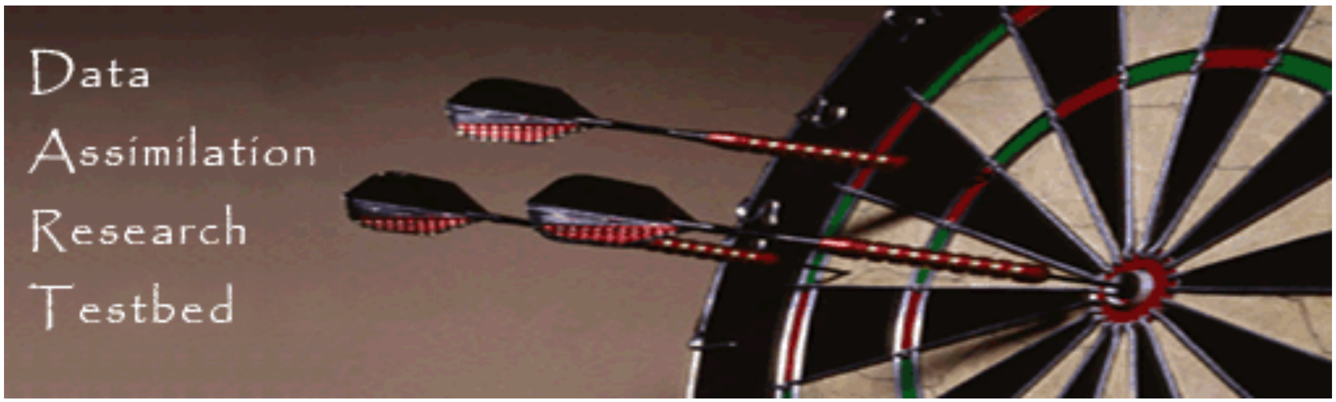
A Loosely Coupled Ocean-Atmosphere Ensemble Assimilation System.



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Ocean Data Assimilation Motivation

The resulting high-fidelity ocean states are needed.
The ensembles provide uncertainty quantification.

- Climate change over time scales of 1 to several decades has been identified as very important for mitigation and infrastructure planning.
- High fidelity ocean states will be needed by the IPCC decadal prediction program.
- The ocean plays a crucial role by providing a source or sink (and system memory) for the atmosphere of many quantities, such as heat, moisture, CO_2, etc.
- Increasing numbers of observations from larger regions of the oceans are making state-of-the-art data assimilation a promising possibility.

Ensemble Filter For Large Geophysical Models

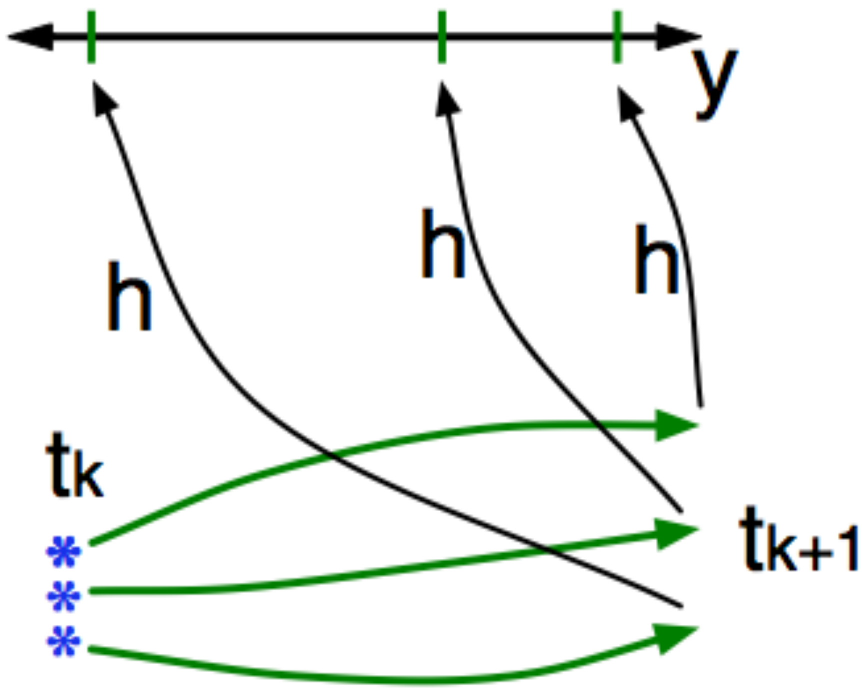
1. Use model to advance ensemble (3 members here) to time at which next observation becomes available.

Ensemble state estimate, $x(t_k)$, after using previous observation (analysis)

Ensemble state at time of next observation (prior)

Ensemble Filter For Large Geophysical Models

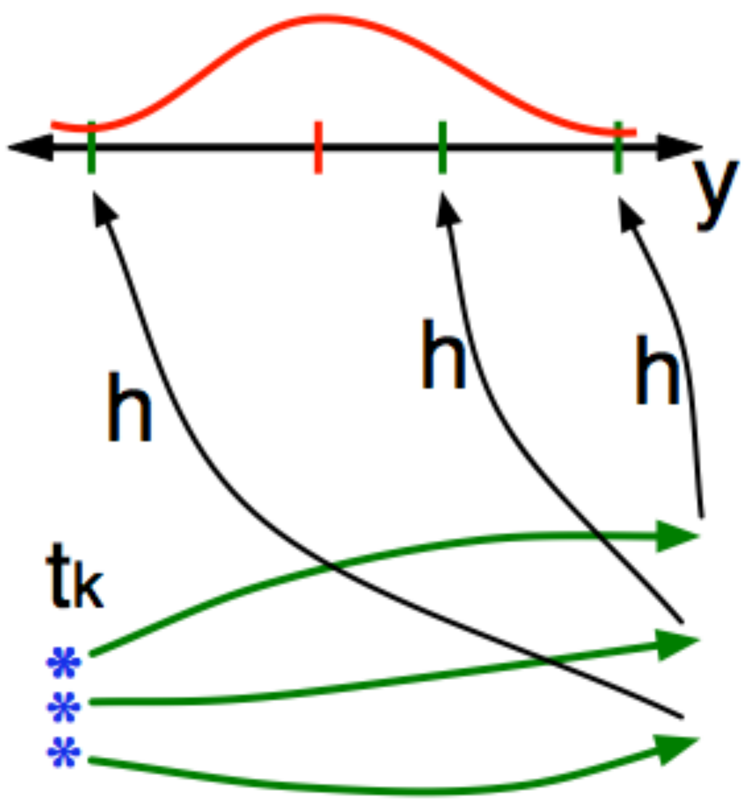
2. Get prior ensemble sample of observation, y = h(x), by applying forward operator **h** to each ensemble member.



Theory: observations from instruments with uncorrelated errors can be done sequentially.

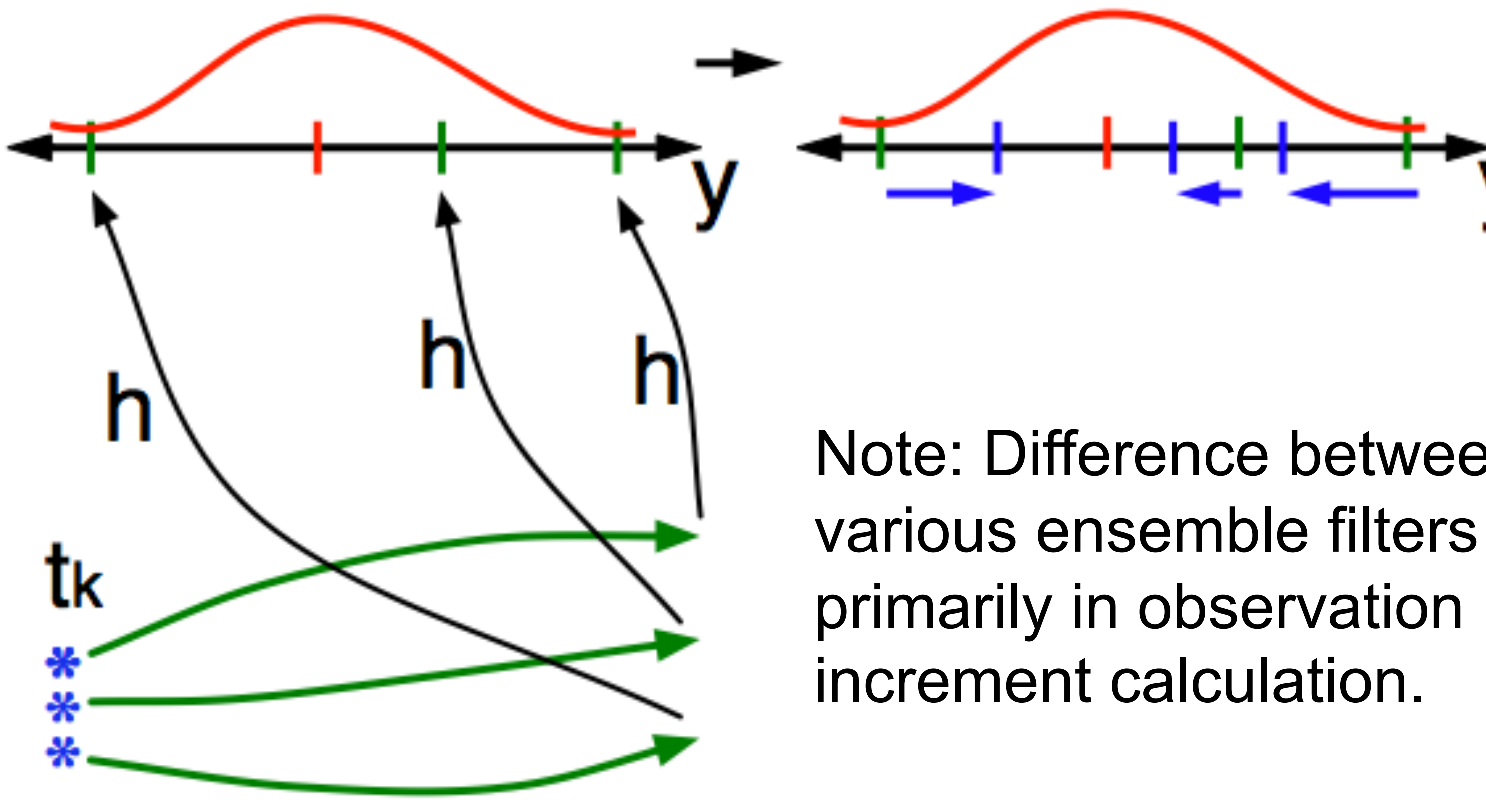
Ensemble Filter For Large Geophysical Models

3. Get observed value and observational error distribution from observing system.



Ensemble Filter For Large Geophysical Models

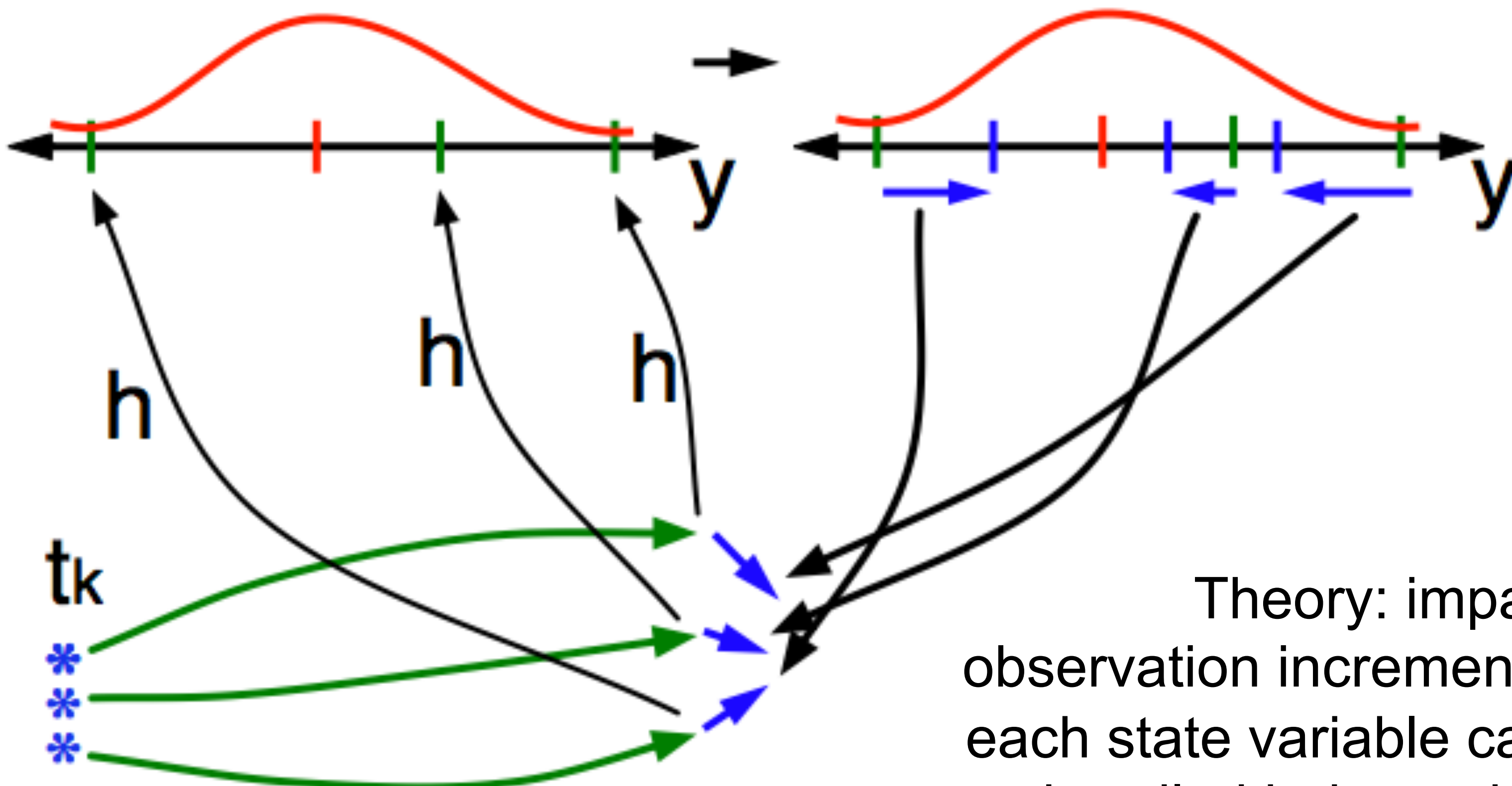
4. Compute the increments for the prior observation ensemble (this is a scalar problem for uncorrelated observation errors).



Note: Difference between various ensemble filters is primarily in observation increment calculation.

Ensemble Filter For Large Geophysical Models

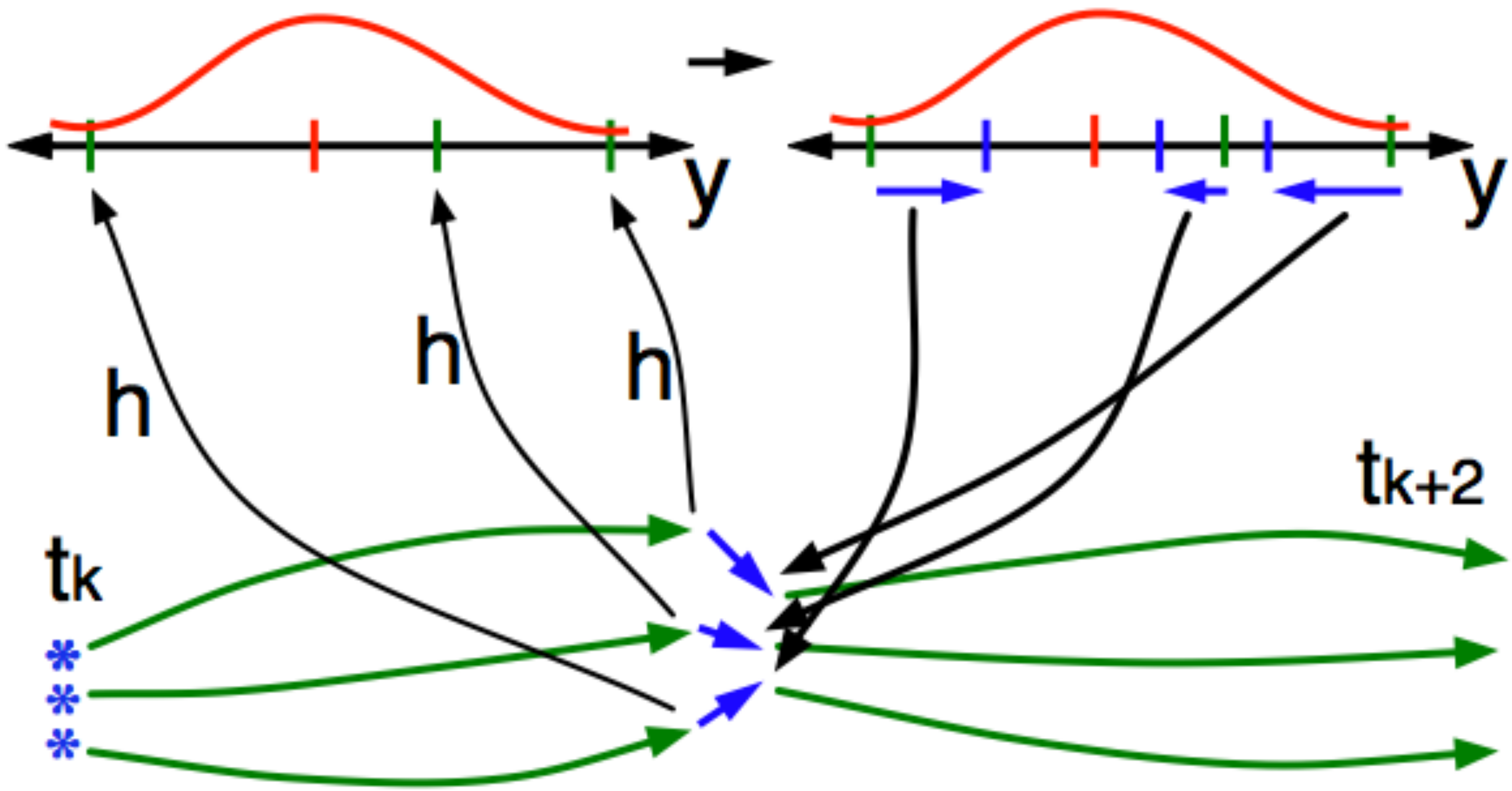
5. Use ensemble samples of **y** and each state variable to linearly regress observation increments onto state variable increments.



Theory: impact of observation increments on each state variable can be handled independently!

Ensemble Filter For Large Geophysical Models

6. When all ensemble members for each state variable are updated, there is a new analysis. Integrate to time of next observation …

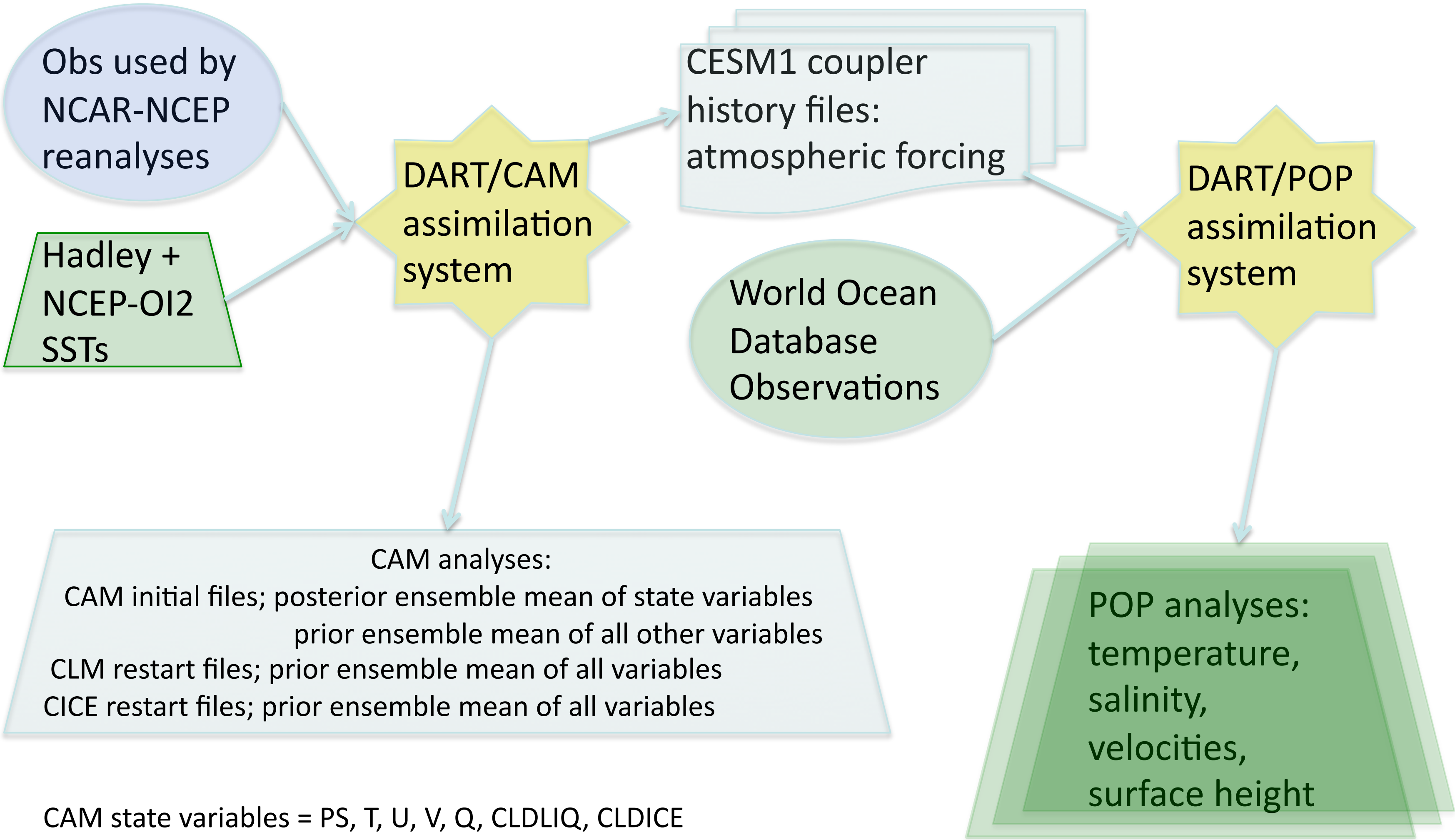


Experiment Overview

Compare the effect of using a single atmospheric boundary vs. an ensemble of atmospheric boundaries on ocean data assimilation with POP.

- "**23 POP 1 DATM**" denotes the experiment using 23 POP members and a single "data" atmosphere (CESM framework).
- "**48 POP 48 CAM**" denotes the loosely coupled experiment using 48 POP members and 48 consistent but unique CAM atmospheres.
- Both experiments were conducted for 1998 & 1999.
- The 48 POP 48 CAM experiment was subsequently chosen to produce initial conditions for the IPCC decadal prediction program.

Coupled Ocean-Atmosphere Schematic

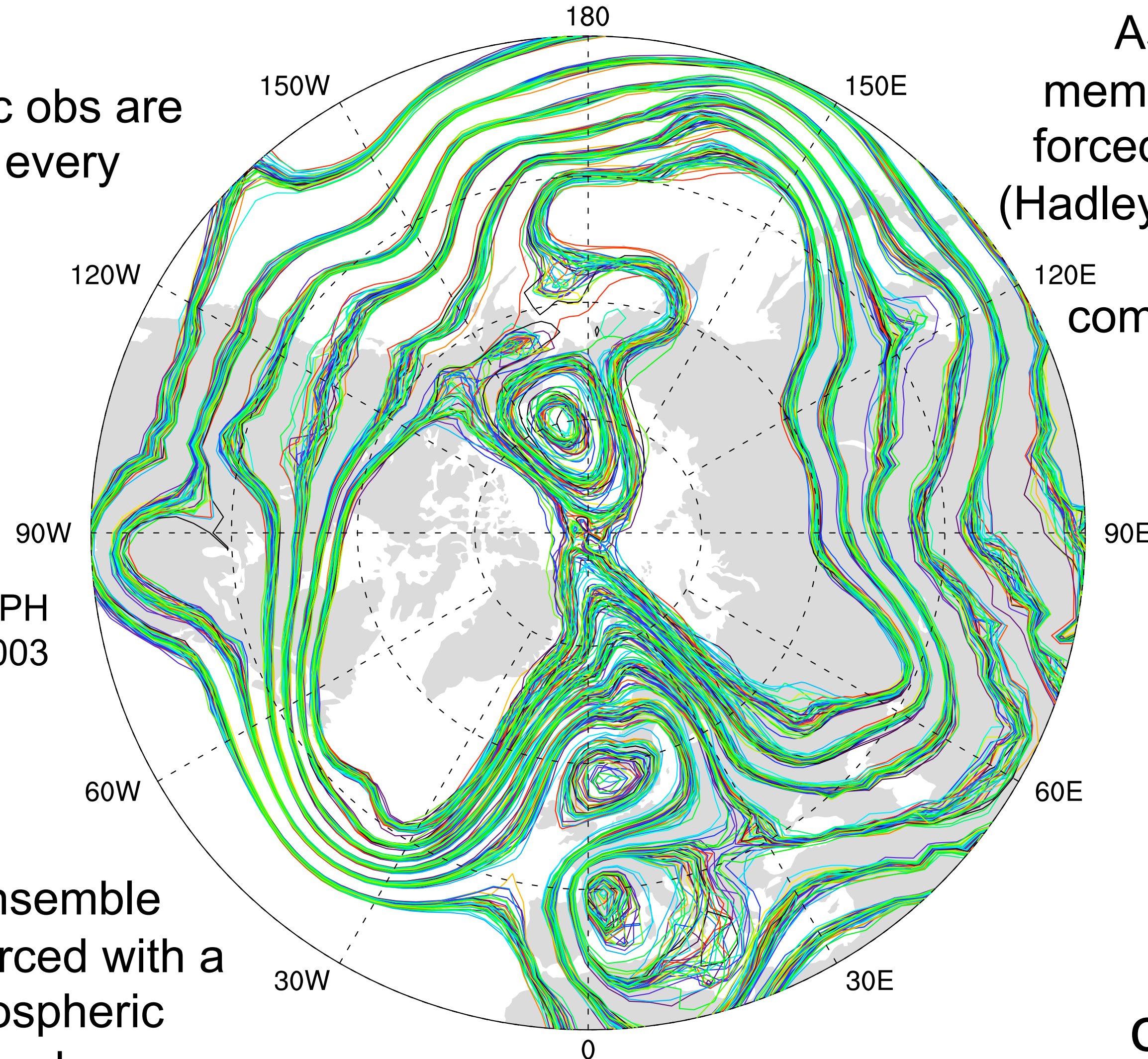


CAM state variables = PS, T, U, V, Q, CLDLIQ, CLDICE
Prior = values before assimilation (but after a short forecast)
Posterior = values after the assimilation of observations at that time

Atmospheric Reanalysis

O(1 million) atmospheric obs are assimilated every day.

Assimilation uses 80 members of 2º FV CAM forced by a single ocean (Hadley+ NCEP-OI2) and produces a very competitive reanalysis.



500 hPa GPH
Feb 17 2003

CONTOUR FROM 5200 TO 5700 BY 100

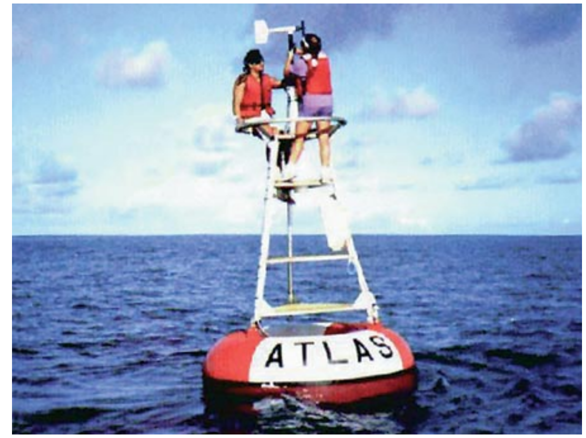
Each POP ensemble member is forced with a different atmospheric reanalysis member.

Generates additional ocean spread.

World Ocean Database T,S observation counts

These counts are for 1998 & 1999 and are representative.

FLOAT_SALINITY	68200
FLOAT_TEMPERATURE	395032
DRIFTER_TEMPERATURE	33963
MOORING_SALINITY	27476
MOORING_TEMPERATURE	623967
BOTTLE_SALINITY	79855
BOTTLE_TEMPERATURE	81488
CTD_SALINITY	328812
CTD_TEMPERATURE	368715
STD_SALINITY	674
STD_TEMPERATURE	677
XCTD_SALINITY	3328
XCTD_TEMPERATURE	5790
MBT_TEMPERATURE	58206
XBT_TEMPERATURE	1093330
APB_TEMPERATURE	580111



- temperature observation error standard deviation == 0.5 K.
- salinity observation error standard deviation == 0.5 msu.

Experimental Configurations

23 POP 1 DATM

1. POP 1-degree displaced pole;
2. 23 ensemble members starting from a ‘climatological’ state;
3. Single ‘data’ atmosphere from CORE;
4. DART assimilates observations once per day in a +/- 12 hour window centered at midnight;
5. The CESM framework is responsible for all model advances.

The **48 POP 48 CAM** experiment differed in that:

1. 48 ensemble members starting from a ‘climatological’ state;
2. Atmospheric forcing from the DART/CAM ensemble reanalysis;

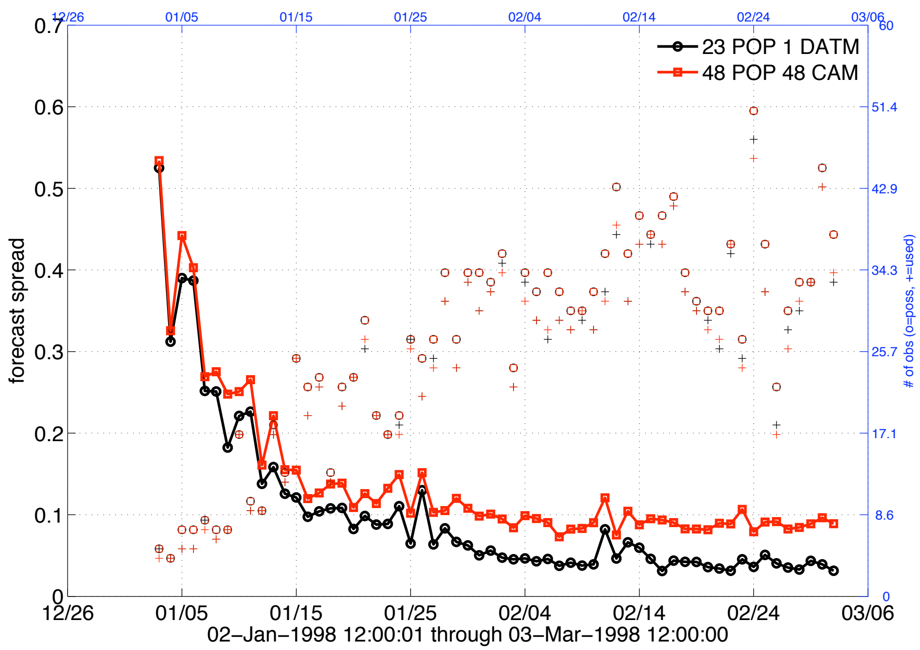
Guide to the following figures:

1. Ensemble mean 1-day lead forecast difference from **observations.**
2. ◘ is # observations available; +,+ is # assimilated.
3. Obs are rejected if too far from ensemble mean (3 std dev here).

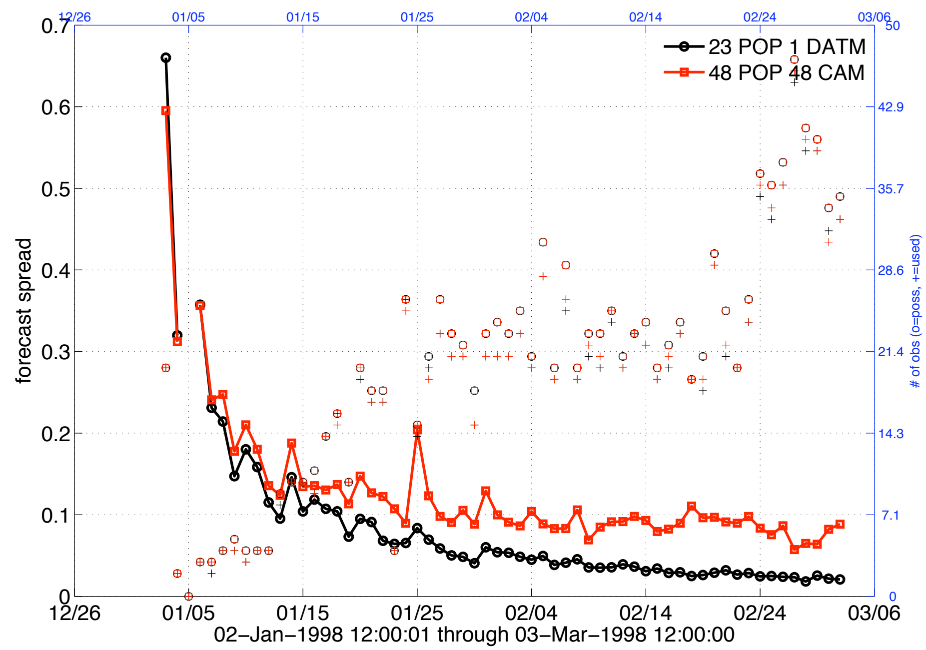
Ensemble *Spread* for 100m XBT (Expendable Bathythermograph)

1. Spread contracts too much for 23 POP 1 DATM;
2. Using single atmospheric forcing is also part of the problem;
3. Model bias adds to the problem;
4. DART Statistical Sampling Error Correction also helps.

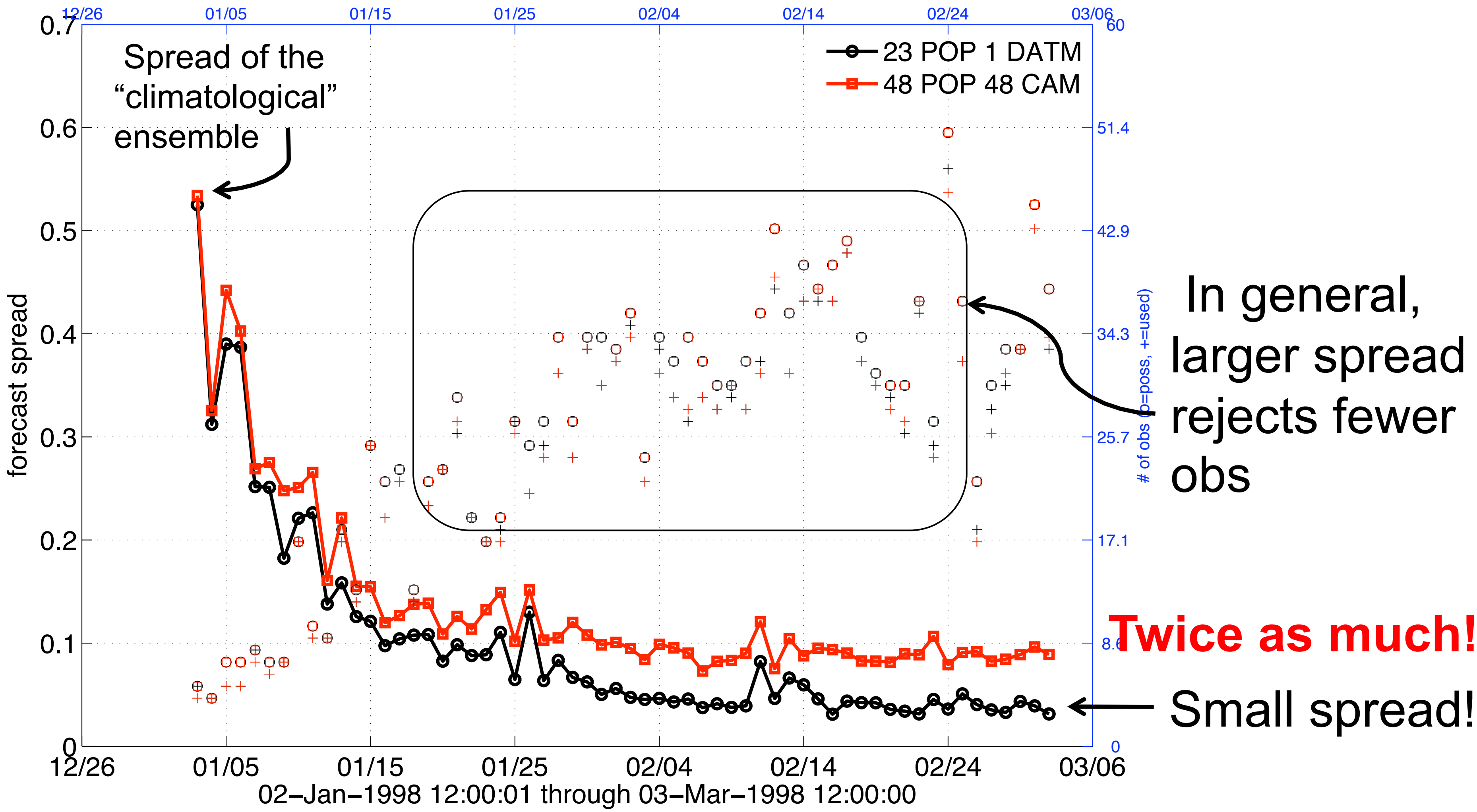
Pacific



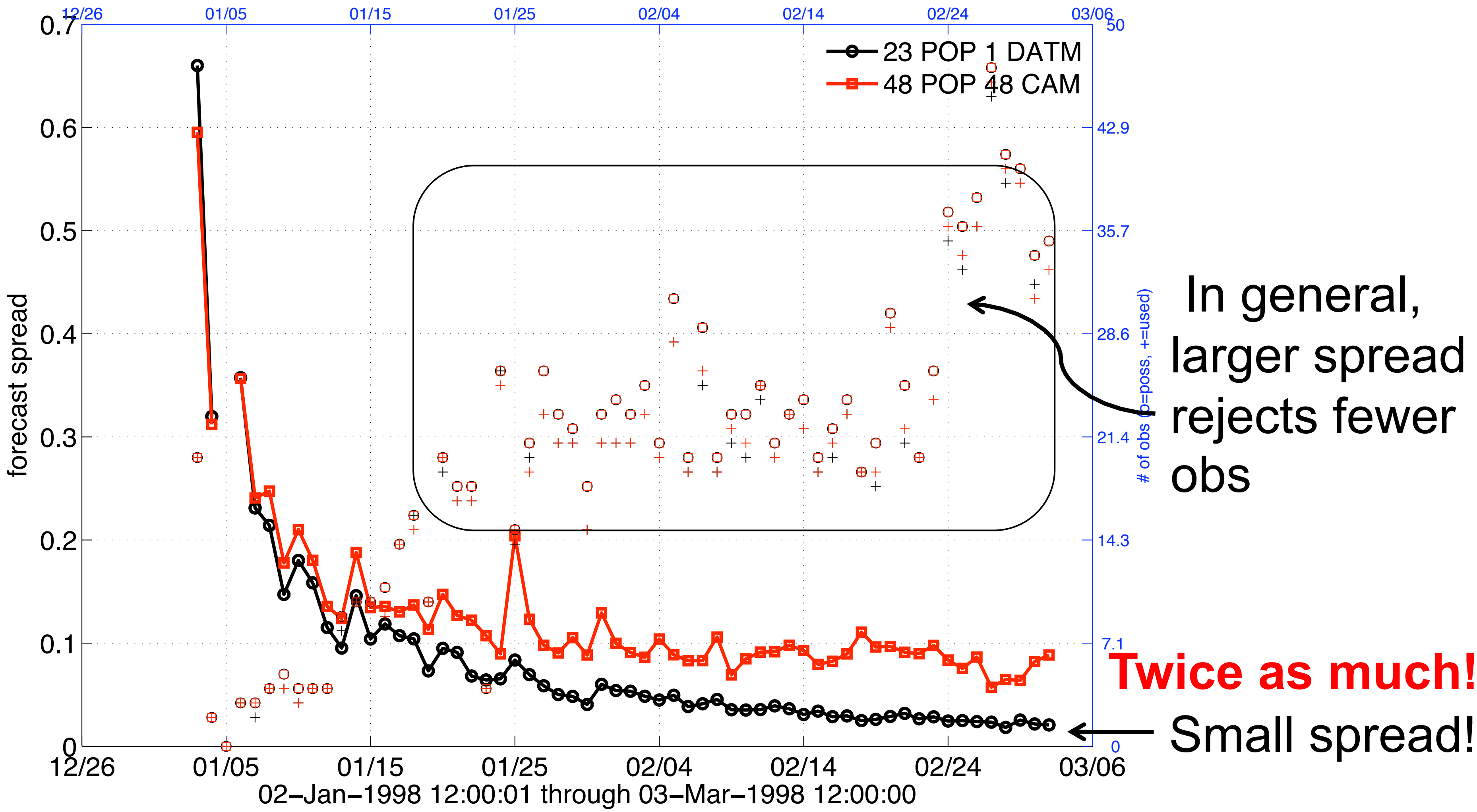
Atlantic



Ensemble *Spread* for Pacific 100m XBT



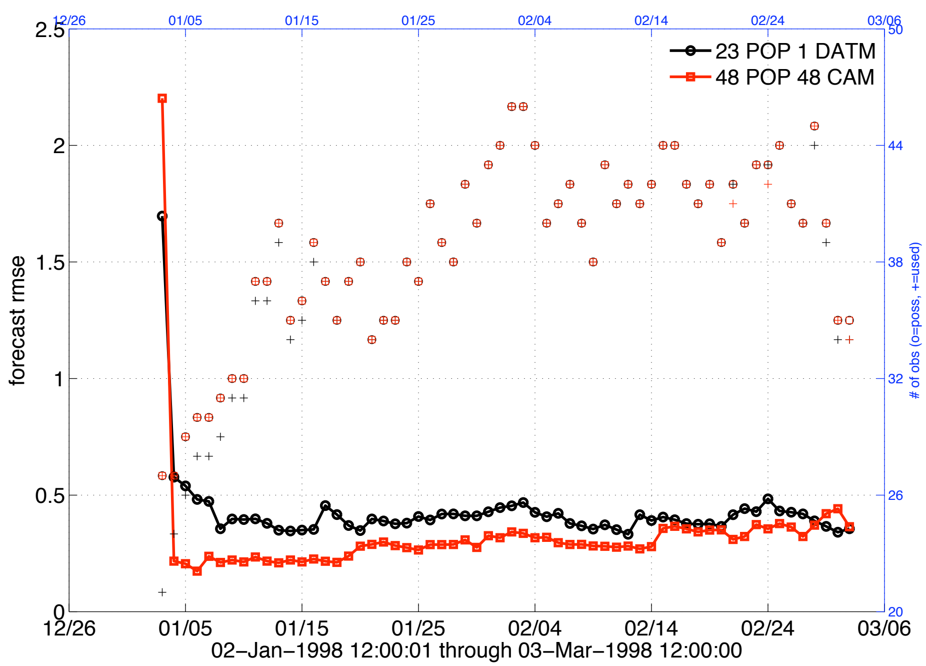
Ensemble *Spread* for Atlantic 100m XBT



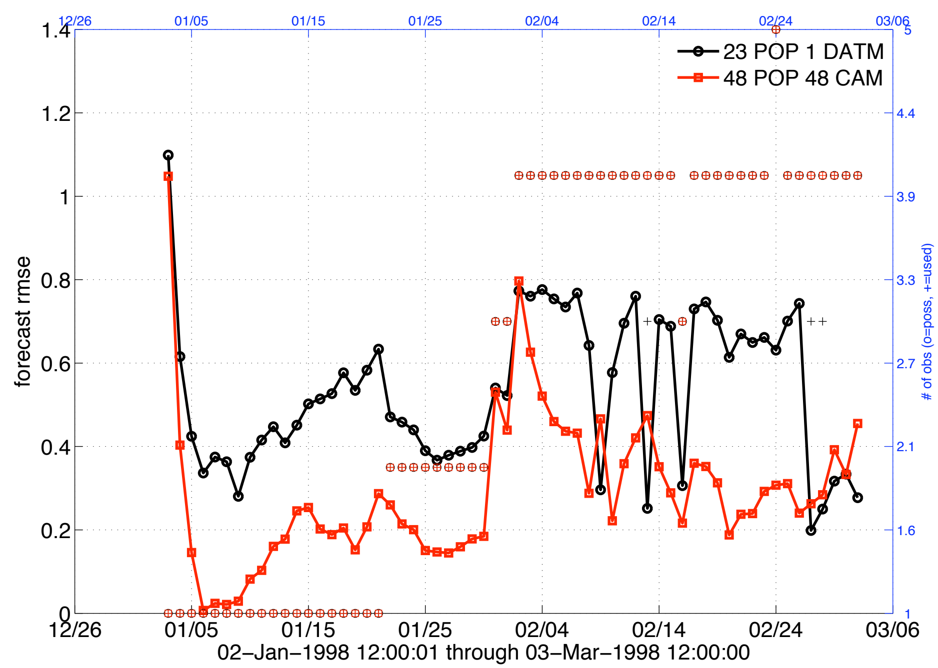
10m Mooring Temperature RMSE

1. Ensemble mean 1-day lead forecast difference from **observations**.
2. ▢ is # observations available. +,+ is # assimilated.
3. Observations are rejected if they are too far from ensemble mean (3 standard deviations here).

Pacific

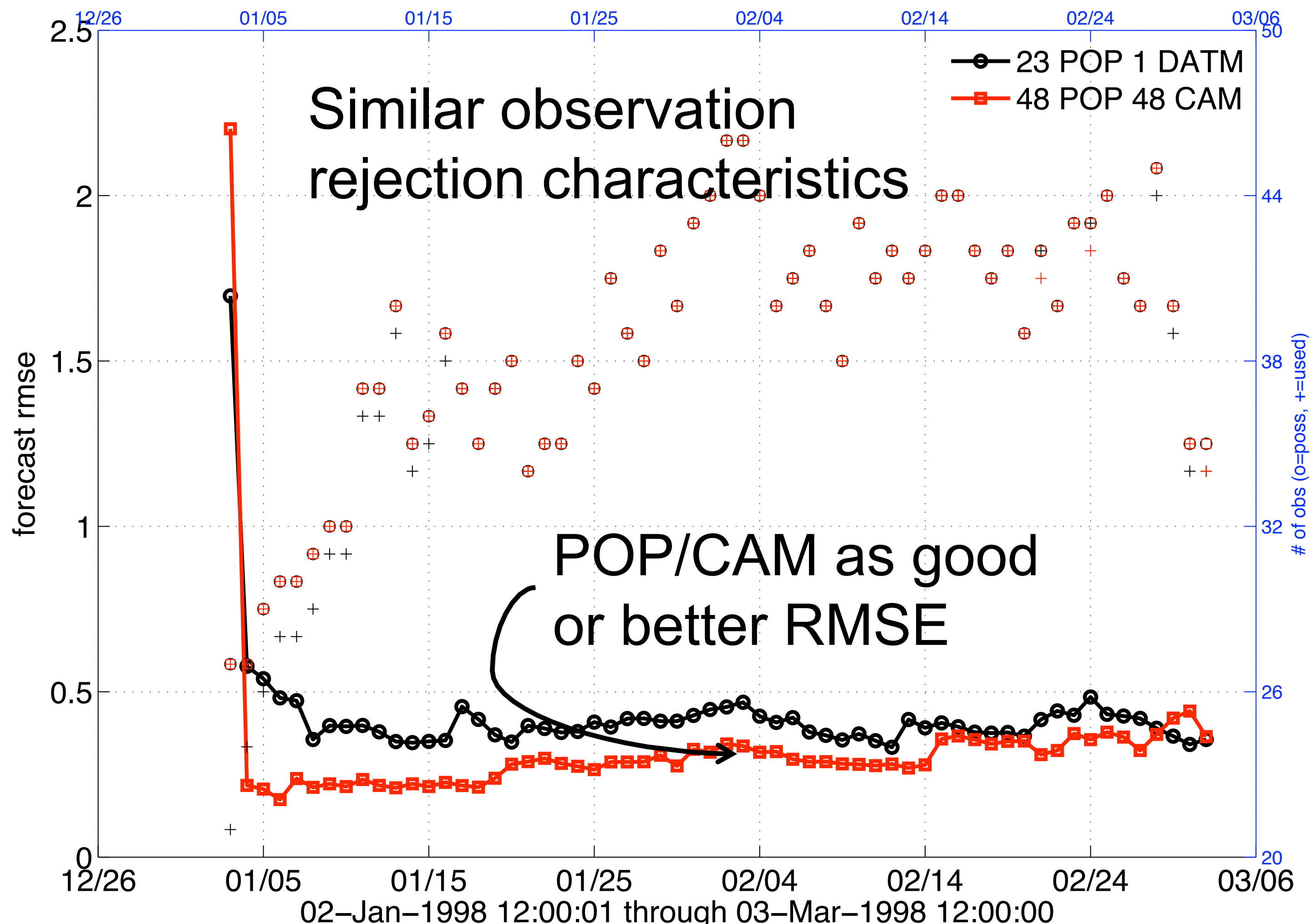


Atlantic



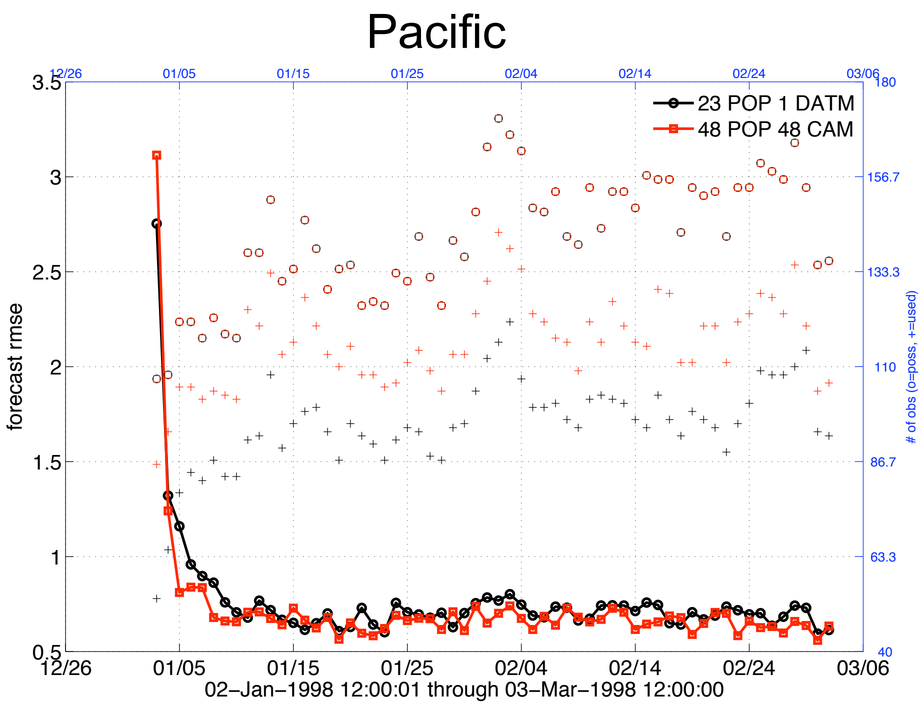
10m Mooring Temperature RMSE – Pacific

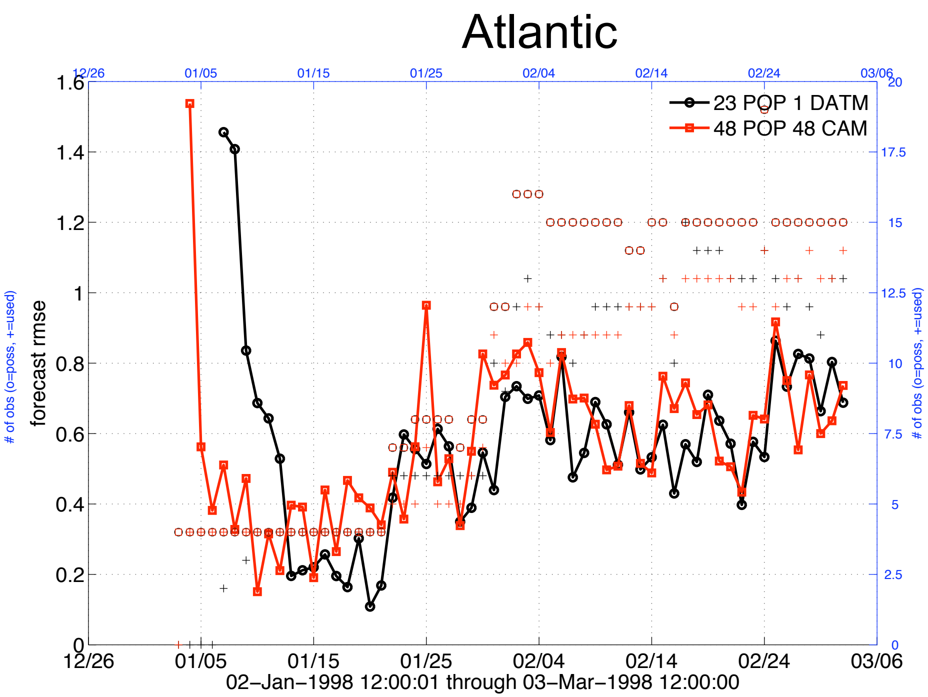
Ensemble mean 1-day lead forecast difference from **observations**.



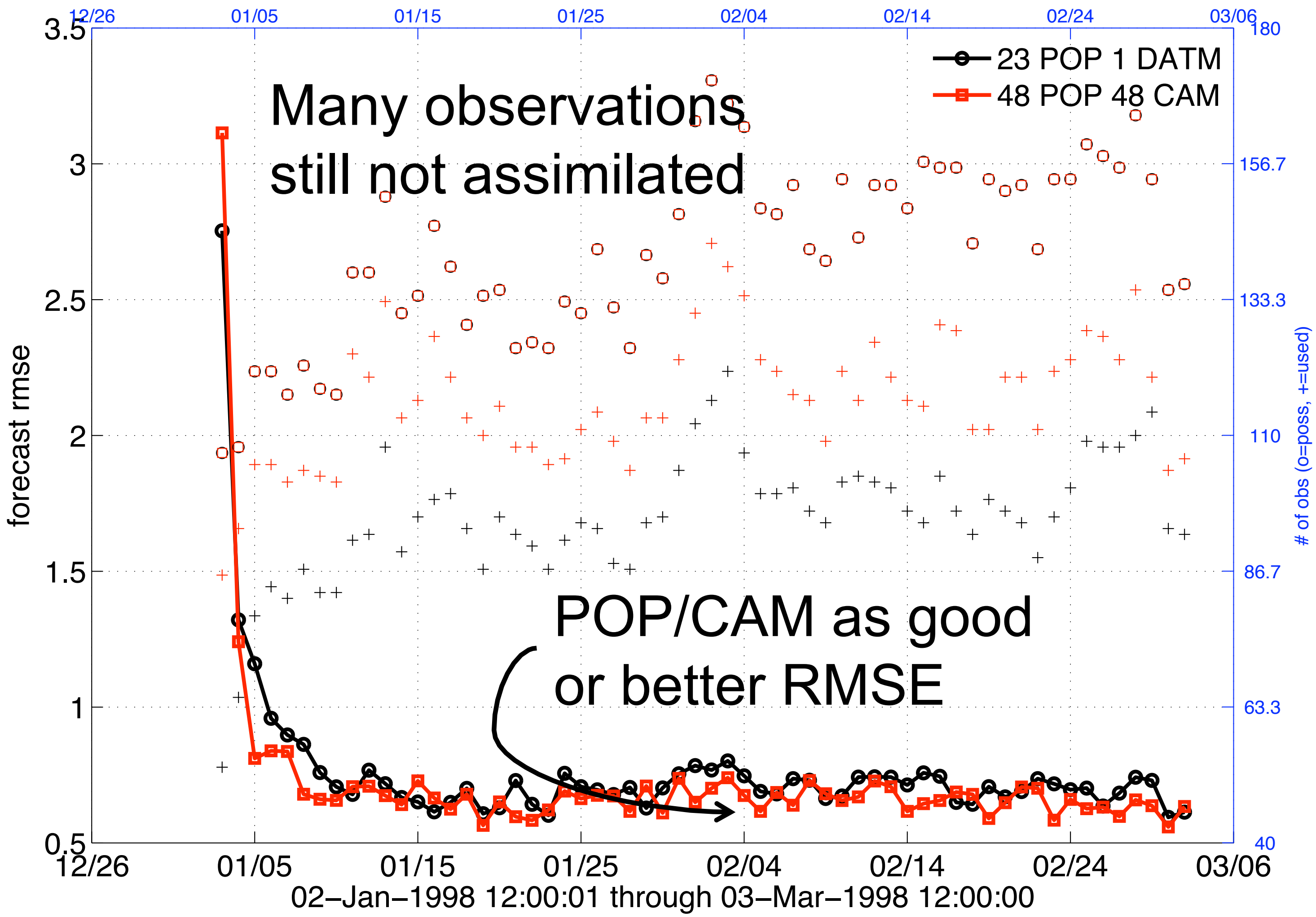
100m Mooring Temperature RMSE

1. 1/3 of the obs are still rejected by 48 POP 48 CAM in the Pacific.
2. Model bias in the thermocline?





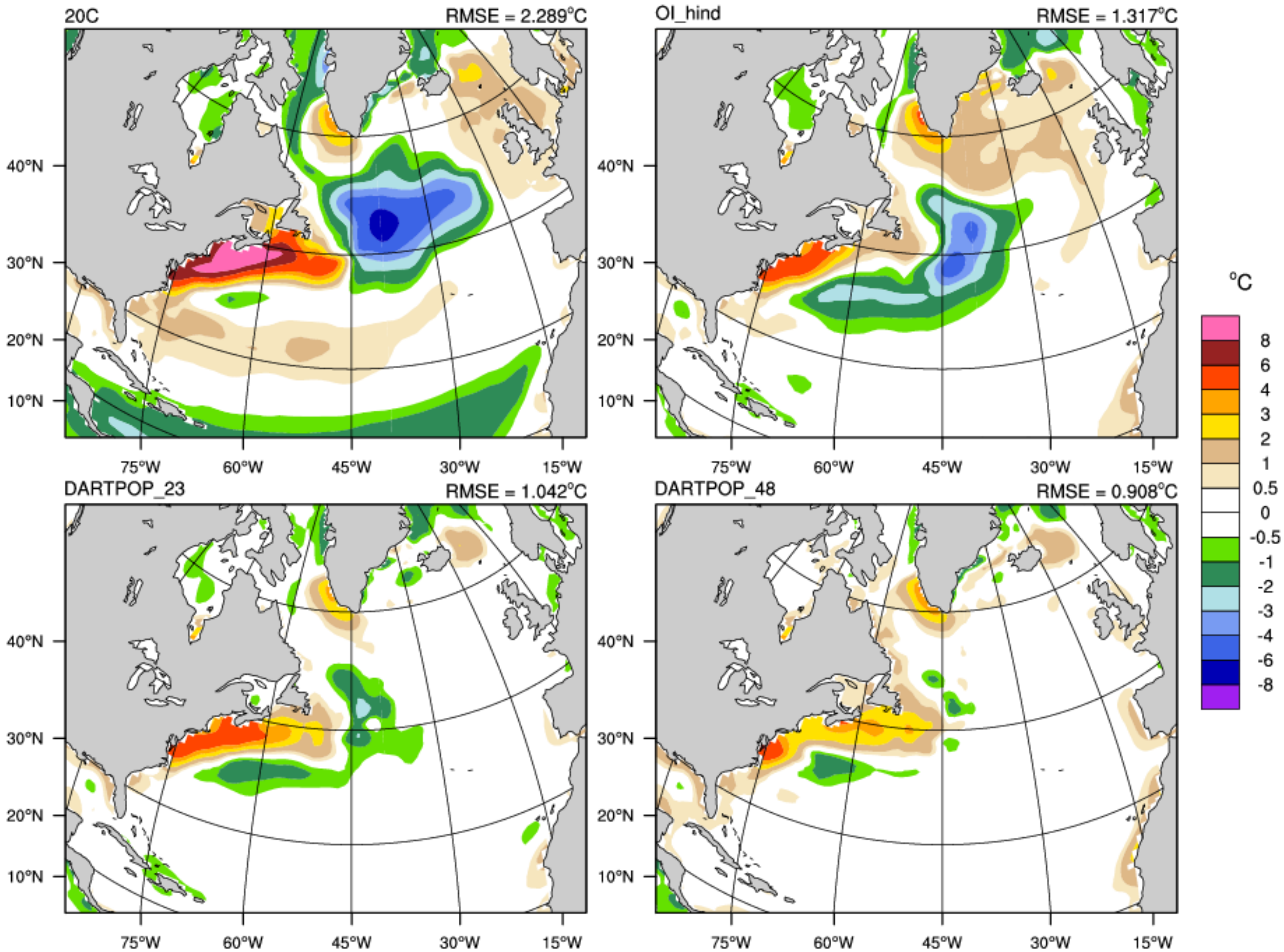
100m Mooring Temperature RMSE – Pacific



Physical Space: 1998/1999 SST Anomaly from HadOI-SST

Coupled Free Run

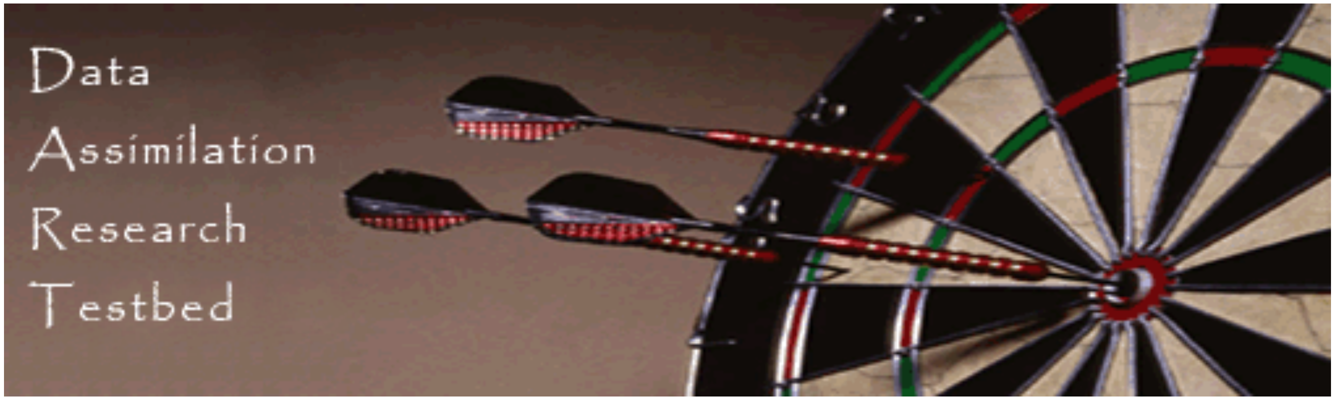
POP forced by observed atmosphere (hindcast)



23 POP 1 DATM

48 POP 48 CAM

Learn about ensemble assimilation and DART tools at:

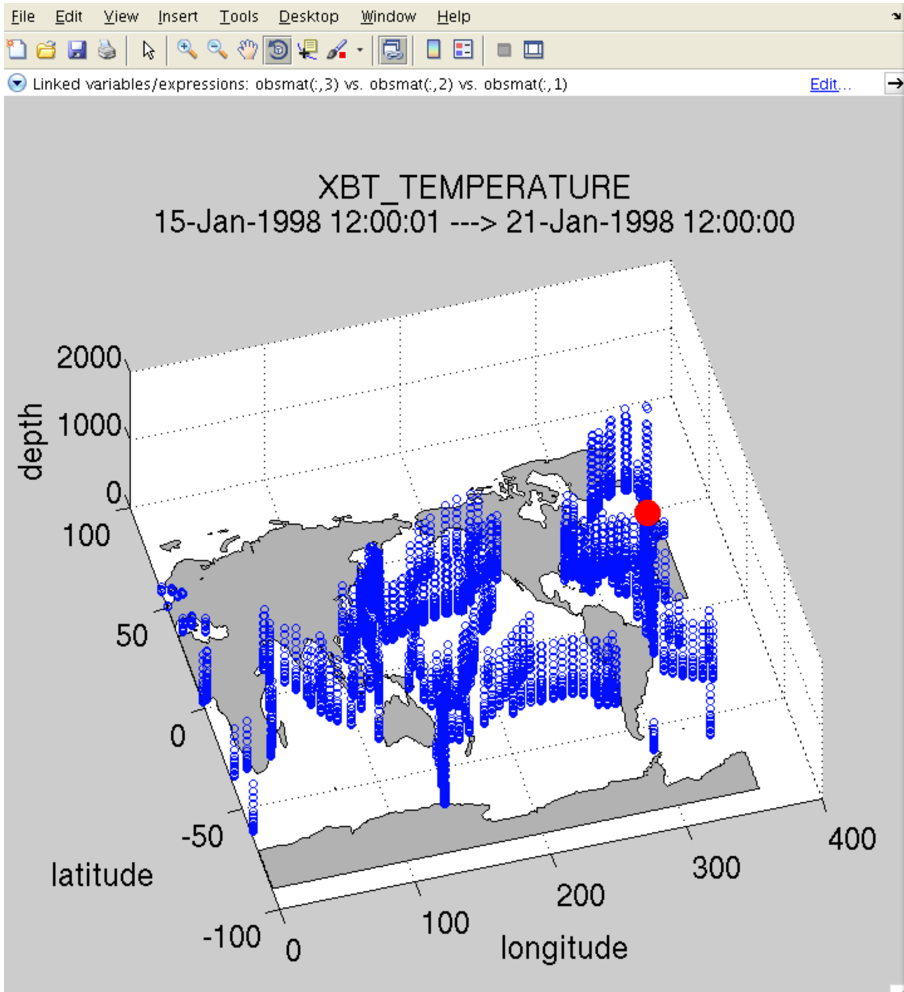


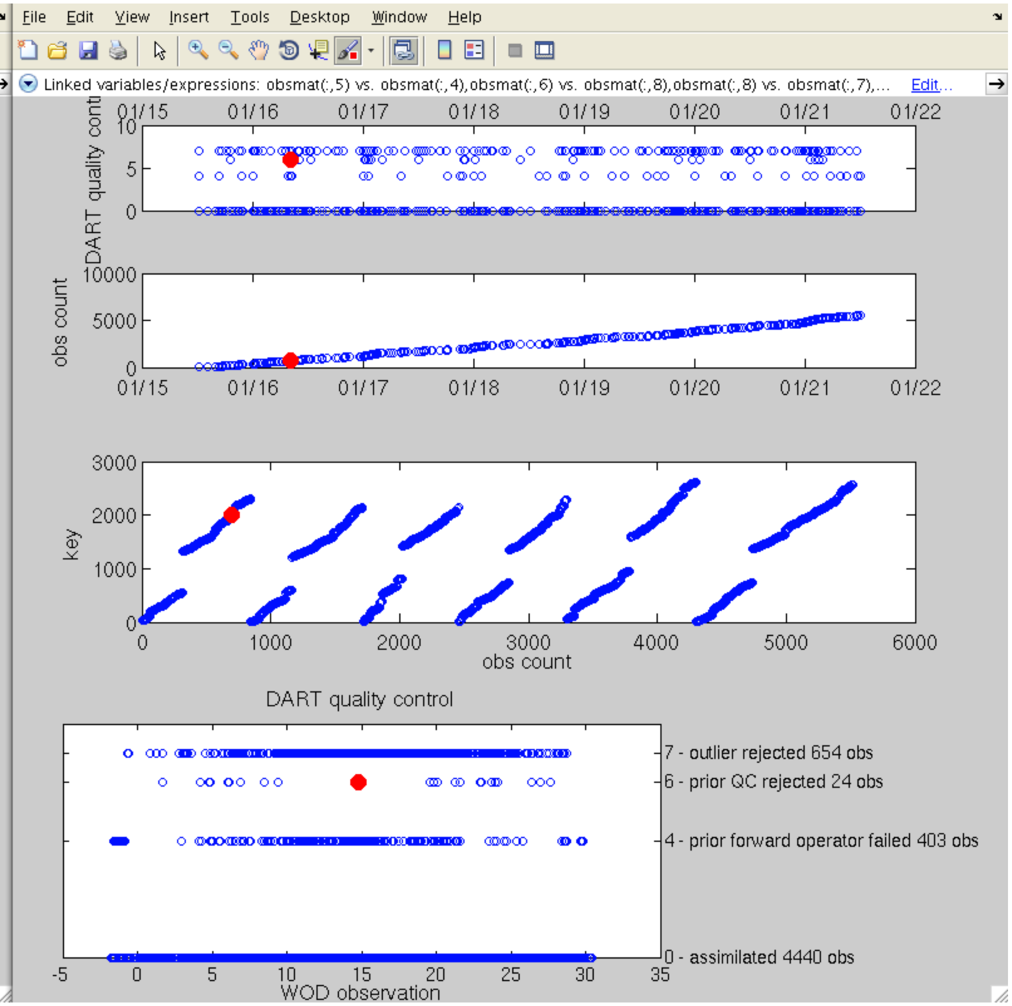
http://www.image.ucar.edu/DAReS/DART/

Anderson, J., Hoar, T., Raeder, K., Liu, H., Collins, N., Torn, R., Arellano, A., 2009: *The Data Assimilation Research Testbed: A community facility.* BAMS, **90**, 1283—1296, doi: 10.1175/2009BAMS2618.1

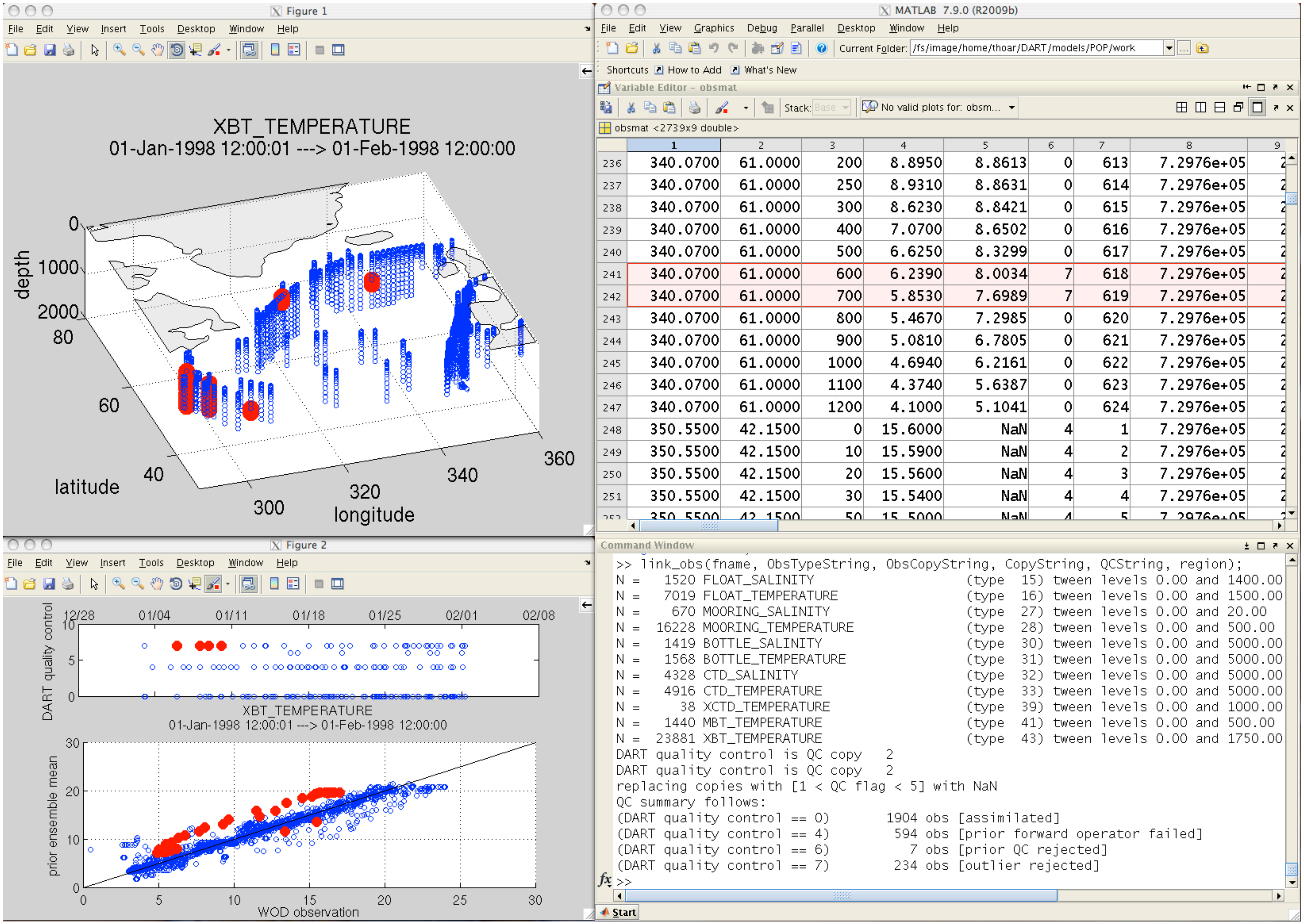
End of Presentation, following slides held in reserve.

Observation Visualization Tools





Observation Visualization Tools



The CAM-DART-POP Implementation

Uses the CESM1 software framework; ocean, atmosphere, and other components communicate through the coupler. A few minor script changes and use of the interactive ensemble capability permit each member of an ensemble of POPs to be forced by a different CAM atmosphere.

Once the additional files are staged, the basic implementation is a trivial addition to the run script that invokes the DART system.

```
# ------------------------------------------------------------------
# See if CSM finishes correctly (pirated from ccsm_postrun.csh)
# ------------------------------------------------------------------
# DART assimilation operating on restarts
# ------------------------------------------------------------------

grep 'SUCCESSFUL TERMINATION' $CplLogFile
if ( $status == 0 ) then
   ${CASEROOT}/assimilate.csh
endif
```