The

Forecasting Ocean Assimilation Model System

Mike Bell 25 Sept 2004

mike.bell@metoffice.gov.uk

Content

- Summary of capability and formulation
- Trouble shooting
- Assessments
- Adapting to changing world

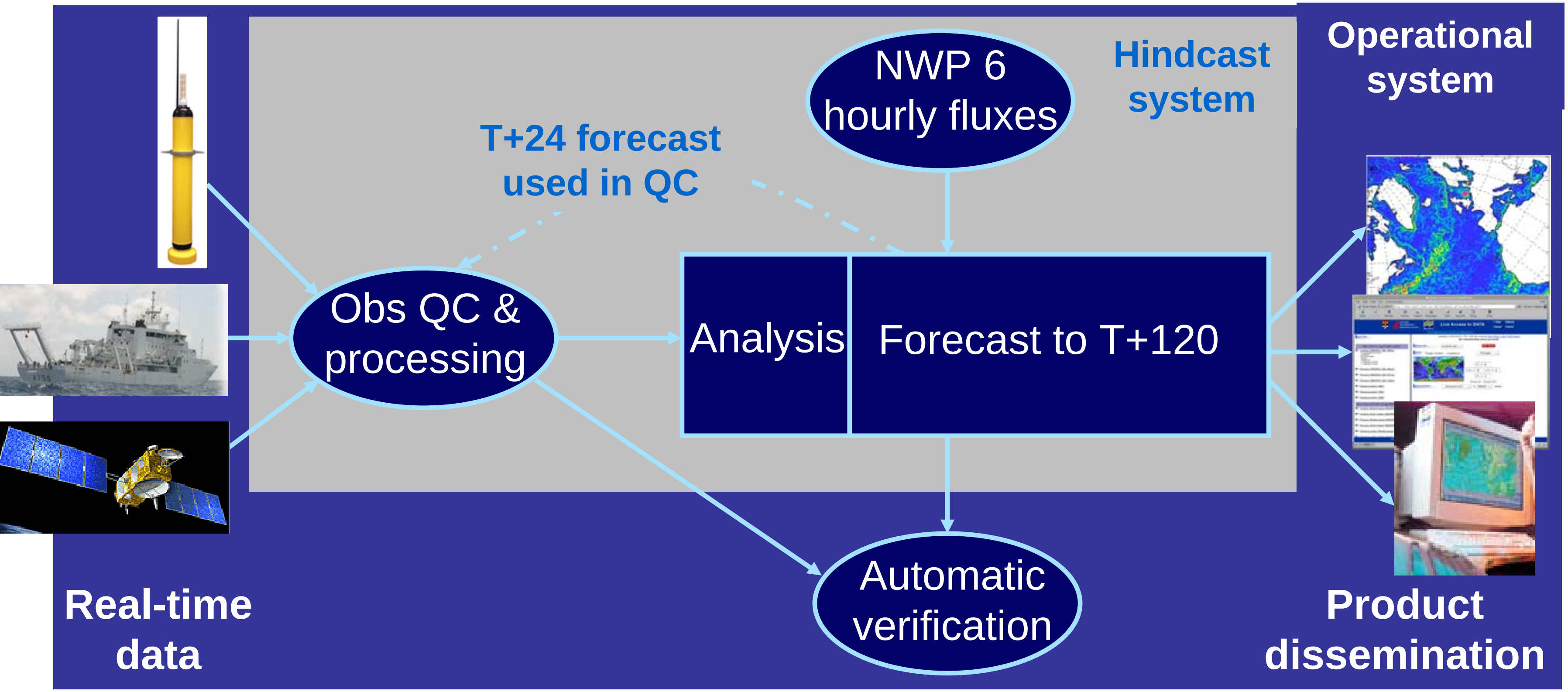
Summary of capability and formulation

The Met Office's Operational Ocean Products

- SST analyses for NWP (global & regional); daily
- Surface waves (global & regional); twice daily
- Storm surges to T+48: NW European shelf; twice daily
- Deep ocean forecasts (T, S, u, v) to T+120; daily (FOAM)
- 3D Shelf-seas (T, S, u, v) to T+48; daily (POLCOMS)
- Seasonal forecasts (coupled OIA); weekly (GloSea)
- SST and sea-ice analyses (HadISST); monthly

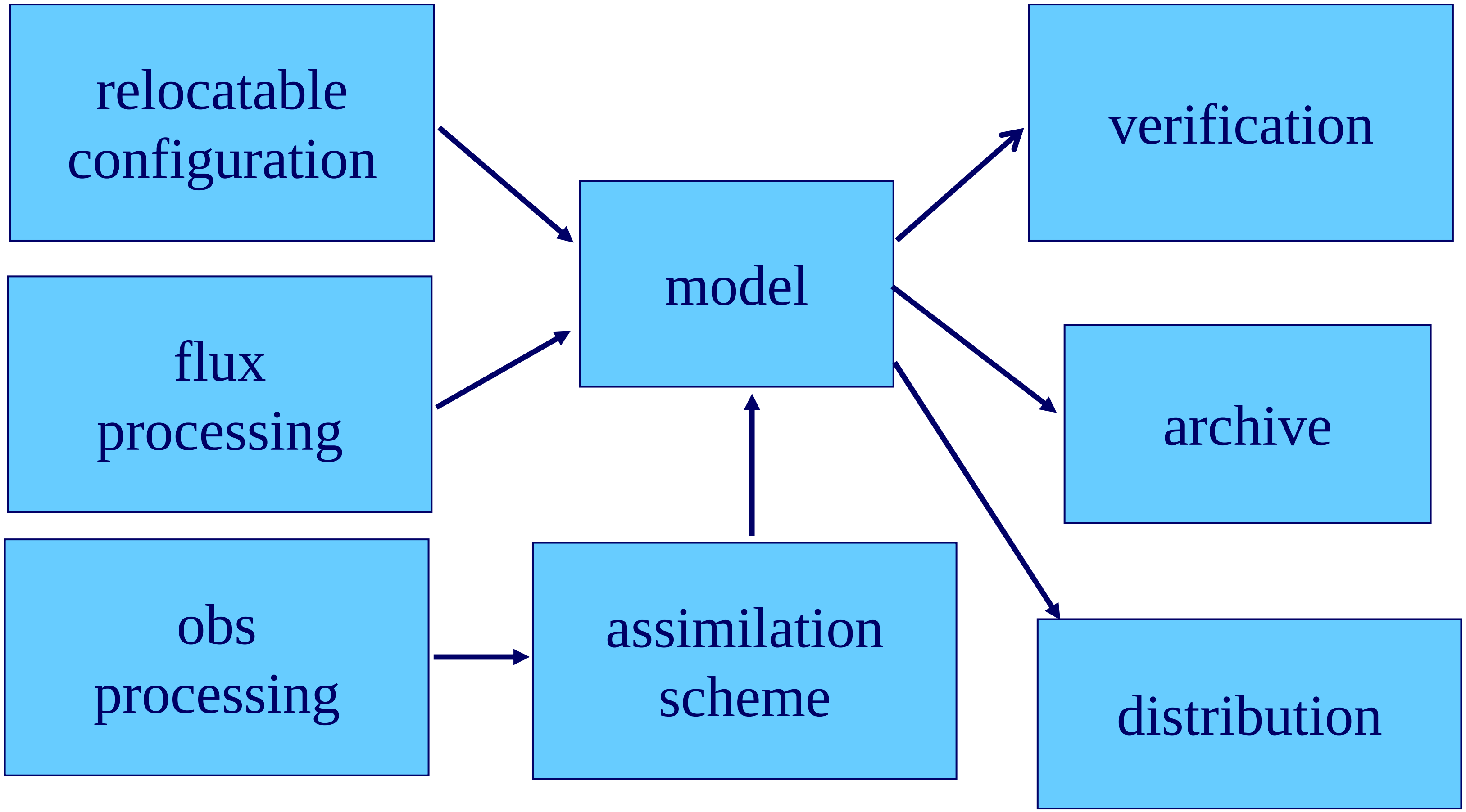
- Operational characteristics:
  - Routine service to existing (paying) users
  - Timeliness determined by user requirements
  - Monitoring and verification
  - Dedicated operational staff

FOAM system

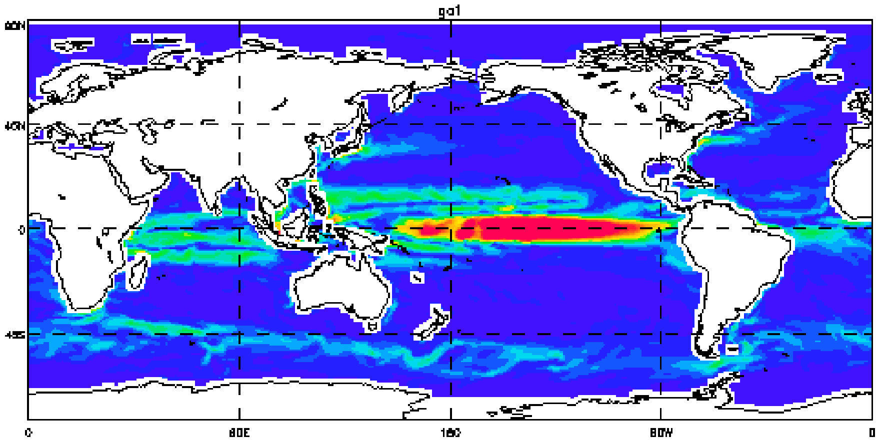


- Operational real-time deep-ocean forecasting system
- Daily analyses and forecasts out to 5 days
- Hindcast capability (back to 1997)
- Relocatable high resolution nested model capability

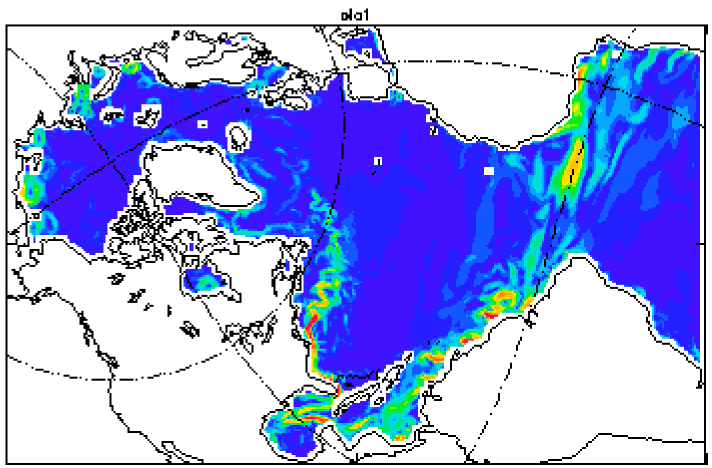
FOAM components



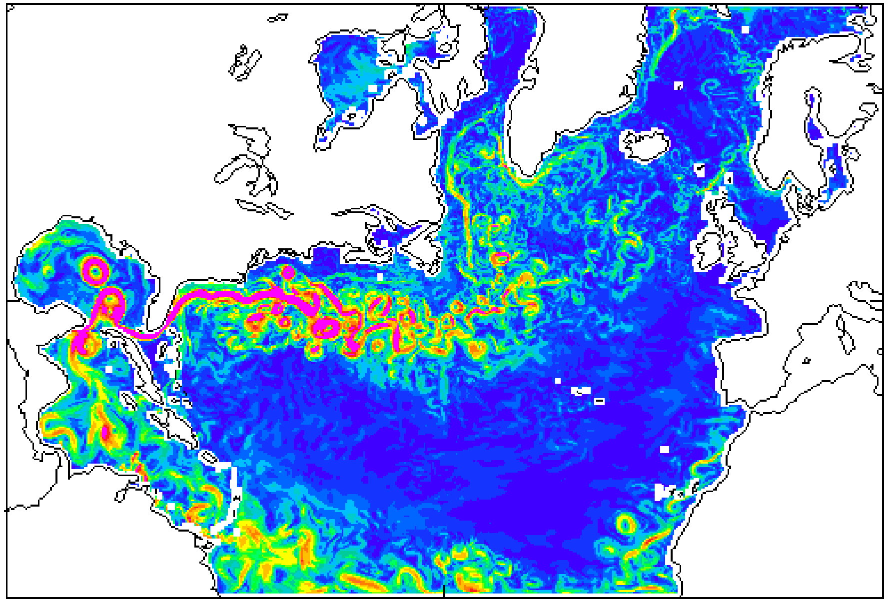
Sample FOAM configurations



1° (operational since 1997)



1/3° (operational since 2001)



1/9° (pre-operational since April 2002)

Data available from http://www.nerc-essc.ac.uk

All these configurations have only 20 levels

Relocatable Nested Configurations

- **Have used various bathymetries (Smith & Sandwell, GEBCO, DBDB2)**
- **Use latitude-longitude grid (with rotated pole in limited area models to give uniform grid)**
- **1-2-1 filter is applied twice to bathymetry to avoid forcing at grid-scale**
- **Grid-scale channels are filled to prevent an instability (appears to be associated with B-grid)**
- **Channels are adjusted using list by Thompson (1996)**
- **Bathymetry in relaxation zone of nested models is "matched" to that of outer model**
- **Flow relaxation scheme used for all prognostic variables with boundary rim of 4-8 points**

Model formulation

- Bryan-Cox B-grid ocean model developed jointly with climate modelling group of Hadley Centre
- Rigid lid + z-levels (so unsuitable for shallow tidal waters)
- Combination of biharmonic and harmonic viscosities
- QUICK 3rd order advection of tracers; Griffies isopycnal mixing; no Gent-McWilliams “eddy flux”
- Kraus-Turner, Pacanowski & Philander and neutral Large K-profile vertical mixing
- Roussenov & Rahmstorf convection schemes
- Sea-ice: Zero layer thermodynamics and “simple advection” (trialling EVP and ITD rheology)
- Trialling partial bottom levels

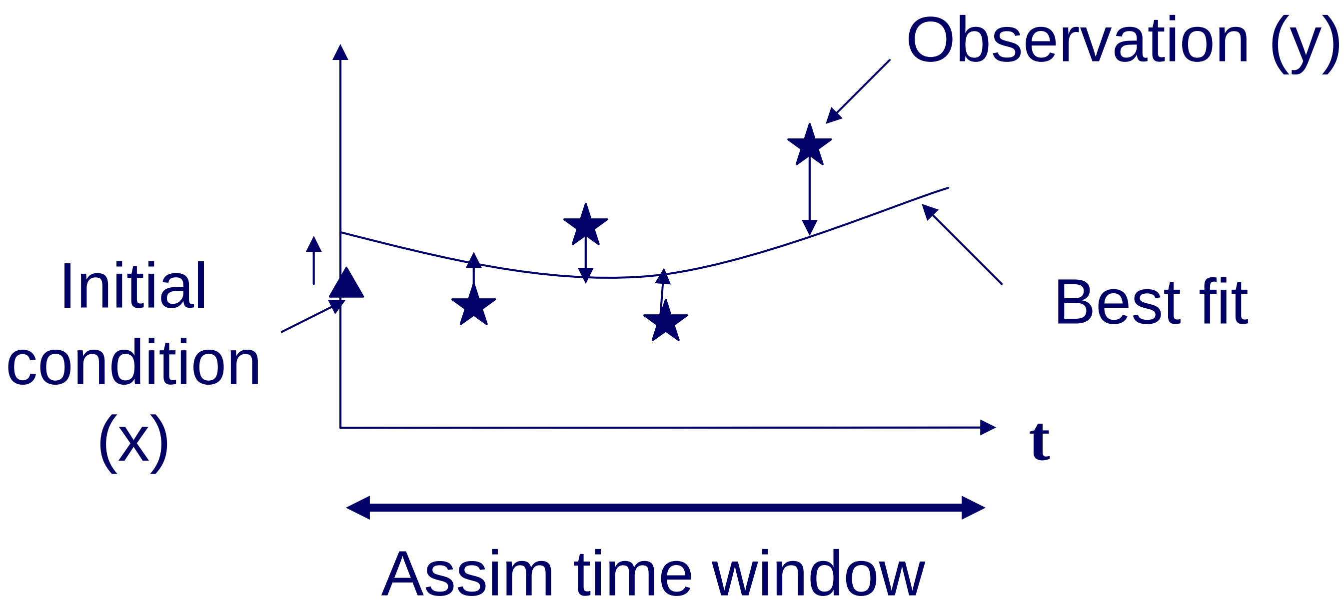
Observations and surface fluxes

- Temperature and salinity profile data at all depths
- Surface temperature data; in situ and coarse grid (2.5º) AVHRR products
- Altimeter data processed by CLS (Jason-1, Envisat, GFO) twice a week
- Sea ice concentration fields from CMC (based on SSMI)
- Surface fluxes from global NWP system: wind stress, wind mixing energy, heat fluxes (penetrating & non-), precipitation minus evaporation; weak Haney relaxation to climate T & S
    - Over sea-ice, both fluxes through ice and leads
- River inflow (based on GRDC monthly climate; largest rivers modified; global only)

Formulation of Assimilation

- **Timely assimilation**
- **Two component background error covariances**
- **Revised FOAM assimilation scheme**

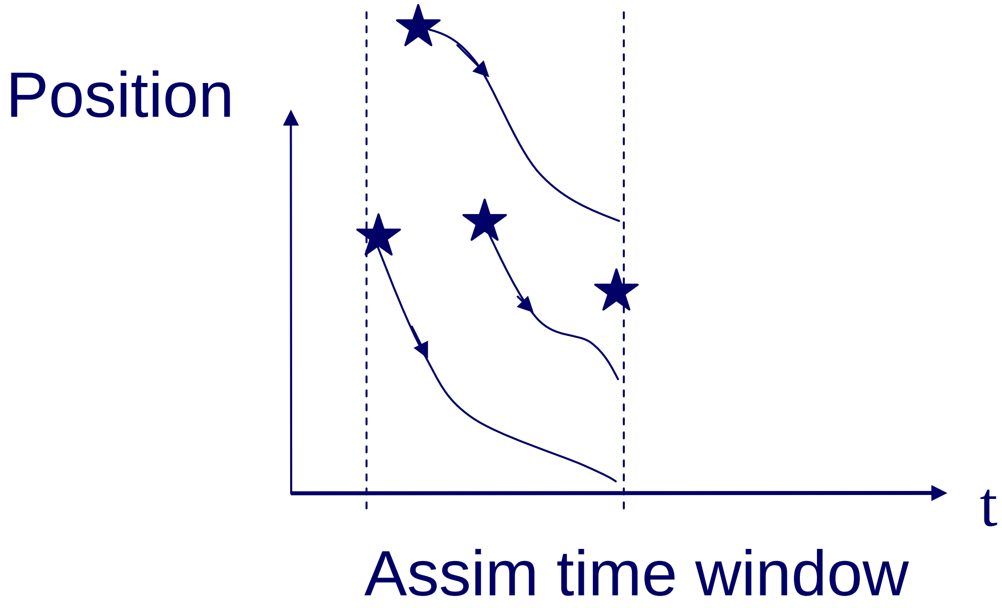
Standard 4D-Variational Assimilation



Adjust the initial condition until the sum of the squares of the normalised errors is minimised

$$J = (\mathbf{x} - \mathbf{x}_b)^T \mathbf{B}^{-1} (\mathbf{x} - \mathbf{x}_b) + [y - h(g(\mathbf{x}))]^T (O + F)^{-1} [y - h(g(\mathbf{x}))]$$

Revised 4D-Var Formulation

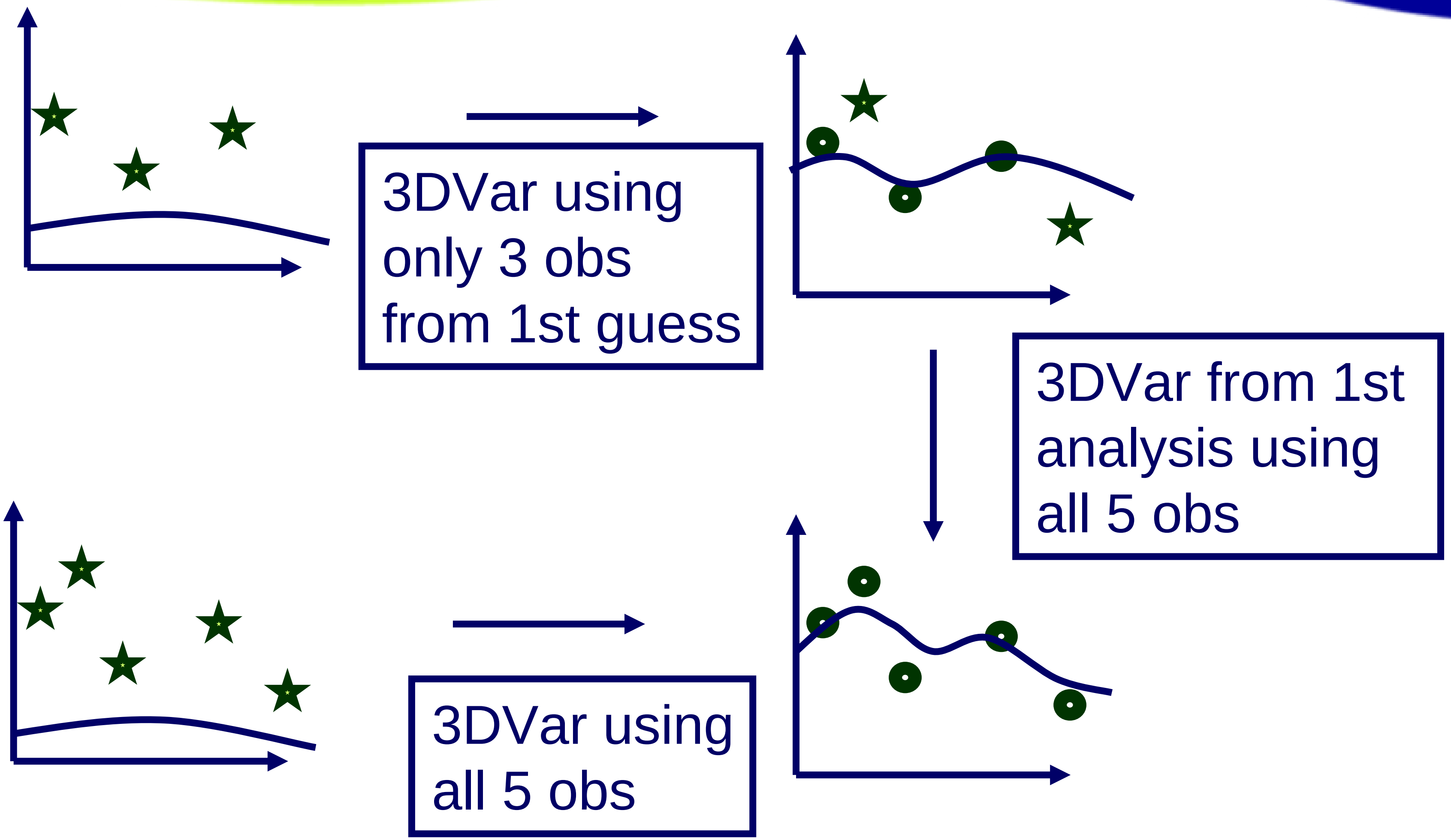


Conceptually easiest for passive tracers

Adjust analysis at final time until sum of the squares of the normalised errors is minimised

$$J = (\mathbf{x}-\mathbf{x}_b)^T \mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_b) + (g(y)-h(\mathbf{x}))^T [G^T (O+F)G]^{-1}(g(y)-h(\mathbf{x}))$$

Sequential combination of observations



Timely Variational Assimilation

- Assimilate observations into the model fields as soon as they arrive
- Keep track of where information from each observation has been received, evolving its location and increasing its estimated error with time
- This method avoids having to calculate the evolution of the temperature (etc.) of each observation - which would be difficult to do accurately enough

Two component background error covariances

- We assume the forecast errors arise from two distinct sources:
  - errors in the internal model dynamics => "mesoscale" errors
  - errors in the atmospheric forcing & biases => "synoptic" scale errors

- Assume separability of the error covariance for each component, i.e. horizontal and vertical correlations can be calculated separately:

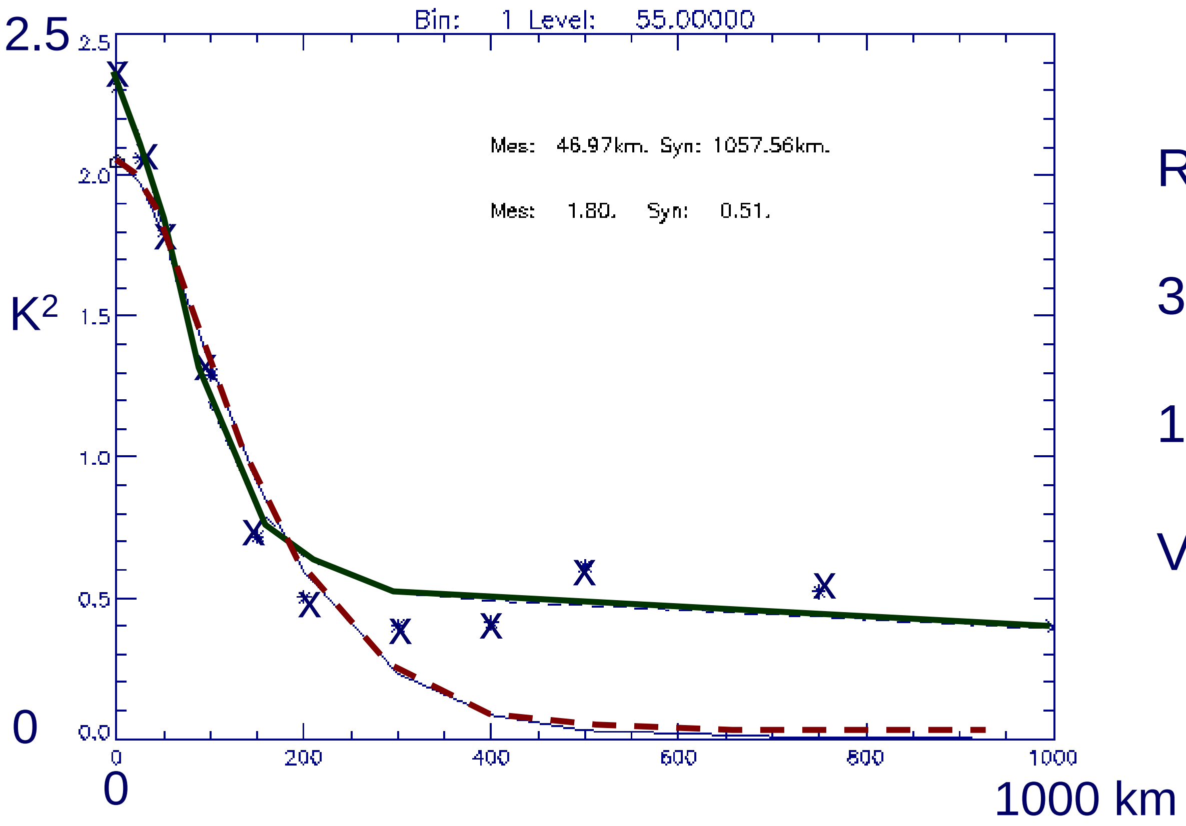
$$\mathbf{B} = \mathbf{B}^m + \mathbf{B}^s$$

- Use collocated observation and model forecast values to estimate covariance values – bin together to have enough statistical information

$$\mathbf{B} = \mathbf{B}_h^m \mathbf{B}_v^m + \mathbf{B}_h^s \mathbf{B}_v^s$$

- Fit the sum of 2 SOAR functions to the (obs-f/c) covariance values to estimate the variance and horizontal correlation scales of the two forecast error components.

Statistics of observation minus background differences



Results based on:

3 years of profile observations

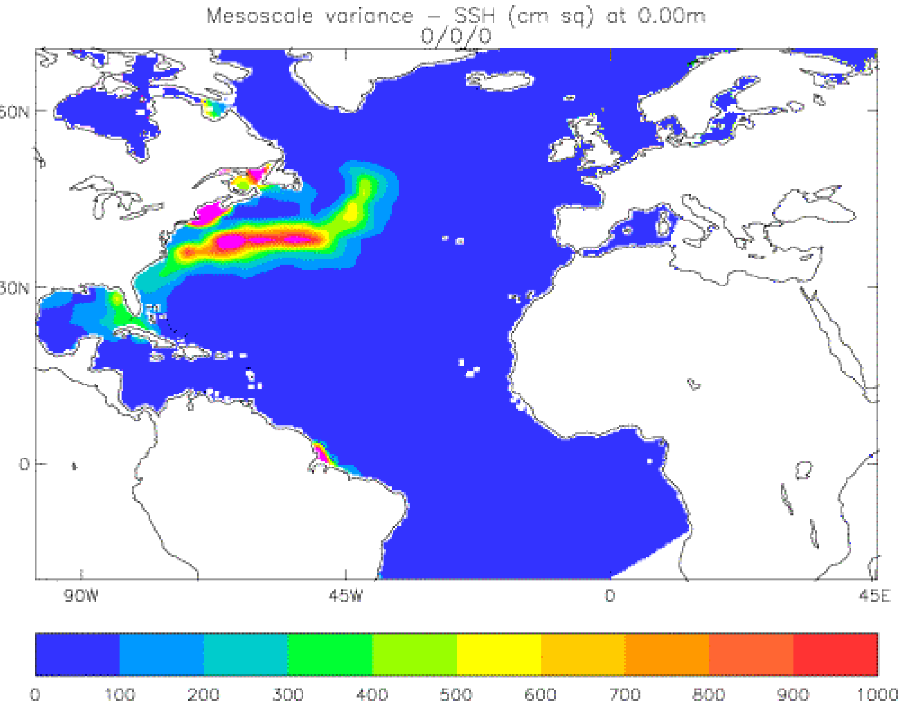
1/3° Atlantic model

Valid at 50 metres depth

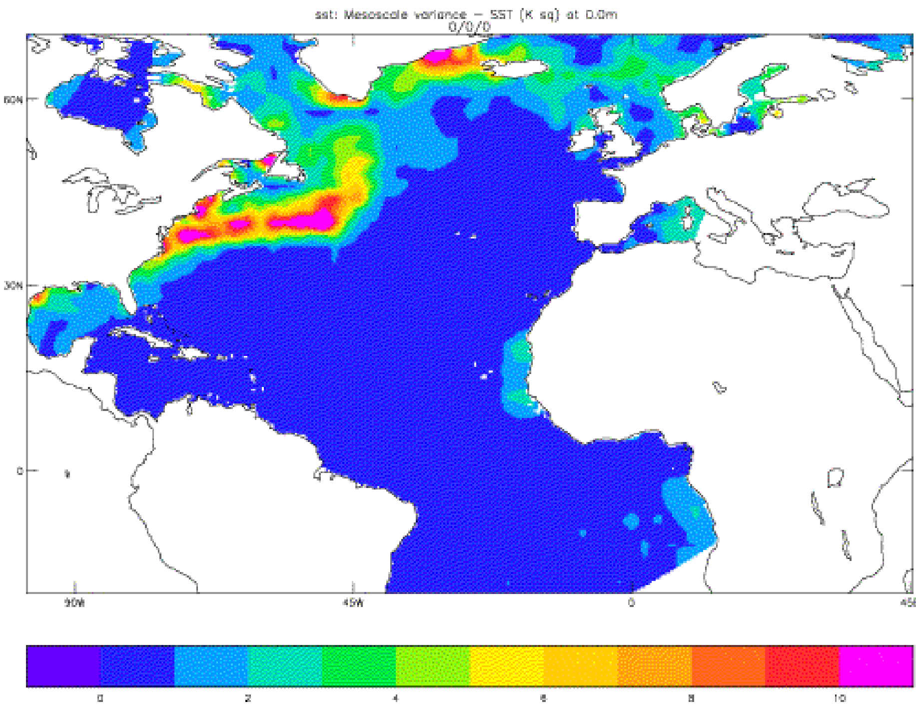
Variance (K^2)	Length (km)	Component
1.80	47	"mesoscale"
0.5	1060	"synoptic scale"

Mesoscale background error variances

Calculated using SSH and SST observations and 1/3º Atlantic FOAM



SSH Variance



SST Variance

Discussion of background error covariances

- Spatial and temporal resolution of results is restricted by the number of observations
- Difficult to extract information about vertical correlations
- Observation errors assumed to be uncorrelated – not always true
- Scales calculated are isotropic – could also calculate anisotropic scales using the same method
- Some of these shortcomings could be addressed by using methods which estimate covariances using model fields, e.g. NMC method, although these methods don't relate the model fields to the "truth".

Outline of assimilation scheme

- **We perform one analysis each day**
  - **Each analysis consists of a number of iterations**
  - **On each iteration observations are separated into groups which are easily related (thermal profiles, saline profiles, surface temperature, surface height)**
  - **For each group of observations (e.g. the temperature profile data), increments are calculated first for the directly related model variables (e.g. the temperature fields) More detail on next slide**
  - **These increment fields are then used to calculate increments for less directly related model variables (e.g. the velocity fields using hydrostatic and geostrophic balance relationships)**
- **The analysis increment fields are smoothly applied over the next 24 hours**

Details of univariate step

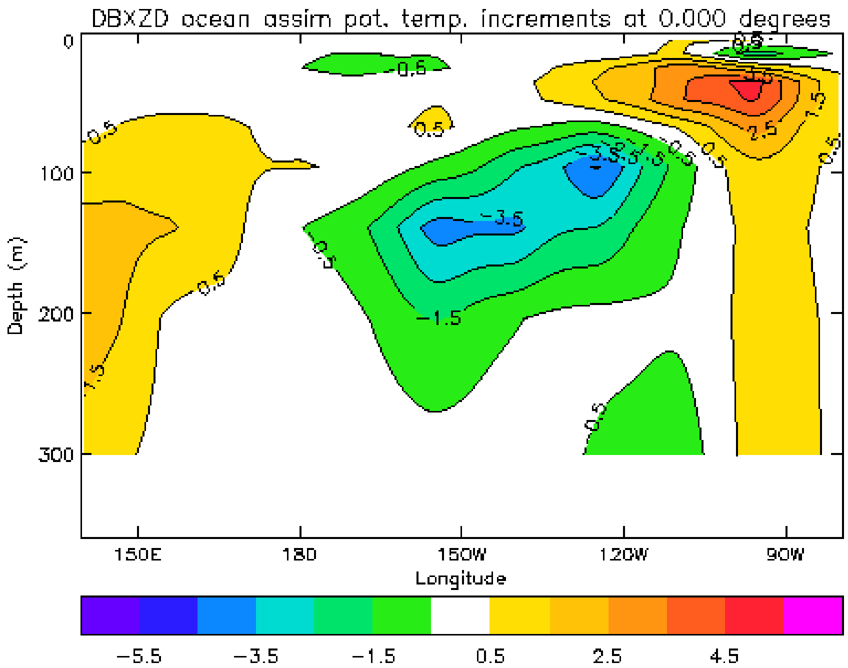
- The analysis equation is $\Delta x = B H^T (H B H^T + R)^{-1} \Delta y$
- We calculate the differences between each observation and the model (the observation increment vector Δy)
- $B H^T v$ is performed either as $B (H^T v)$ using a recursive filter or as $(B H^T) v$ by explicit calculations for each observation in its neighbourhood
  - Filtering performed for each component in 2 or 3 dimensions
- A simple approximation is made to the matrix inverse
  - More efficient techniques could be implemented
- We make increments to the observations so that the iterations converge to the 3DVar solution (Bratseth 1986)

Overview of assimilation scheme

- One analysis per day, multiple iterations per analysis
  - Iterations of different observation types interleaved
- Technique for assimilating obs in a timely manner
- Two component error covariance model
  - Decomposed into mesoscale and synoptic scale components
  - Inhomogeneous variances and correlation scales estimated based on 3 years obs - model statistics
- Modified Cooper and Haines scheme
  - Vertical displacement maximum in thermocline
- Satellite SST bias correction
- Pressure correction scheme to control biases in tropics
- Quality control of profile data (track, stability, background and buddy checks)

Troubleshooting

Data assimilation increments at the equator



surface

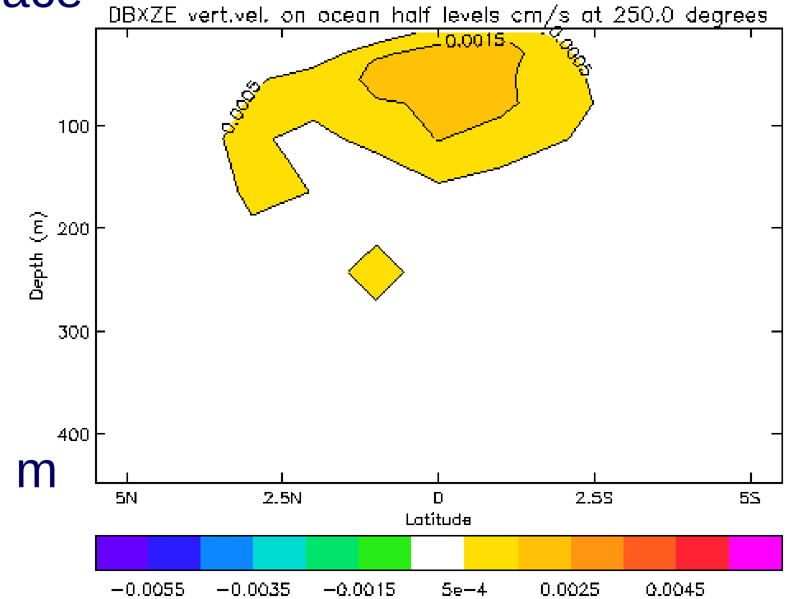
300 m

Annual mean temperature increment from assimilation along the equatorial Pacific (contour interval =°C per month)

Met Office

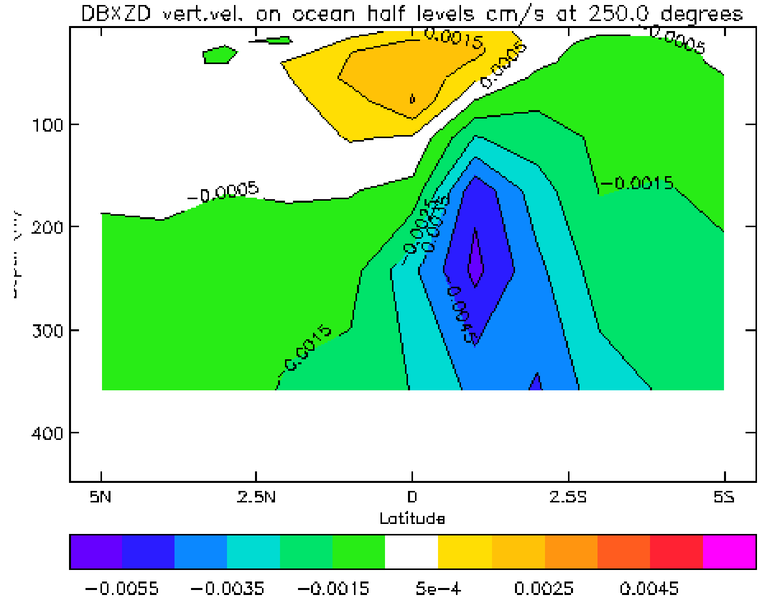
No assimilation

surface



400 m

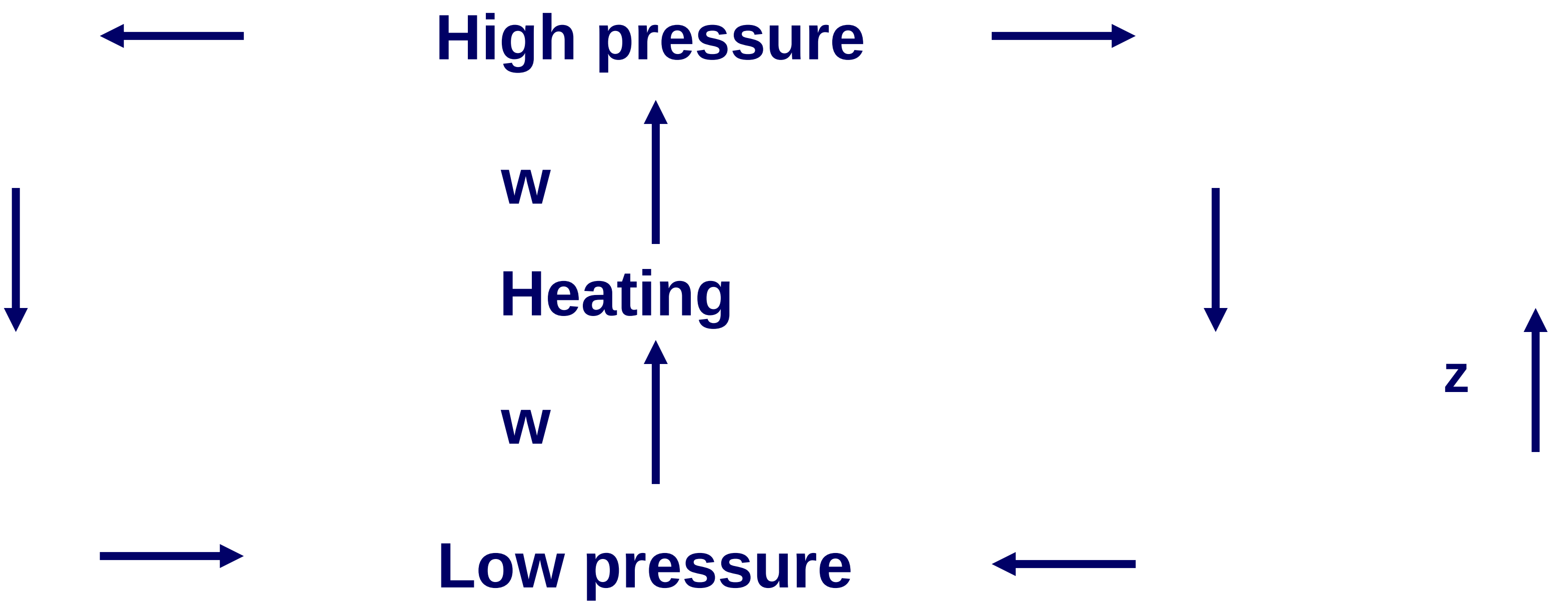
With assimilation



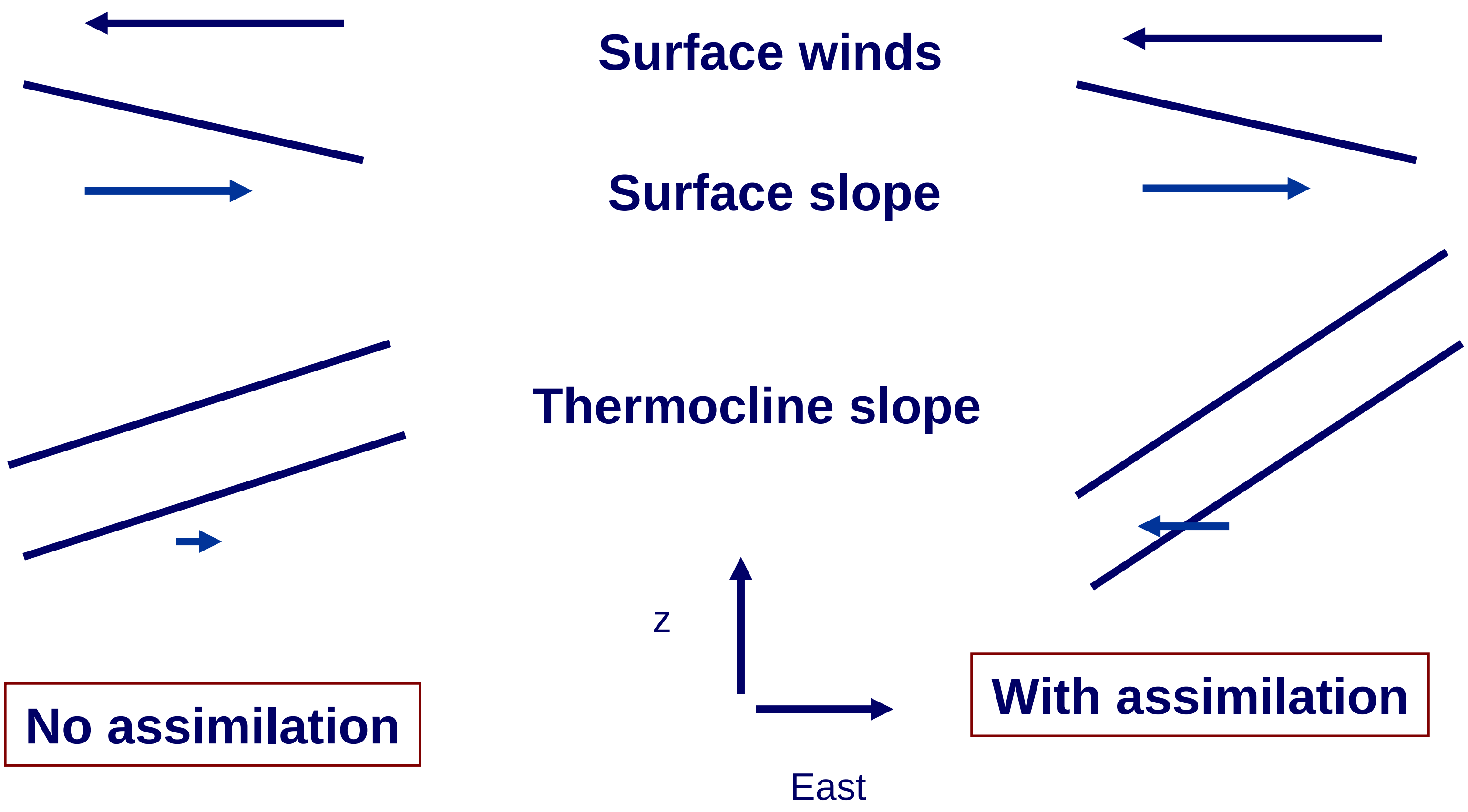
Annual mean vertical velocities at 110 ^oW (5 ^oN to 5 ^oS)

contour interval = 10^{-3} cm/s = 100 m/day

Circulations induced by assimilation at equator where model is cold



Balance of forces along equator in Eastern Pacific



Central ideas of pressure correction scheme

Where thermal increments of the same sign are repeatedly being made the balance of forces in the model is incorrect

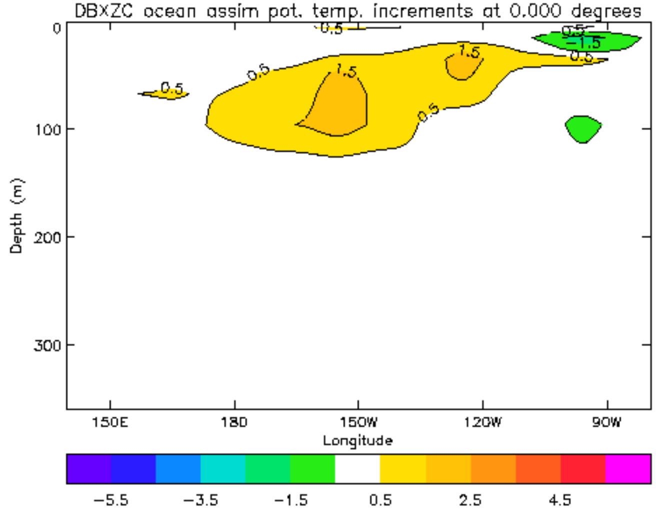
Pressure fields in the opposite sense to those generated by the standard data assimilation increments need to be accumulated and applied

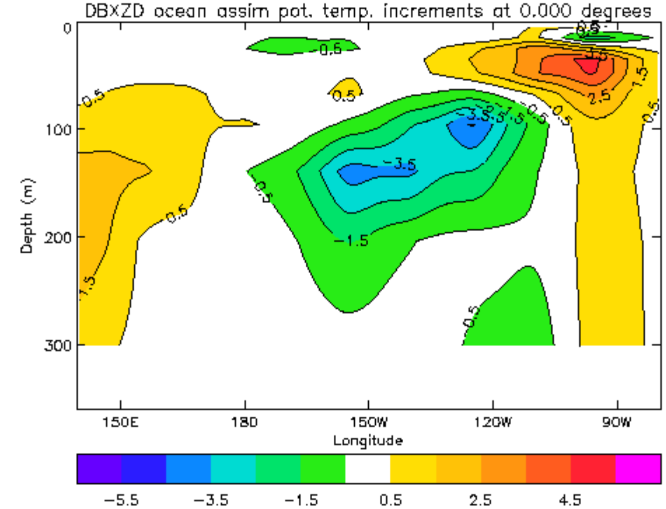
These increments are of small amplitude and large spatial scale so should not cause instabilities

Results for pressure correction scheme

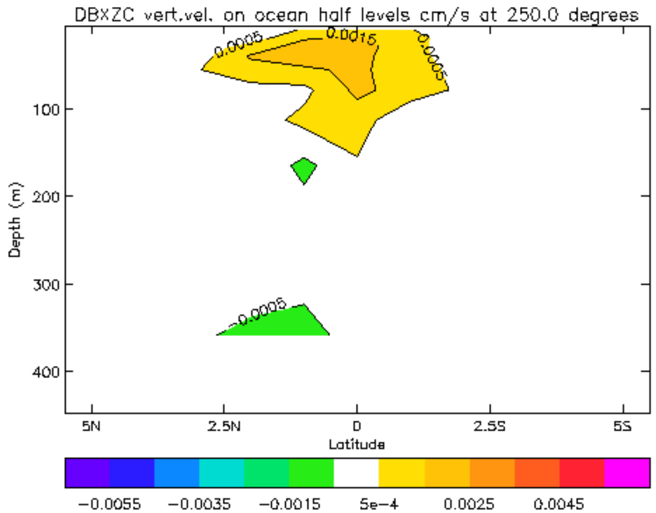
Pressure Correction Scheme | Original Scheme

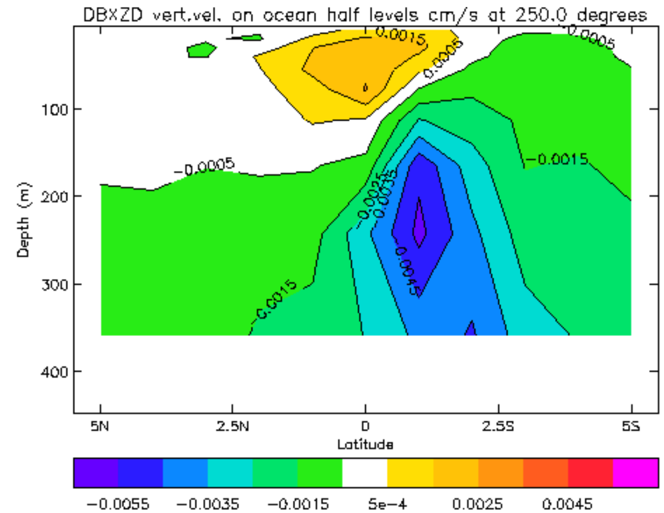
Assimilation increments





Vertical velocity

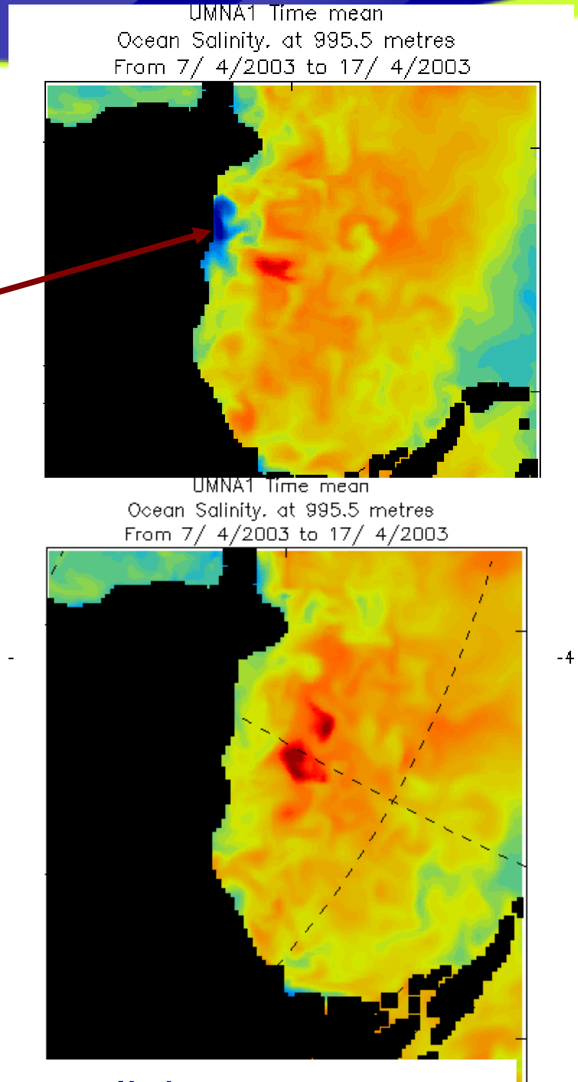




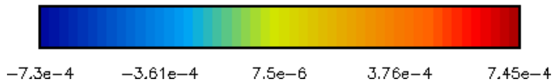
Impact of deep salinity data

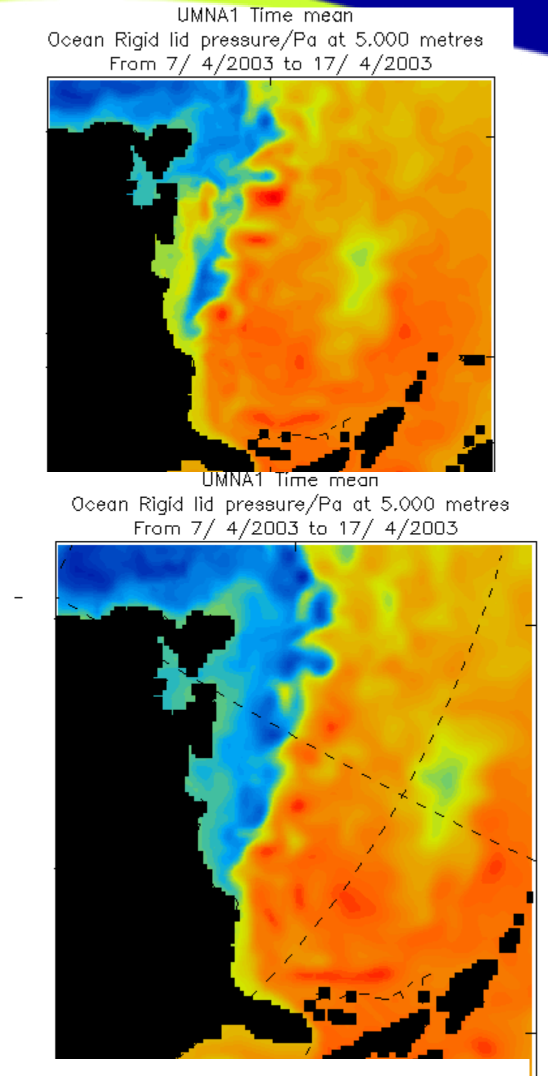
Problematic observation

Observation Failed by quality control

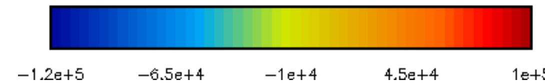


Salinity at 1000 m





Rigid lid pressure

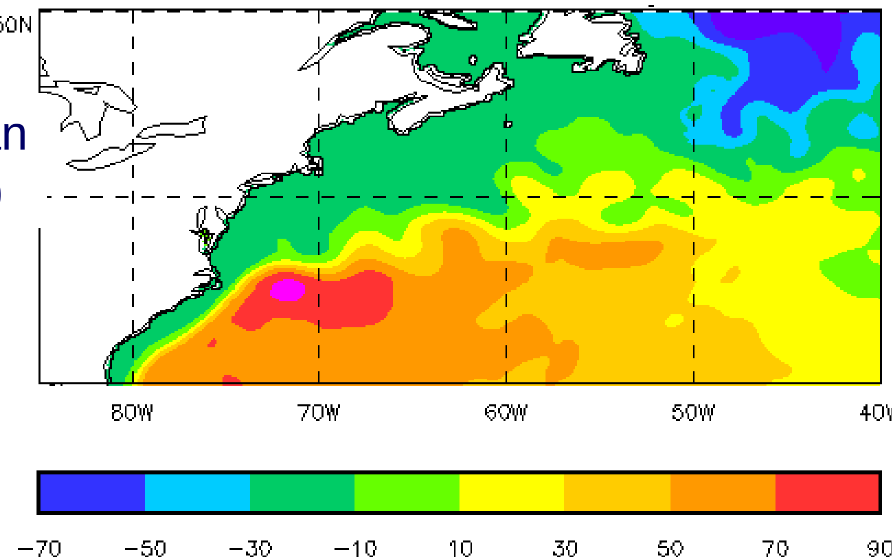


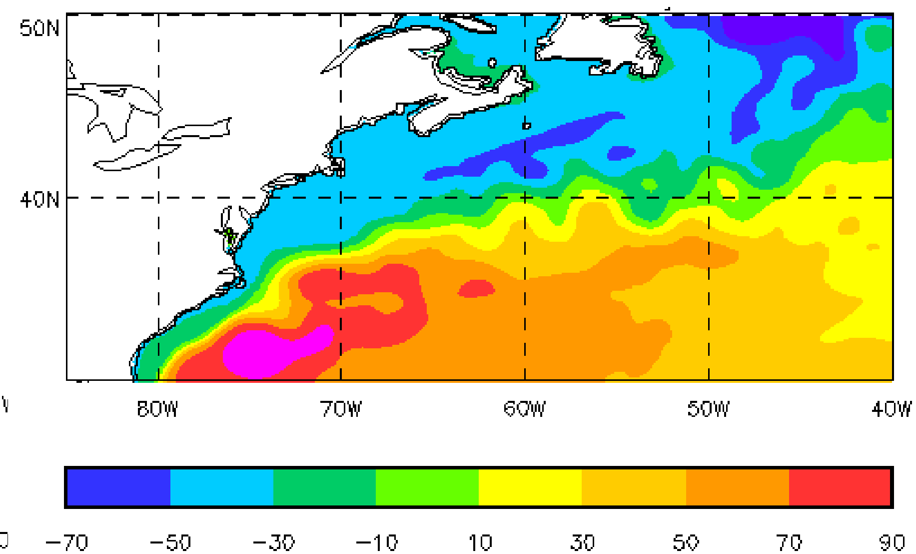
Surface height with biharmonic viscosity (1/9º)

Free run

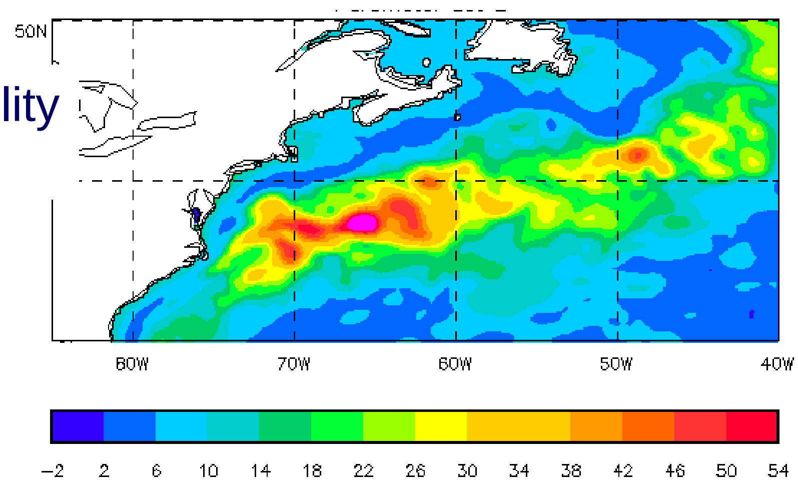
Assimilation

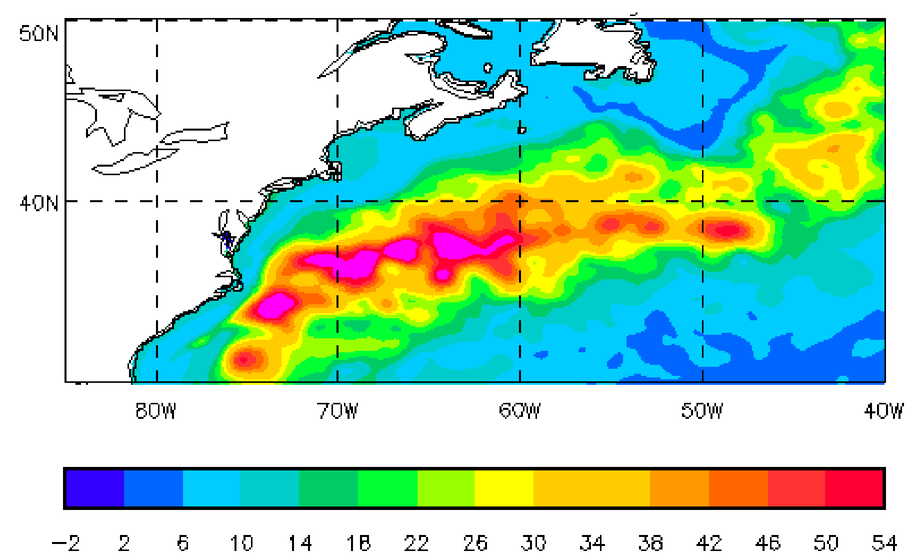
Mean (cm)





Variability (cm)





Impact of viscosity on Gulf Stream

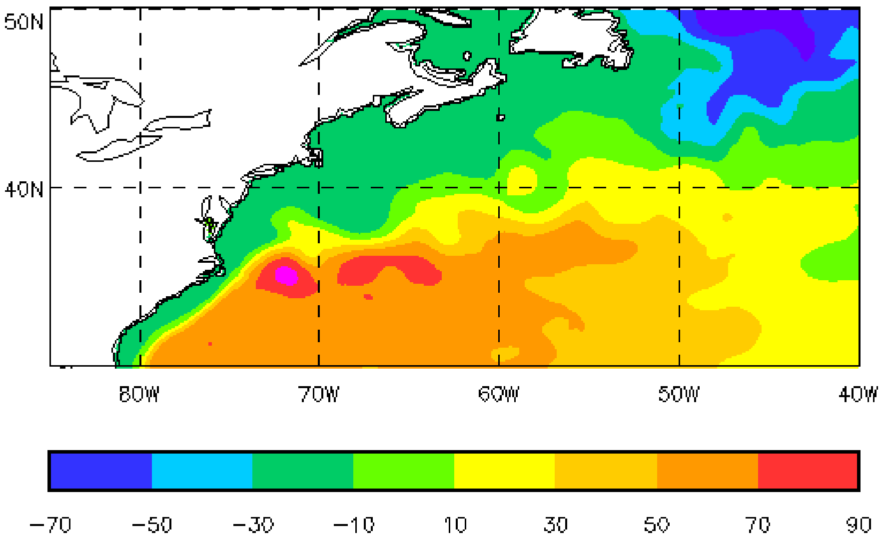
- Chassignet & Garraffo found separation of 1/12º MICOM isopycnal model to be sensitive to formulation of viscosity
- Just biharmonic viscosity gave too much mesoscale activity and unsatisfactory separation
- Just Laplacian viscosity improved separation, but not enough penetration of Gulfstream jet
- Best results with combination of biharmonic and Laplacian viscosity
- Dave Storkey repeated experiments with effectively Laplacian viscosity

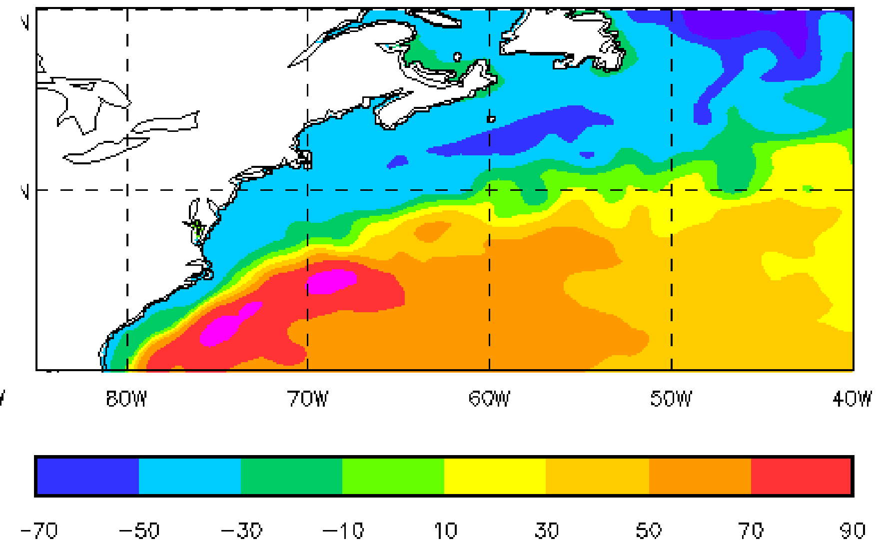
Surface height with Laplacian viscosity

Free run

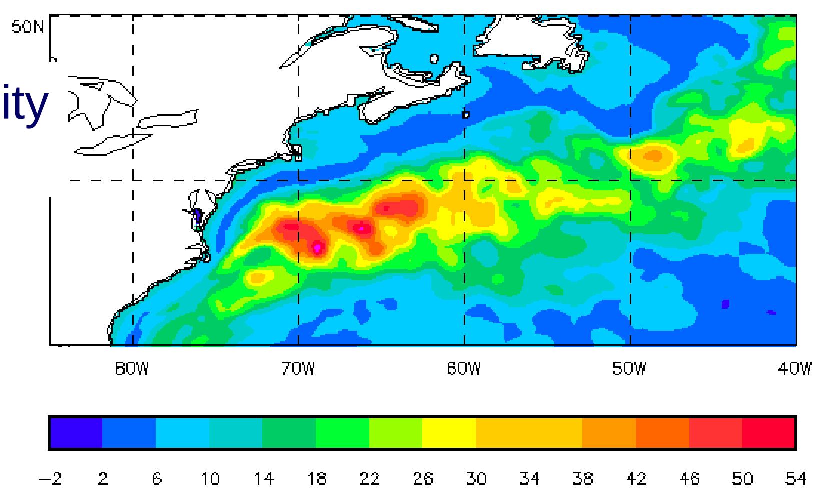
Assimilation

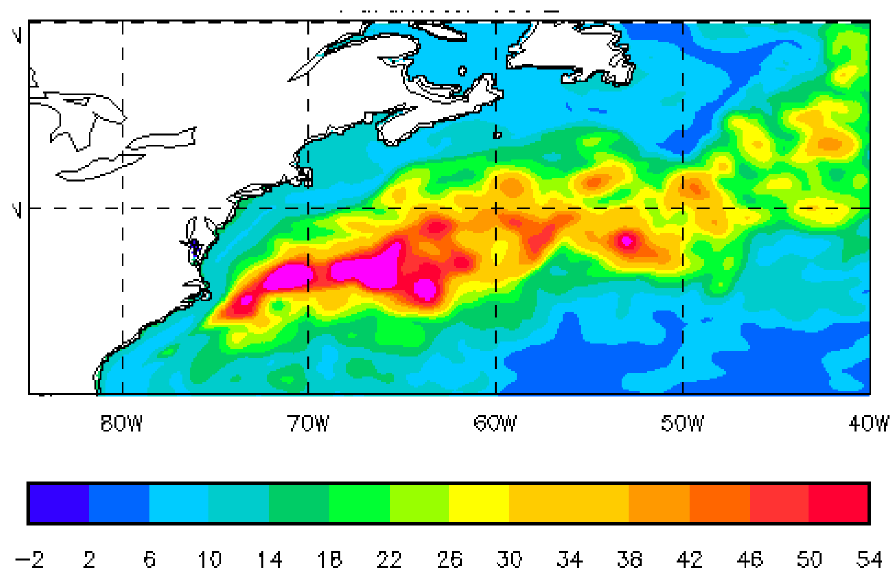
Mean (cm)





Variability (cm)





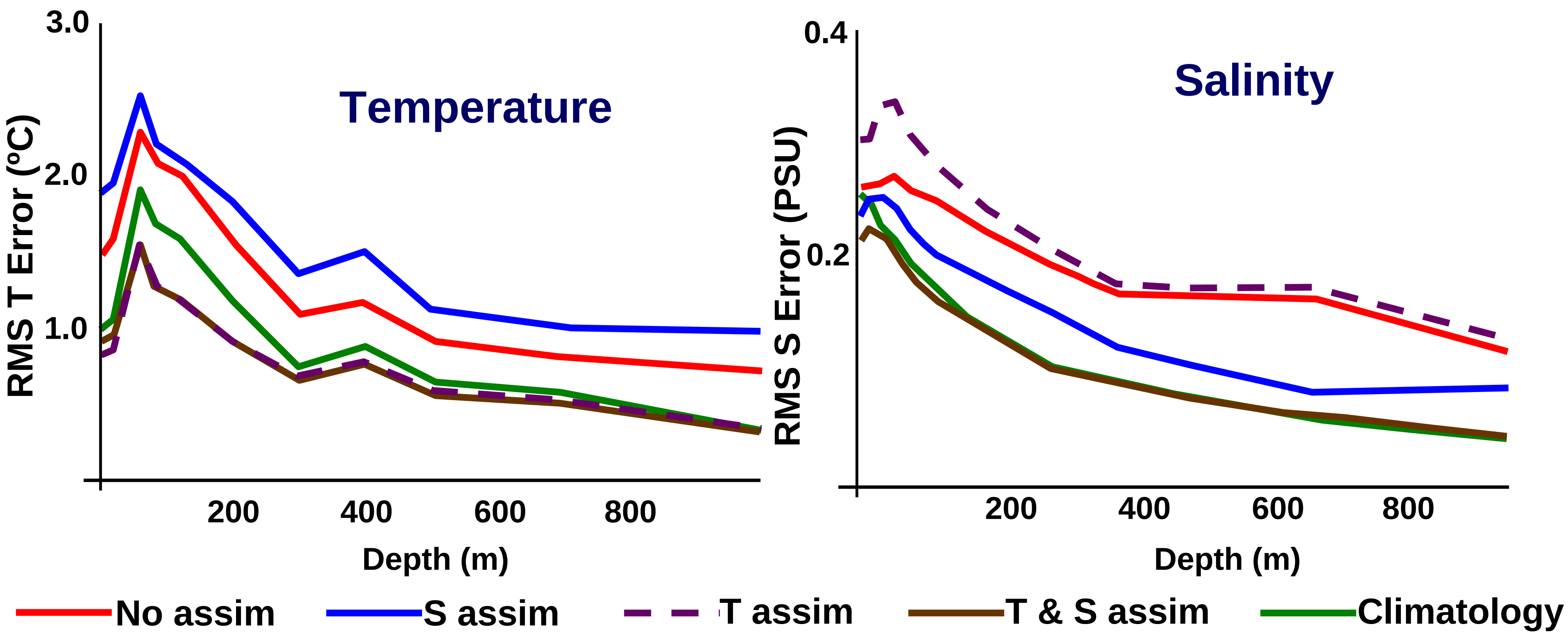
Assessments

Impact of assimilation of Argo data

- **Aim: Investigate impact of Argo data in isolation**
- **5-month runs of the operational global 1º model**
  - **Running for Jan - May 2003**
  - **Forced by 6-hourly NWP surface fluxes**
  - **Initial state taken from operational model**
  - **Assimilating only Argo data - no other data types**
- **Experiments run:**
  - **Assimilating temperature and salinity profiles**
  - **Assimilating temperature profiles only**
  - **Assimilating salinity profiles only**
  - **Control run assimilating no data**
- **Note !**
  - ➢ **Argo data also important to improve assimilation, model parametrisations and for validation**
  - ➢ **No conservation of T/S relationships in assimilation**

Impact of assimilation of Argo data

- **RMS errors against observations that have not yet been assimilated for final month of integrations**

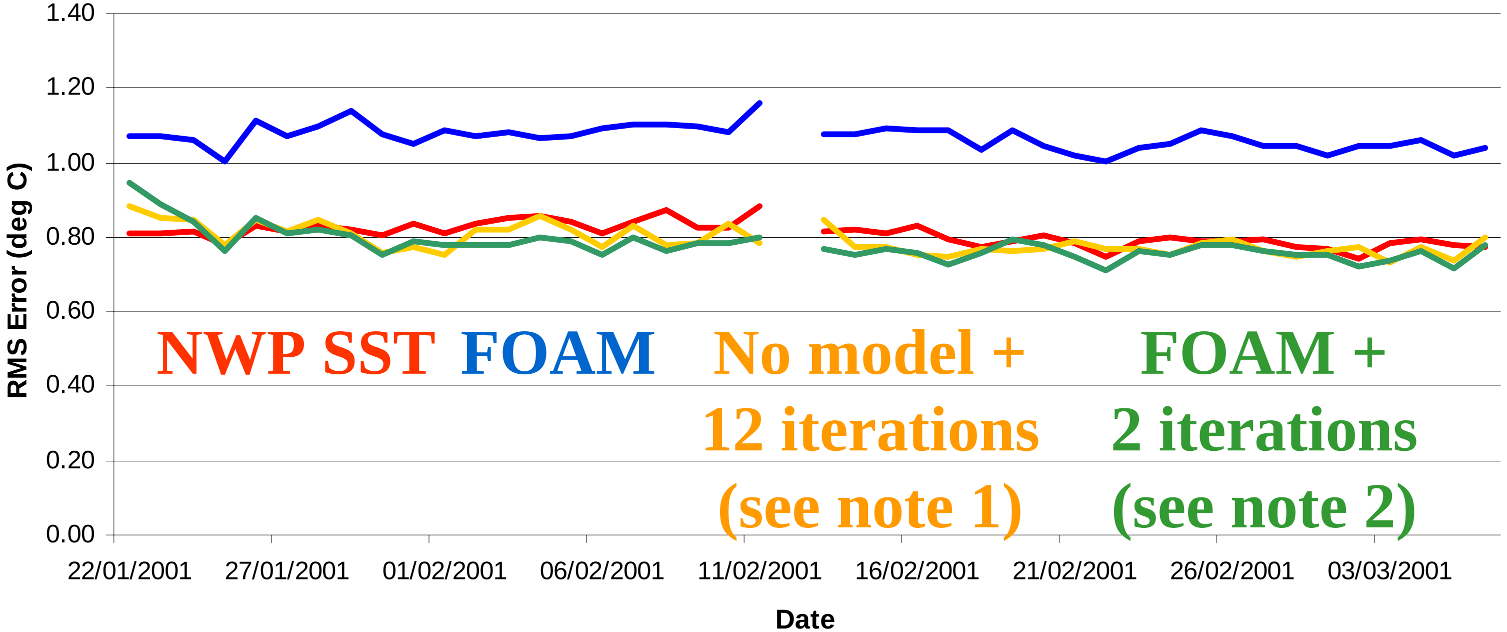


SST assimilation: tuning experiments

- 6 week integrations of global and North Atlantic models
  - Operational configuration (daily cycle)
  - Assimilating ‘operational’ SST data (no profile data)
  - Comparison to current operational FOAM system and NWP SST analysis

- Main investigations:
  - Impact of iterating AC scheme
  - Sensitivity to assimilation parameters
  - Impact of satellite SST bias correction

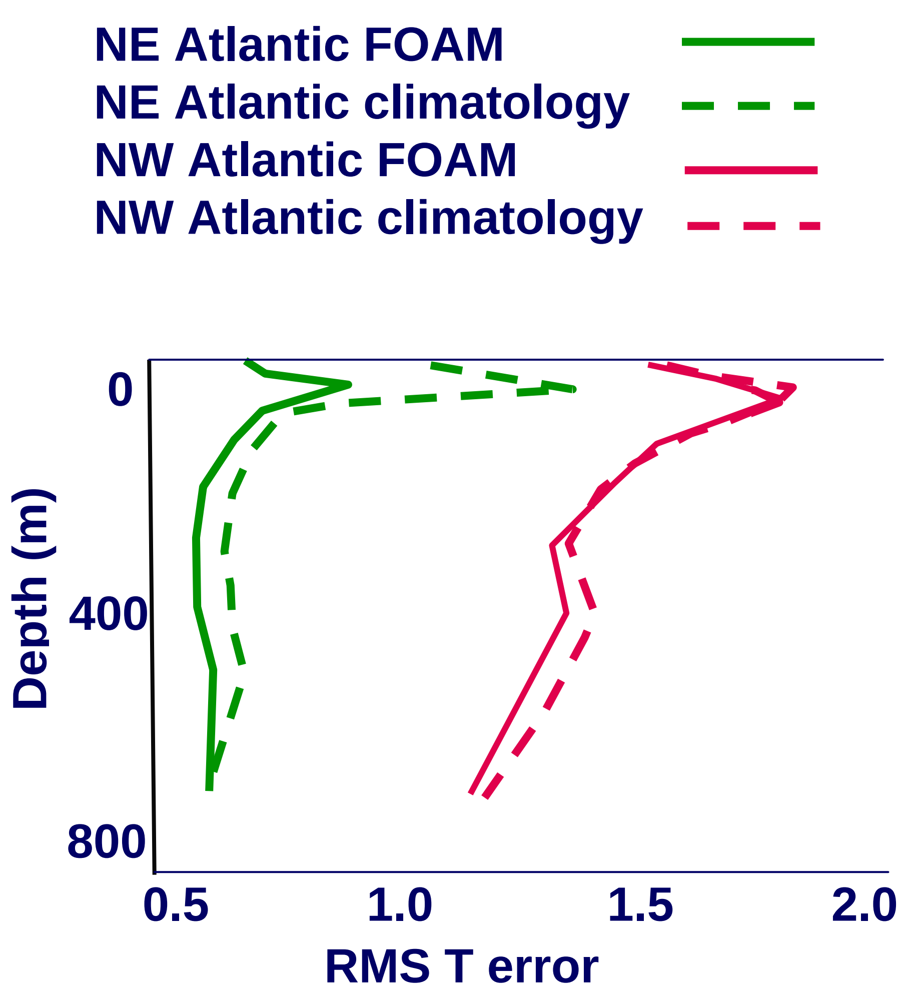
RMS SST errors against satellite data



Note 1: FOAM analysis scheme with 1 day time window and iteration of horizontal scales as in NWP analysis

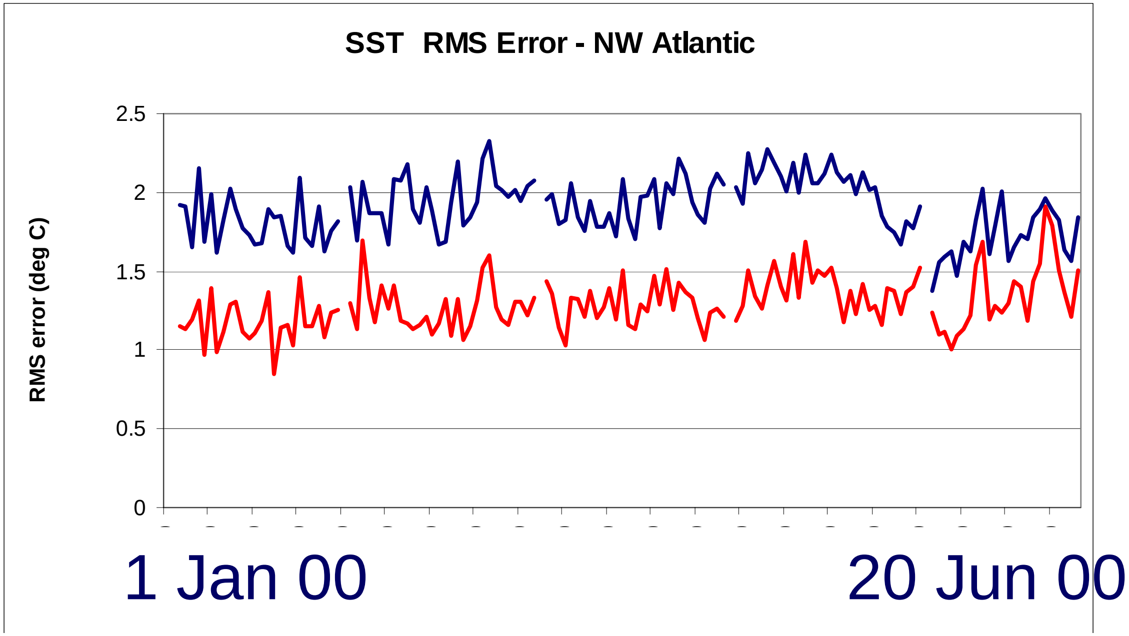
Note 2: FOAM model with 2 iterations per model step: 1st using 500 km scale, 2nd using 100 km scale

Verification statistics of old assimilation scheme



1/9º N Atlantic analyses:
June 2002 – June 2003
“old” assimilation scheme

Impact of new assimilation scheme on statistics



New system

Old system

Six month integrations of 1/3º Atlantic model

- **Early tests of new assimilation system gave encouraging results**
- **Results from year long integrations of 1/9º North Atlantic model not satisfactory at moment**

Changing Priorities

Changing context

- **FOAM project proposed to Navy in 1985 by Howard Cattle and Adrian Gill during Cold War**
- **By 1995 Navy requirement for high resolution open ocean forecasts had diminished; forecasts of shelf seas and coastal waters main priority**
- **GODAE started in 1997. Demonstration motivated by need to transition ocean satellites to operational funding**

Changing context: last 5-10 years

- **Consolidation of freely available ocean community models and user groups**
- **Software for Earth system models (e.g. OASIS coupler and PRISM) emerging**
- **Need for sustainable management of ocean environment, particularly near coast, recognised (GMES program of EC and ESA)**
- **Building on GODAE, Mersea project is strengthening coordination and collaboration in Europe**

Transition to NEMO

- NEMO=Nucleus for European Modelling of Ocean
- Jointly owned by consortium who undertake to maintain and develop it (CNRS, Mercator, Met Office)
- Free-ware
- Initial version is based on OPA
- Will be developed for shelf seas (in collaboration with POL)
- Met Office will transition climate simulations, seasonal forecasting and short-range forecasting to this system

Broadening Applications

- We have set up an Ocean Customer Group containing representatives of
  - DEFRA (Environment, Food and Rural Affairs)
  - Environment Agency
  - Maritime Coastguard Agency
  - DTI (Trade and Industry)
  - oil companies
- Seeking to build joint programs to support their activities, particularly on European Shelf
- What will be the main use of deep ocean forecast systems ?
  - Coupled two-week ensemble atmospheric forecasts ?
  - Boundary data for shelf models ?
  - Monitoring of climate circulation (e.g. THC) ?

National Centre for Ocean Forecasting

- **We will become UK's National Centre for Ocean Forecasting**
- **In association with NERC labs:**
  - **POL, PML**
  - **SOC, ESSC**
- **Strengthens and recognises need for science base for operational ocean forecasting**
- **Improves our visibility**

Short-term priorities

- Improvement of mesoscale surface currents; altimeter assimilation in high resolution models; investigation/demonstration of forecast skill
- Transition to NEMO
- Improvement of mixed layer forecasts
- Development of sea-ice assimilation
- Deep ocean ecosystem, ocean colour assimilation, air-sea CO_2 flux (CASIX)

Questions & Answers