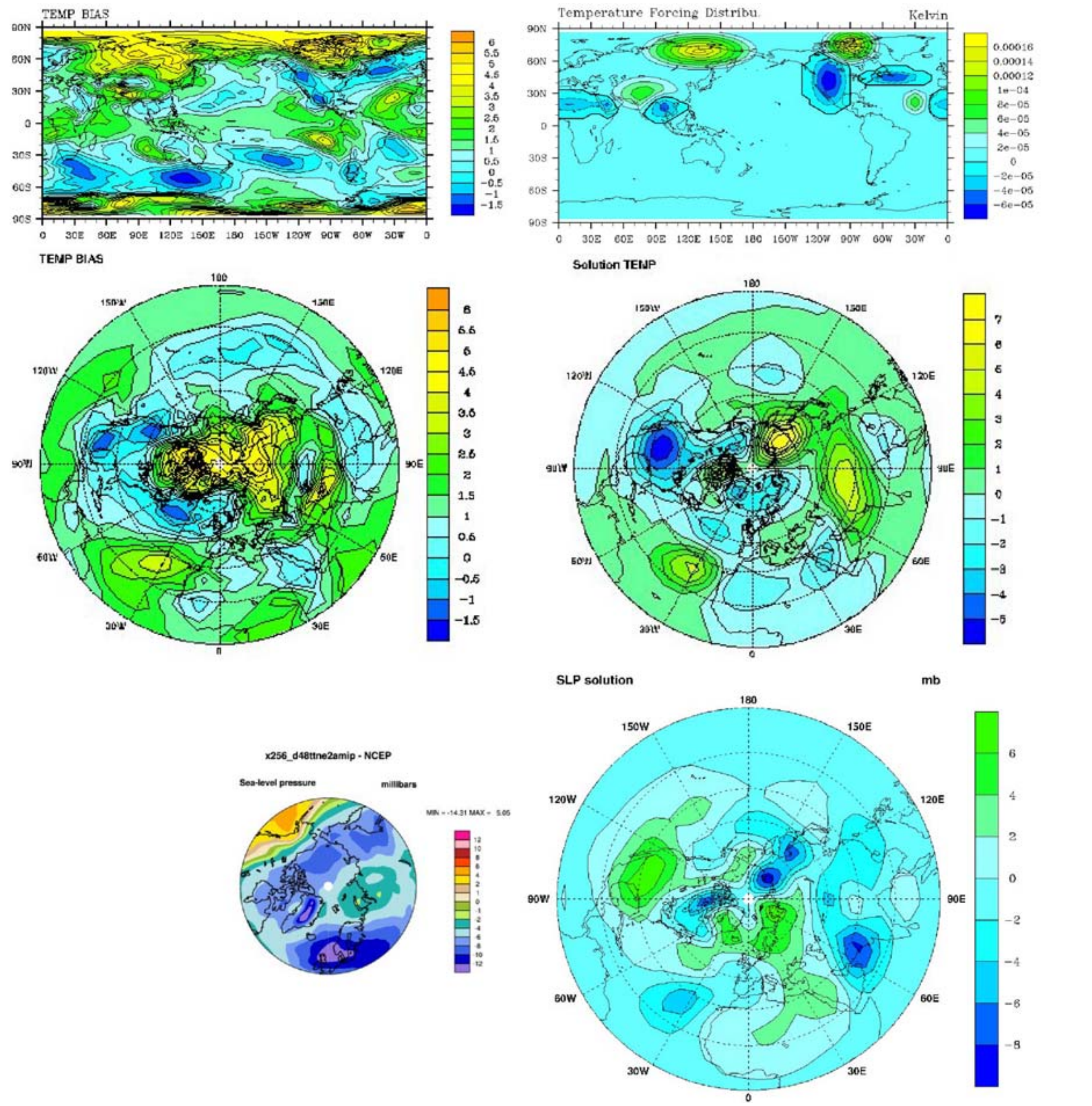

Figure 2-3. Example test calculation with anomalous T forcing in stationary wave model (SWM) of Branstator (1990) compared with bias fields. Top left, interpolated T bias at σ = 0.811 (CAM3 vs NCEP RA1, DJF); top right, 9 ellipses of T forcing input into SWM based on T bias. Middle right, SWM solution of T at σ = 0.811 for the input T forcing, Middle left, polar view of T bias for comparison. Lower right, SWM sea level pressure (SLP) solution. Lower left, SLP bias (CAM3 vs NCEP RA1, DJF; posted at NCAR-CGD website) for comparison, drawn to same scale as SWM SLP solution. The color bars vary between all panels. No tuning was done to improve the match in SLP, but extrema in T bias at 850mb guided forcing magnitudes. The key result is that the SLP bias is partly represented by a stationary wave related to T. Causes of the T forcing are diabatic and dynamic. For example, the SWM SLP max near Novaya Zemlya is most closely linked to the T forcing over the Saharan and Arabian deserts.

III. April 2006 – March 2007 (Year 3)
In the past 12 months (April 2006 – March 2007) we can report the following activities:

A. We deduced the forcing fields that create the Arctic region bias from running Branstator's SWM 'backwards'. Symbolically, the SWM can be written as: Ax = F where F is the forcing, x is the solution sought, and A is a very large square matrix dependent on the basic state (3-dimensional DJF fields of vorticity, divergence, temperature, and ln of surface pressure). To run the SWM 'backwards' we specify x and find the F. By specifying the bias fields as x, then we obtained the following important SWM backwards results:

1) *Local forcing dominates the Arctic region bias.* Solutions in Arctic region are unchanged whether forcing was allowed or zeroed out south of 30N. (This is useful to eliminate considering the large forcing and bias over the Himalayas.) The bias and forcing were successfully partitioned geographically: various portions of the bias field (e.g. the Beaufort negative bias) can be (and were) successfully isolated from other parts of the bias field.
2) *Some bias regions are independent, some regions are coordinated.* The Barents SLP bias (positive) is linked to the North Atlantic bias (negative) while the Beaufort bias (negative) is not to the North Pacific, Barents, or Atlantic in any strong way.
3) *The North Atlantic/Barents dipole bias and forcing have mixed vertical structure.* The bias field is baroclinic for temperature (T) and equivalent barotropic for vorticity. The associated forcing is: baroclinic T forcing and equivalent barotropic vorticity forcing. For T the largest forcing tends to be at the surface and in the upper model levels. For vorticity the largest values tended to be in the middle or upper troposphere. See figs. 3-1 and 3-2.
4) *The Beaufort region bias and forcing have mixed vertical structure.* The Beaufort region bias is mainly in the stratosphere and warm for T and equivalent barotropic (positive) for vorticity. The associated forcing is equivalent barotropic for T and baroclinic for vorticity; both forcing fields have larger values in the upper troposphere. See figs. 3-3 and 3-4.
5) *Thus the forcing is very different for these two regions of the Arctic bias field.*

B. We used the SWM to see the response of isolated forcing by individual fields.
1) *Artificial thermal forcing could reproduce parts of the SLP bias.* Inspection of the low level T bias field suggests multiple monopoles in T forcing tendency. Elliptically-shaped monopoles of various vertical structures were tested. When a limited number of those T forcing centers are used to force the SWM, one obtains a solution field similar to the SLP bias over the Arctic. See Fig. 3-5.
2) *Specific monopoles seem linked to specific parts of the bias.* A subset of T tendency monopoles (mainly N. Siberia >0 tendency, and Sahara-Arabia deserts <0 T tendency) appear to be the main forcing for Beaufort high <0 bias and Barents >0 bias.

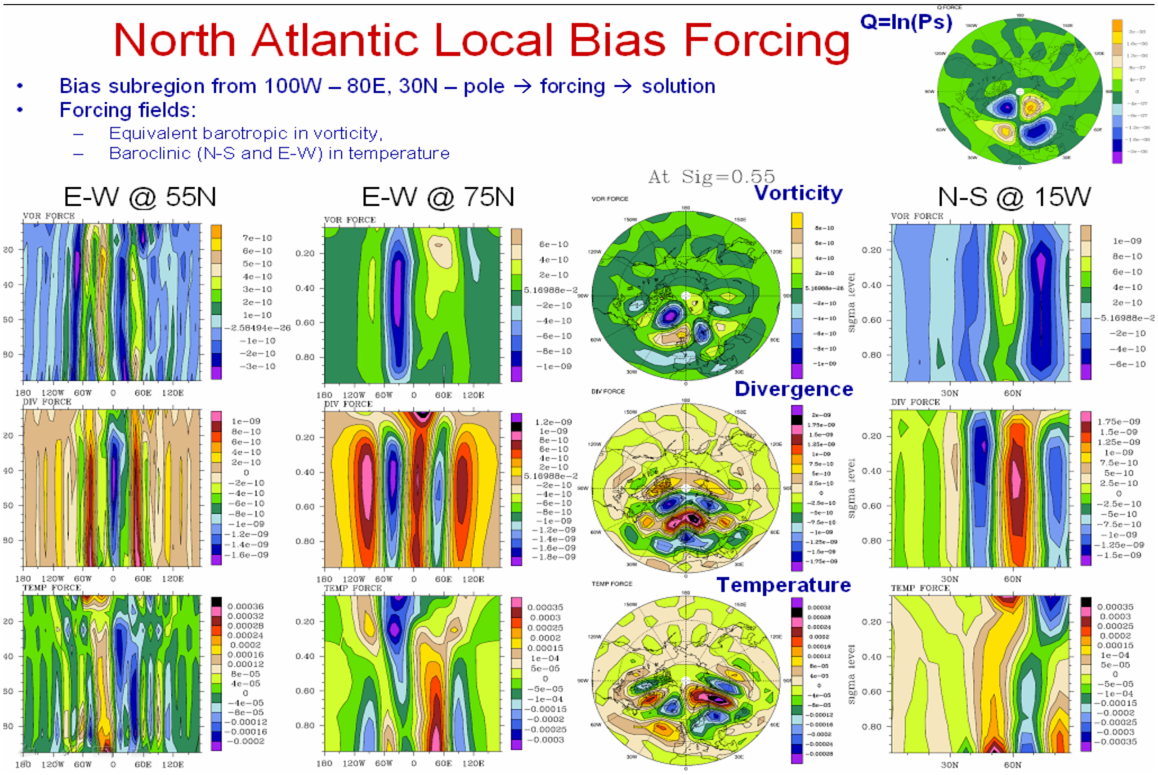

Fig. 3-1: Vertical and horizontal structure of forcing in SWM for North Atlantic & Barents region bias.

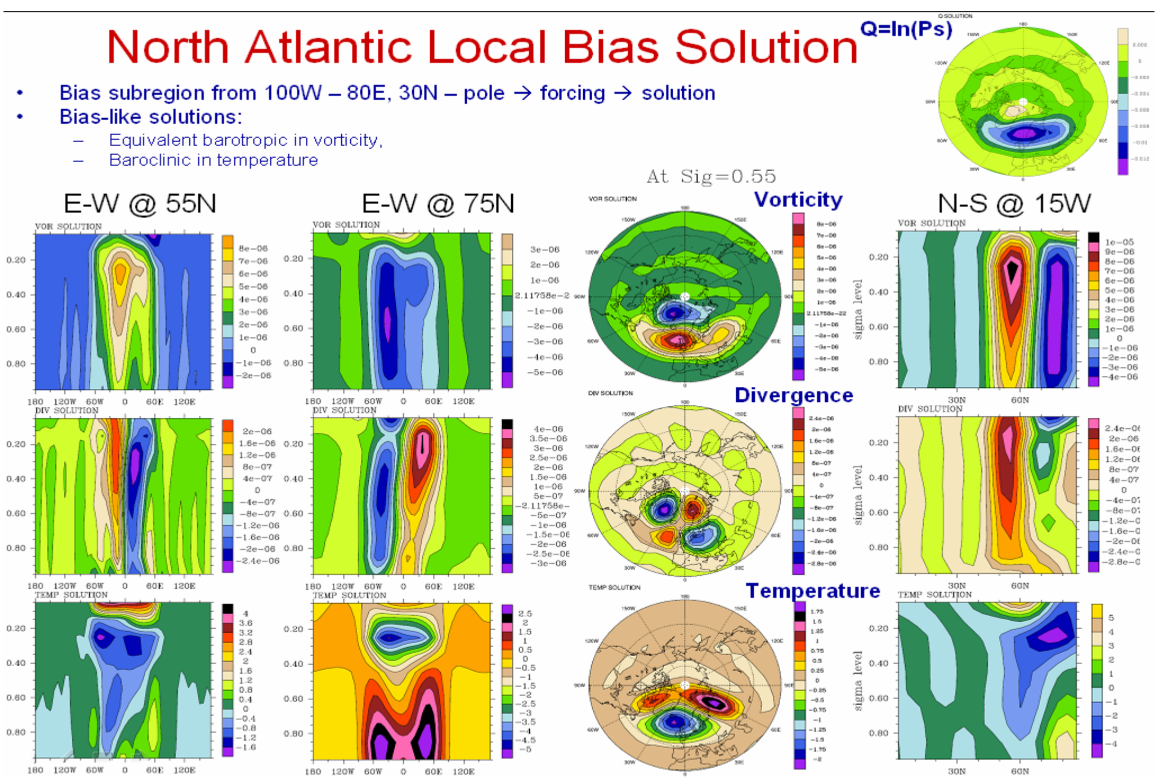

Fig. 3-2: Vertical and horizontal structure of SWM solution created by forcing in figure 3-1.

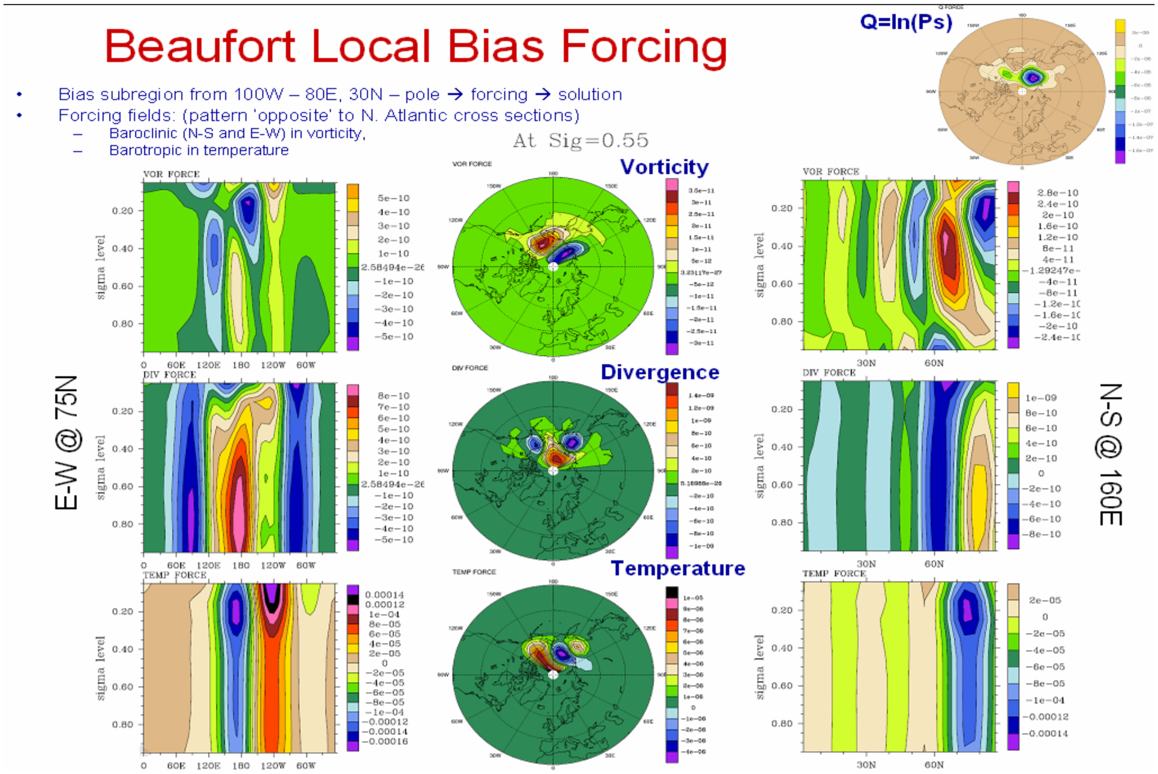

Fig. 3-3. Vertical and horizontal structure of forcing in SWM for Beaufort Sea region bias.

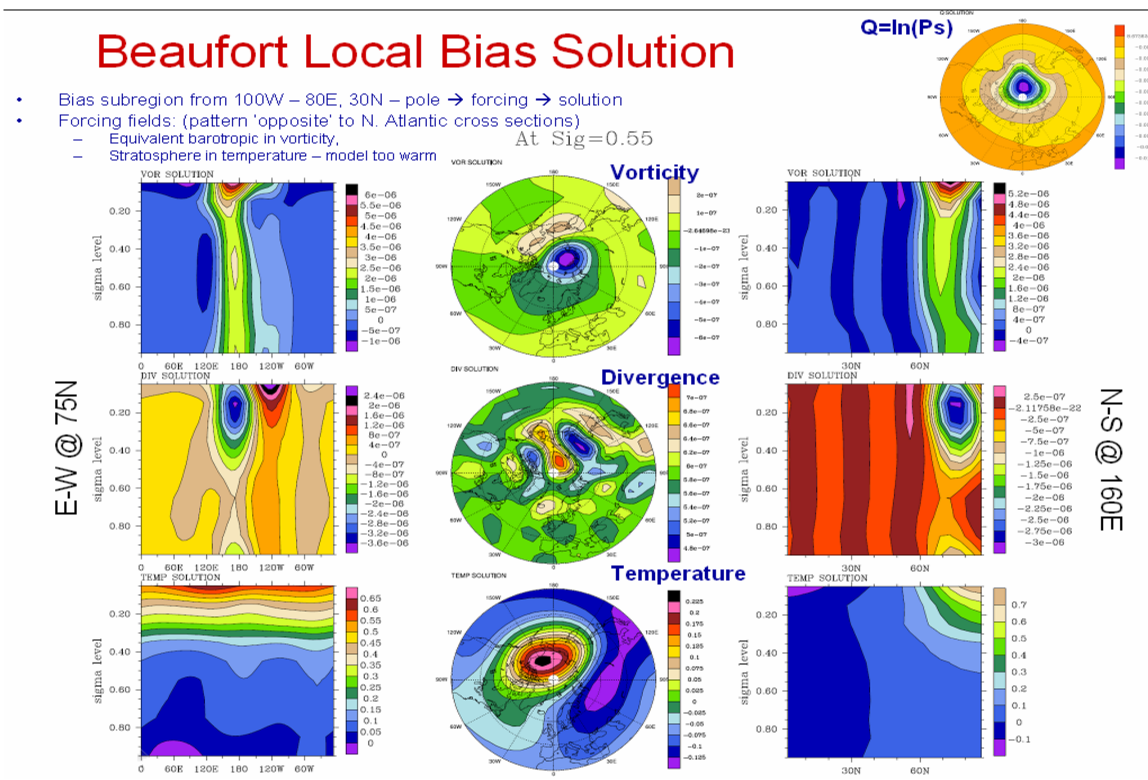

Fig. 3-4: Vertical and horizontal structure of SWM solution created by forcing in figure 3-3.

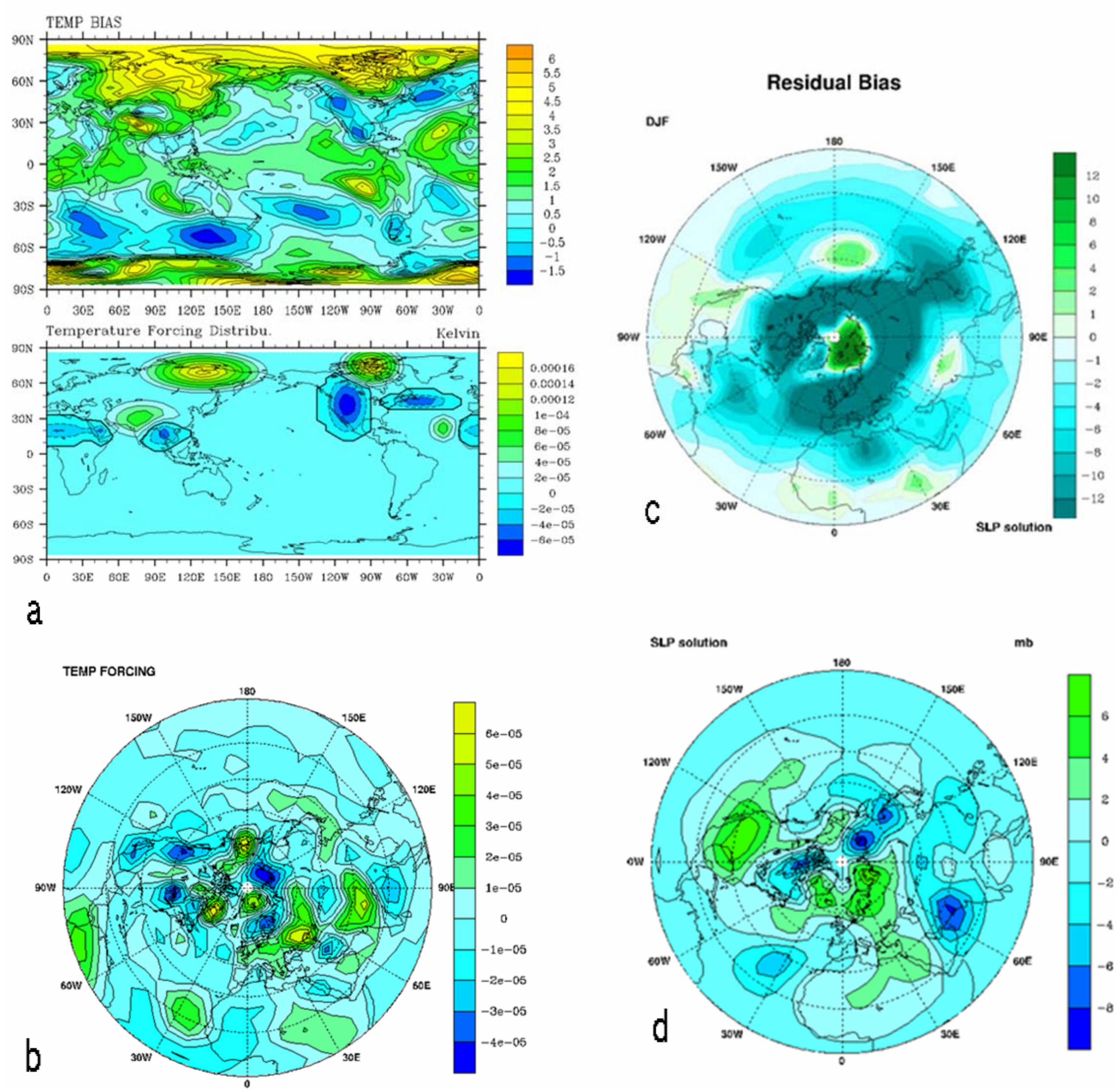

Fig. 3-5. SWM solutions for function-specified monopole temperature forcing. a) Temperature (T) bias at σ = 0.991 and 9 monopoles of temperature forcing inspired by that T bias. b) Actual temperature forcing from bias field. c) Actual SLP (residual) bias after subtracting the dominant EOF of the CAM model. d) SLP solution from the 9 monopoles in T forcing. Notice how the SLP solution captures most features of the residual bias.

III. April 2007 – March 2008 (Year 4)
In the past 12 months (April 2007 – March 2008) we can report the following activities:

A. We made additional calculations of the solutions obtained from parts of the forcing fields, where the latter are found from running Branstator's SWM 'backwards'. To run the SWM 'backwards' we specify x and find the F. By specifying the bias fields as x, then we obtained the following important SWM backwards results:

1) *Bias solutions from just temperature, just vorticity, just sea level pressure and various combinations of these.* Solutions in Arctic region are predominantly from the temperature and vorticity forcing. Sea level pressure (SLP) also affected by SLP forcing.

B. We formulated and tested a temperature bias equation. This equation is constructed from taking the difference between model and observations for each term of the temperature conservation equation. When evaluated over a long time average (multi-years of the same season) the terms in the temperature bias equation fall into 4 groups of terms:

1. the linear terms in the 'backwards' form of the SWM.
2. the nonlinear terms having bias multiplying bias.
3. the nonlinear terms from time mean contributions from transients.
4. the diabatic heating bias.

Each group of terms may be compared with the forcing found from running the SWM backwards.

1) *Terms 1 (those present in the SWM) are the largest in magnitude in the Arctic region.* This key result validates using the SWM for the study of the temperature bias. This group has largest values in the tropical convective regions (not a focus of this study).

2) *Terms 2 (bias-bias nonlinear terms) are the smallest of the 4 groups of terms.* There is little interaction between the bias and itself. The wind bias has little advection of the temperature bias. Again, an important validation of using the SWM.

3) *Terms 3 (nonlinear transient bias) are horizontal and vertical heat fluxes in ERA-40 data minus the corresponding heat fluxes in the CAM model.* These terms have important contribution mainly in the midlatitude storm tracks, especially the North Atlantic. This is consistent with our working conclusion that mishandling of the North Atlantic frontal cyclones is important for the bias in the 'European side' of the Arctic. The forcing was generally positive across the North Atlantic with some tendency to be larger in the lower troposphere. At low resolutions comparable to the SWM, the pattern tends to be dipolar (positive over Scandanavia, negative over Iberia) consistent with CAM's storm track error.

4) *Terms 4 (diabatic heating bias: CAM minus ERA-40) are found as a residual of a potential temperature conservation equation.* Therefore these terms have slightly different origin than the temperature bias equation, though they are nearly as large as the Terms 1 group. Accordingly, these terms look like the term 1 group in the tropics (a region outside the scope of this study). At the start of the north Pacific and Atlantic storm tracks the term tends to be negative and positive downstream (especially N. Atlantic).

5) *The calculation can be made at much higher (vertical and horizontal) resolution than is possible with the SWM*. However the patterns do change notably between SWM low resolution and much higher CAM resolution. The difference lowered the effectiveness of the forcing found from the SWM to stimulate (or neutralize, depending on the forcing sign) the bias in CAM.

6) *We calculated vertical average heating using precipitation (P) minus evaporation (E) in CAM and ERA-40.* This calculation was suggested by K. Trenberth, who finds the P-E to be acceptably accurate in ERA-40. Results currently under analysis.

C. We made an initial test of the temperature and vorticity forcing fields from the SWM in CAM3.0. The forcing fields were scaled up to T42, 26L resolution. There are large differences in how friction and diffusion are handled in the SWM versus CAM; one difference concerns the high wavenumber dependence in CAM that cannot be used in the SWM. Various tests were tried. The response of CAM to the added forcing has some elements of the bias (a successful result) however, additional tests are needed.

D. Our plans for the final grant extension. We shall finish our analysis of the temperature bias equation. We shall formulate and study results from a vorticity bias equation. We intend to make a few more test runs of CAM with appropriate forcing.

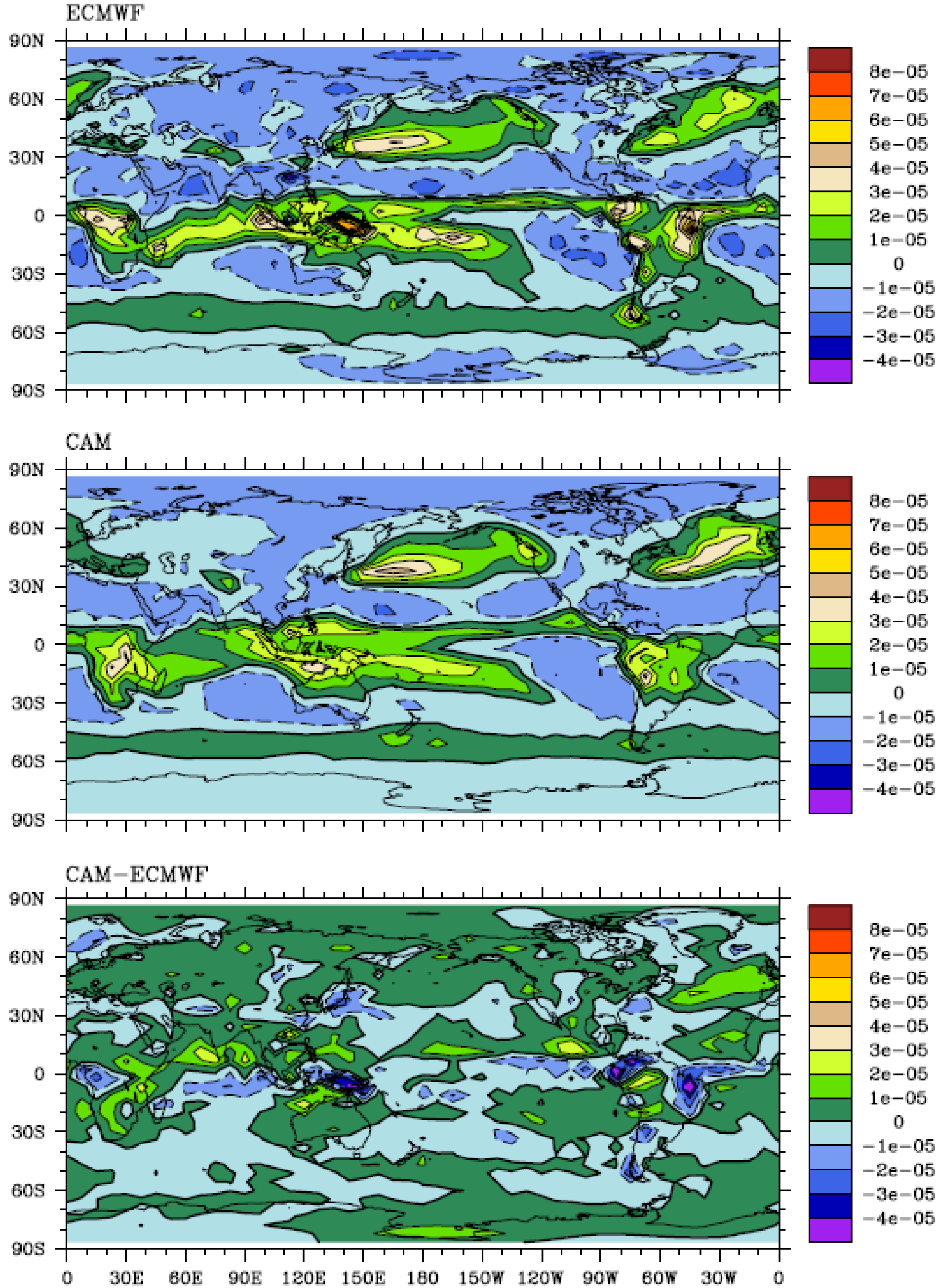

Fig. 4.1. Diabatic heating during DJF. Top panel uses ERA-40 data; middle panel in CAM3.0 T42 AMIP simulations; bottom panel is difference field: CAM minus ERA-40. The bottom panel is the same as terms 4 in the temperature bias equation. Level is sigma =0.7.

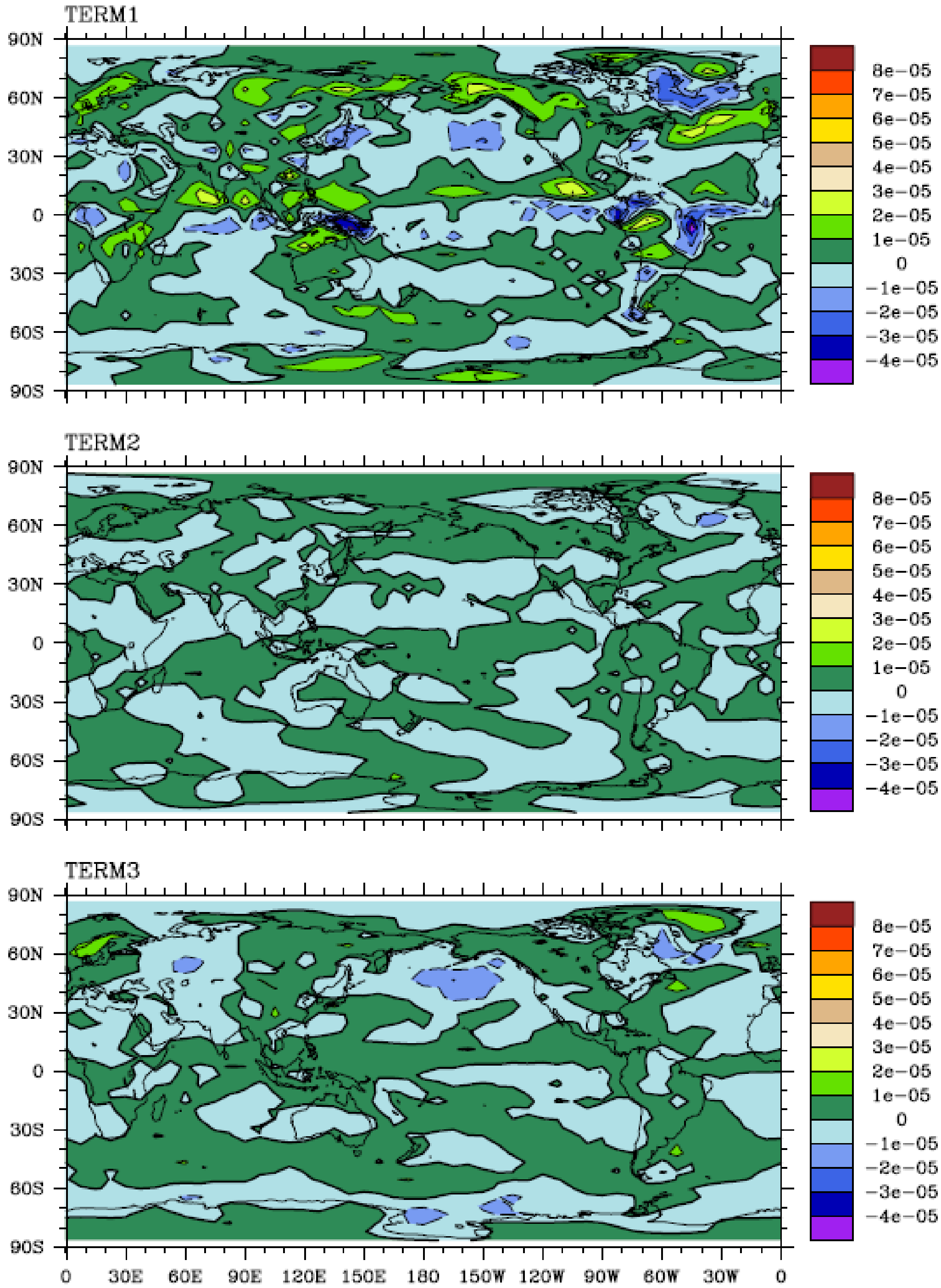

Fig. 4.2. Groups of terms in the temperature bias equation. Term1 are all terms in the SWM. Term2 are all nonlinear bias-bias terms. Term3 are transient terms. The level is sigma=0.7.