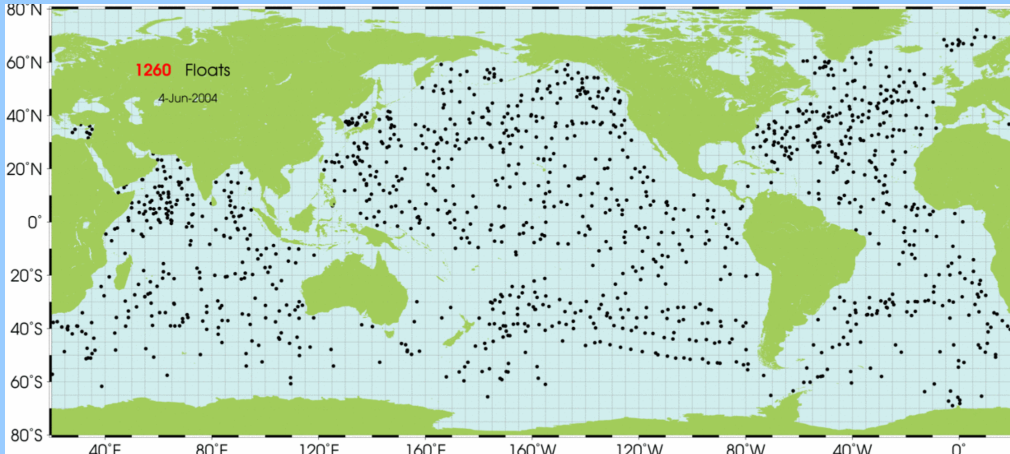
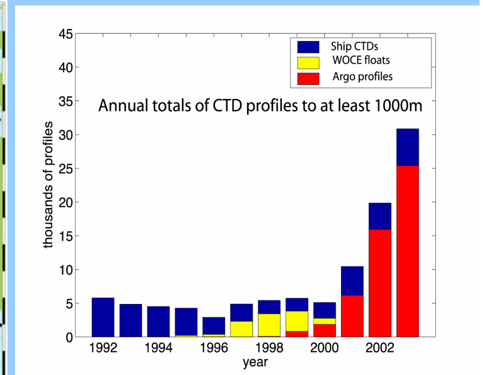
Practical Considerations of Ocean State Estimation.

Detlef Stammer
Institut für Meereskunde
Universität Hamburg.

2nd ENVISAT Summer School:
Earth System Monitoring and Modelling
August 2004

The Argo Float Array

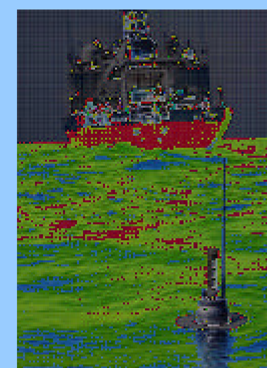




Global snapshots of upper-ocean temperature, salinity and circulation are collected every 10 days – about 40,000 profiles this year.

Status: array is 42% of completion; 18 nations are providing floats.

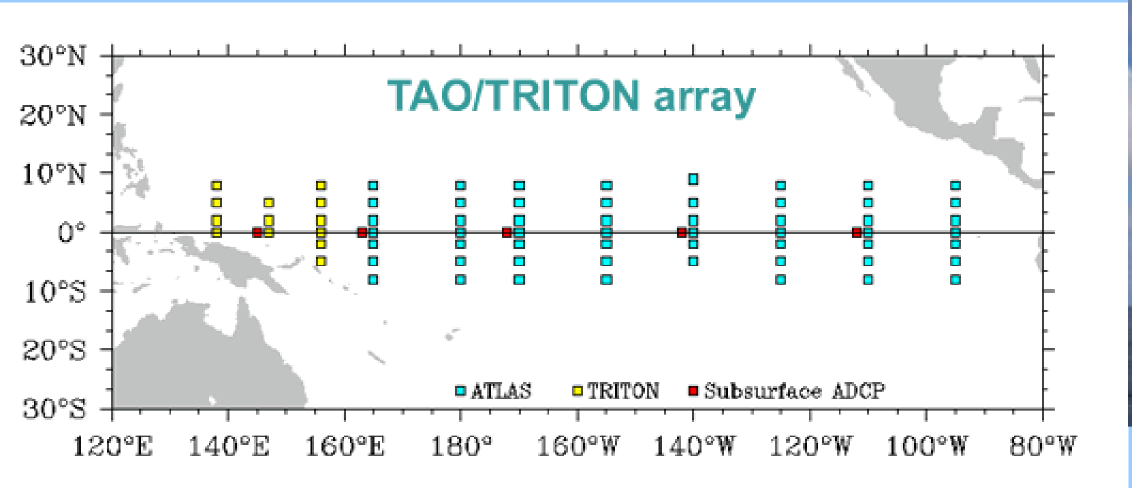
Coverage is expanding to global this year; All data are freely available.



Japan-Argo float deployment

? The Challenge: Complete initial array, and sustain it.

The Tropical Mooring Network



Servicing a TAO mooring

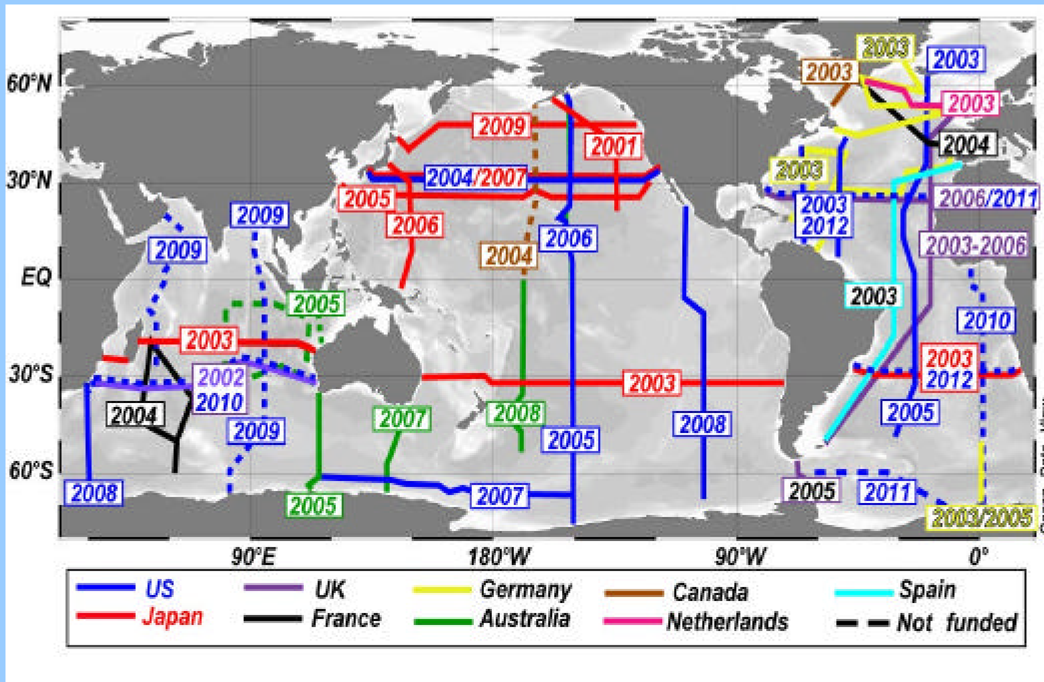
The TAO/TRITON tropical moored buoy array is the backbone of the ENSO Observing System for temperature and velocity profiles and surface meteorological data.

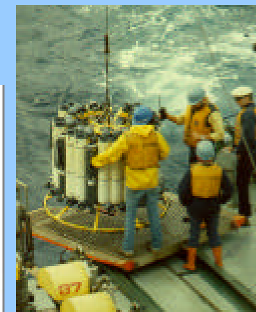
Status: The Pacific TAO and Atlantic PIRATA mooring networks are undergoing transition to operational support. Expansion of the tropical arrays into the Indian Ocean is being planned.

The TAO/TRITON network set the standards for sustained ocean observations and for real-time open-access data delivery.

Challenge: maintain its quality and flexibility under changing responsibilities.

Deep Ocean Repeat Hydrography





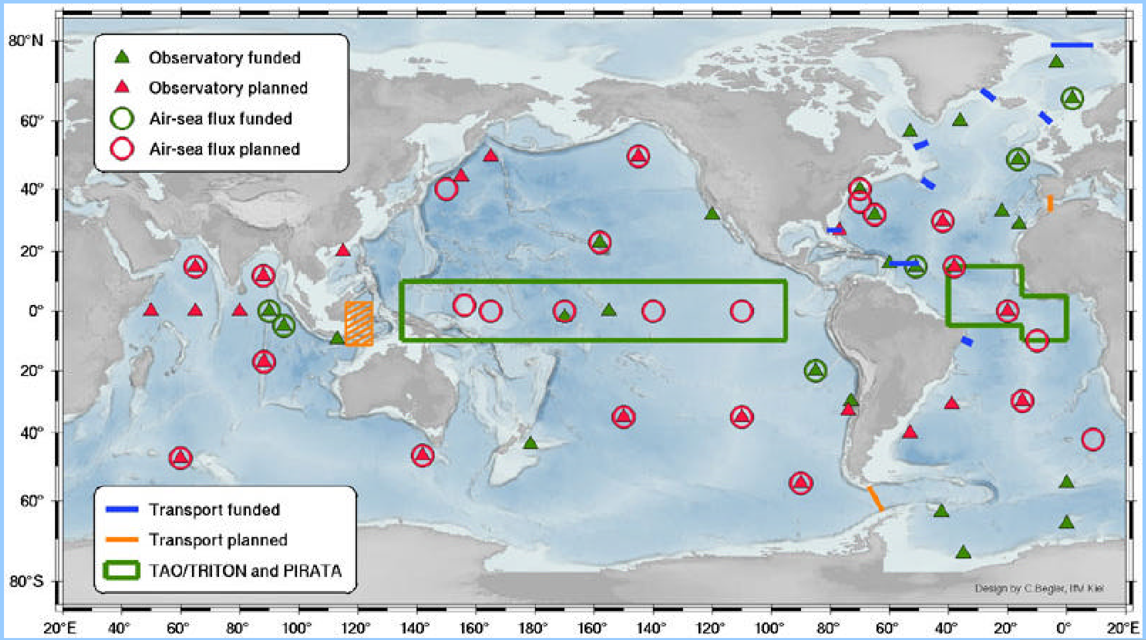
Status/plans of repeat lines.

The repeat hydrography program will provide decadal time-scale sampling of ocean transports and inventories of climatically significant parameters:

Carbon system components, nutrients, freshwater and heat.

Potential: joint evaluation of hydrography and carbon/tracer.

Time-Series Stations

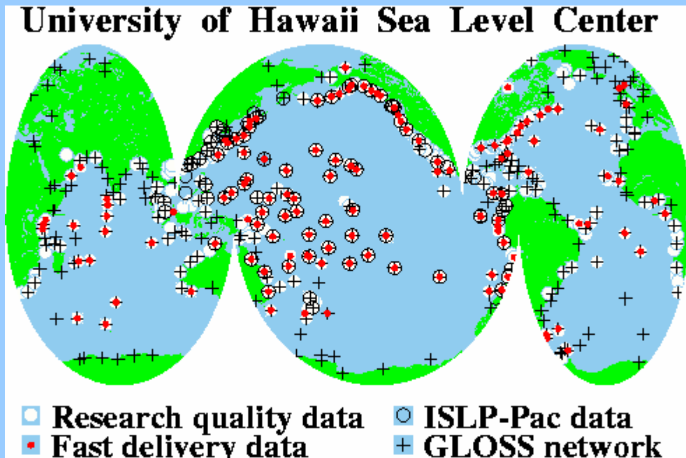


Time-series stations include air-sea fluxes, full depth physical and bio/geochemical sampling, and transport arrays.

Important also for surface flux measurements.

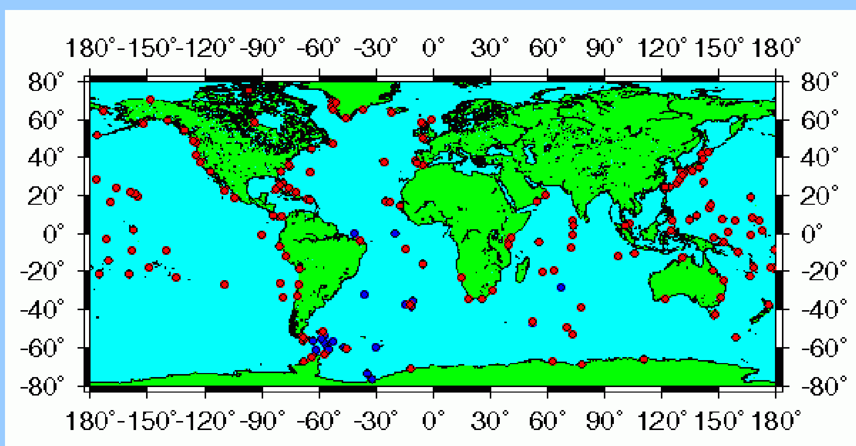
Hawaii Ocean Time-Series mooring

The Sea Level Network

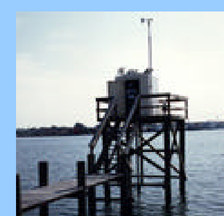


Sea level data are essential for inter-calibration of satellite altimeter missions and for regional applications.

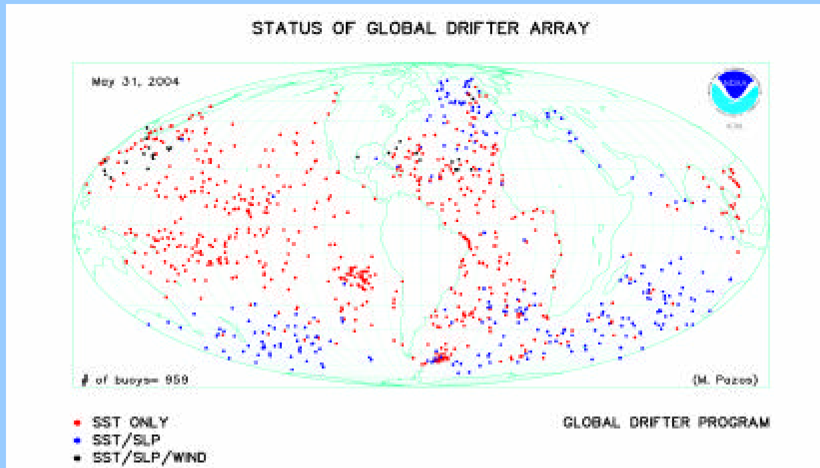
"Fast delivery" data from UH: http://uhslc.soest.hawaii.edu/



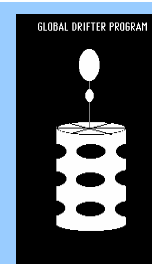
"Delayed-mode" data from BODC: http://www.bodc.ac.uk


Island sea level gage

The Global Surface Drifter Program



http://www.aoml.noaa.gov/phod/dac

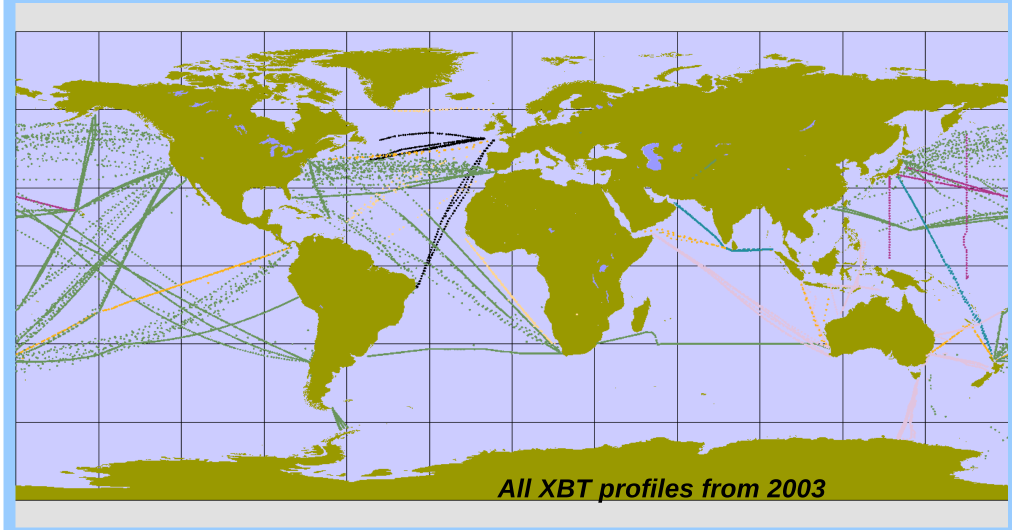


Status: **The surface drifter array is presently expanding toward global 5º x 5º sampling.**

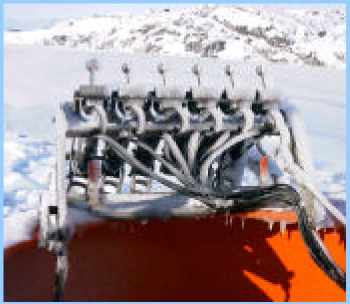
Surface drifter observations provide a global database for describing

- **the mean and variability of the near-surface circulation;**
- **testing models of the surface layer;**
- **calibration of satellite sea surface temperatures and barometric pressure.**

The Upper Ocean Thermal Networks

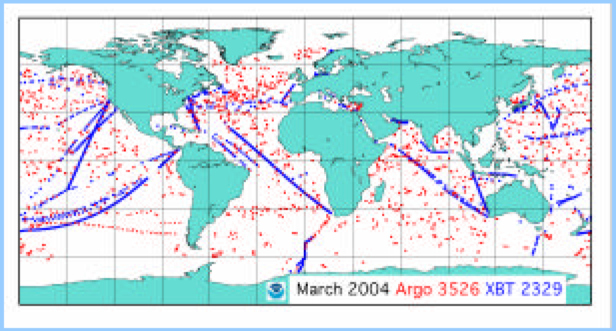


All XBT profiles from 2003



XBT autolauncher in Drake Passage

XBT and Argo profile locations March 2004



As Argo is implemented, the XBT networks are transitioning away from broad-scale sampling to repeat line-oriented modes such as the High Resolution XBT network.

What is missing in situ?

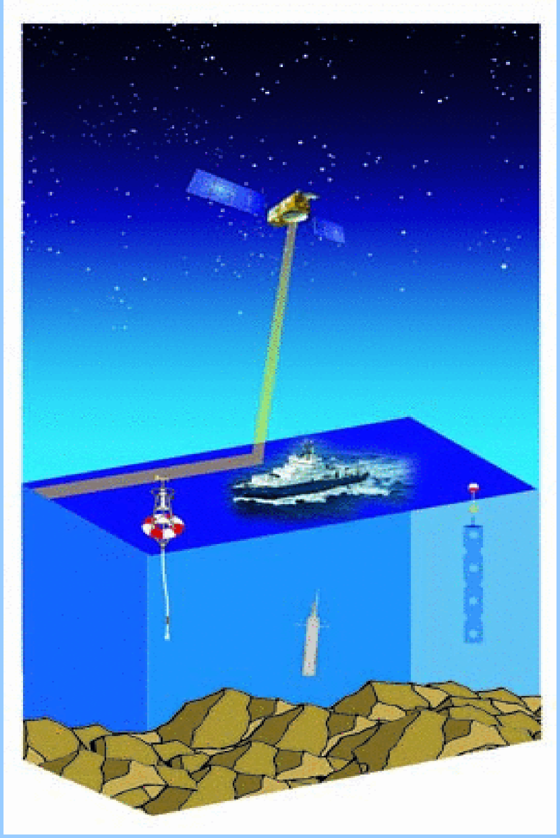
Floats, moorings, acoustic tomography, and XBT lines may all be effective in specific areas.

There is presently no comprehensive plan for sampling the ocean's boundary currents. Gliders and other autonomous vehicle technologies offer a potentially cost effective solution for sustained observations of many boundary currents.

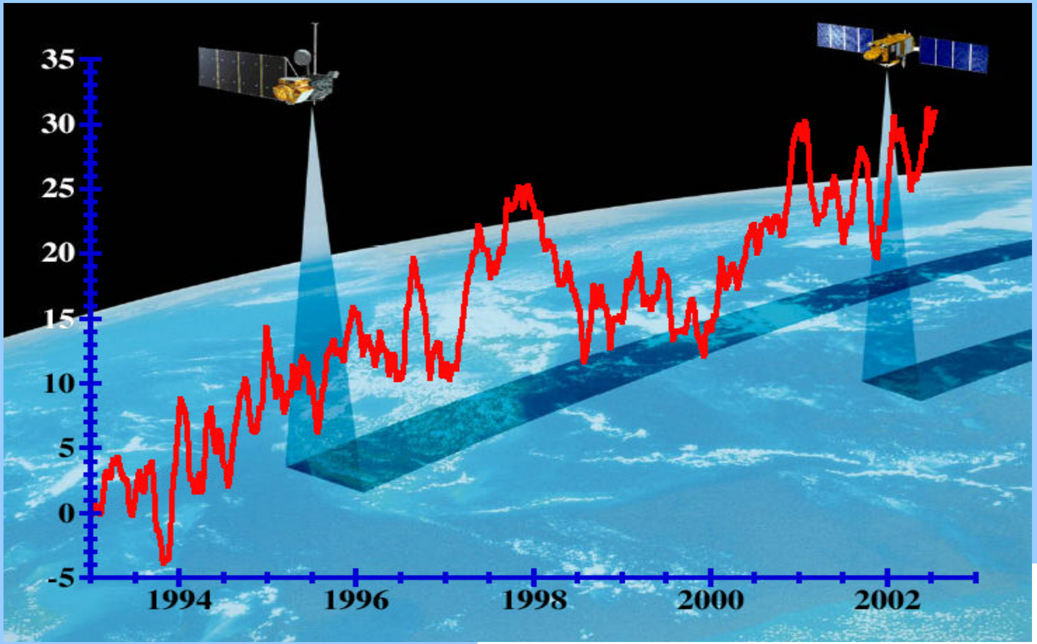
Satellites Observing Component:

There are many essential remote sensing measurements for oceans and climate.

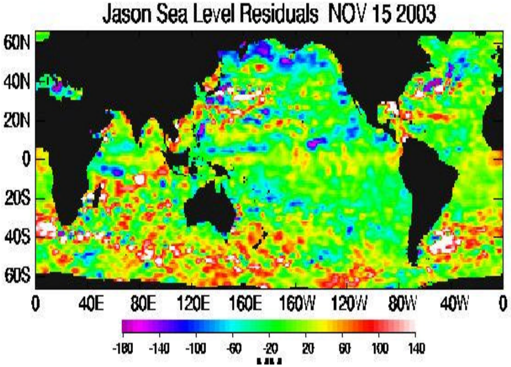
- Altimetry and the geoid;
- SST;
- Sea-ice extent and volume;
- Surface winds;
- Ocean colour;



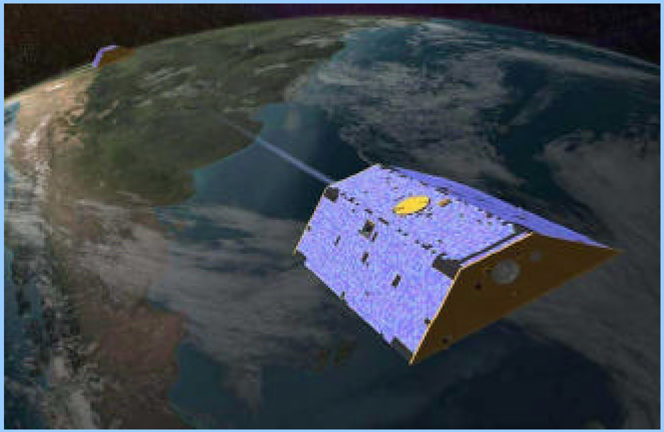
Altimetrie



Measurements of the ocean surface topography enable scientists to improved understanding of ocean circulation and its effect on global climate, and regional and global sea sea level changes.

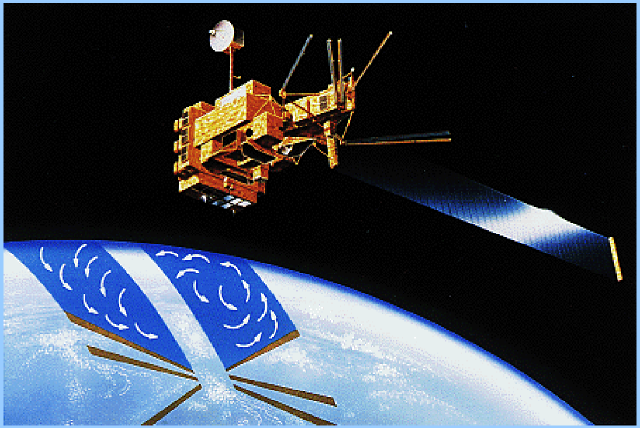


GRACE and GOCE



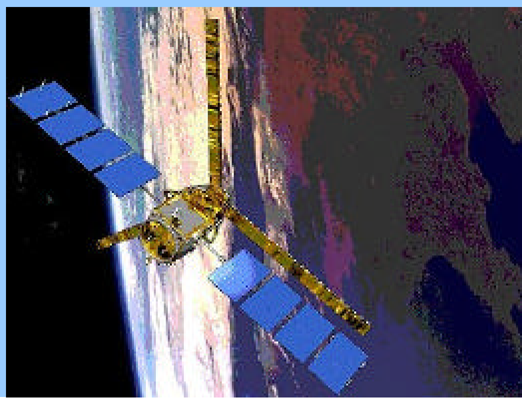
Time-mean and time-variable gravity field required to infer absolute currents and bottom pressure changes from altimetry.

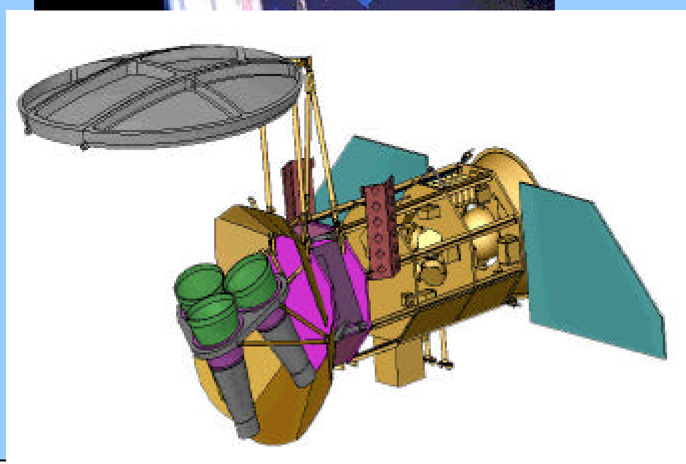
NSCAT, QSCAT, ADEOS-II



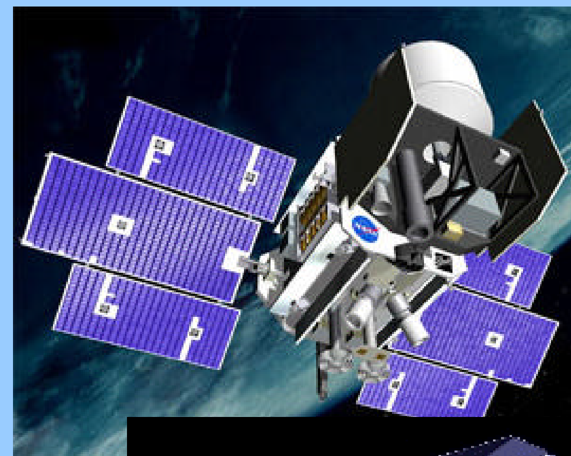
Acquire all-weather, high-resolution measurements of near-surface wind speed and direction over the global oceans

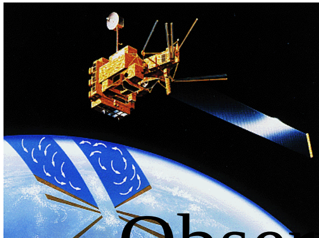
SMOS, AQUARIUS:
soil moisture and
surface salinity





IceSat, CRYOSAT:
measurements of ice
distribution and ice volume.





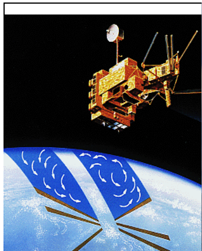
Observing System

?Future ocean observing system:

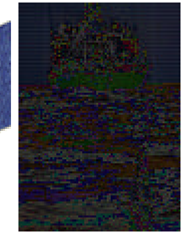
- Anticipate technological advances.
- More comprehensive, including non-physical variables.
- Data access and dissemination will be more dynamic and timely.
- Sustained and routine: reliable and broadly supported.

?Broad consensus on the “next steps”

- Balanced and integrated: satellites and in situ..




hallenges

- **Complete the installation of a comprehensive global climate observing system, and sustain it for long enough to demonstrate its value (~10 years). Observations under ice, longterm, autonomous; biogeochemical variables.**

- **Sustain present-day climate-quality Earth observing satellite capabilities. New observations: Salinity, ice and snow, hydrology.**

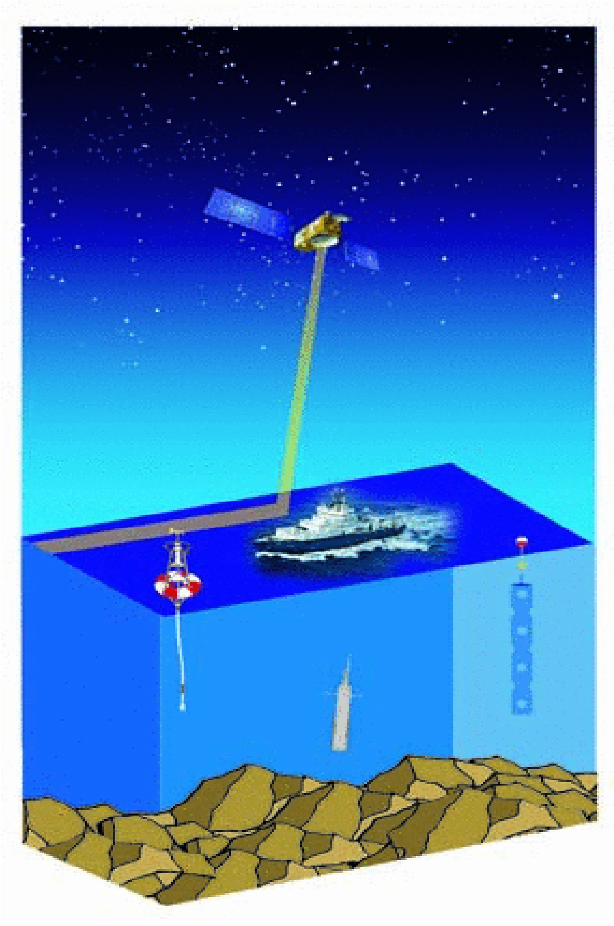
- **Build effective long-term partnerships between research institutions and operational agencies to provide oversight, technical capacity, and sustained support for observations.**

- **Harmonize the evolution of the observing system with the growing capabilities of data assimilation, to**
  - **provide data for model initialization and statistics for data assimilation,**
  - **provide independent information for testing models and guide model improvements through model-data comparison studies.**

Data Assimilation

- **Ocean data assimilation is now established as a component of modern oceanography and climate studies.**
- **Approaches and applications span a wide range of spatial and temporal scales and encompass various different disciplines, such as physical, chemical and biological oceanography.**

Ocean Data Assimilation



Different gaols:
- Real-time (NAVY)
- Initailisation (SIP)
- Climate Reanalysis

Different Approaches:
- Simple (nudging, filters)
- Rigorous (smoothers)

ECCO Results

GODAE

The Global Ocean Data Assimilation Experiment

– a comprehensive, integrated observing system with the data assimilated into state-of-the art models of the global ocean circulation in near real-time.

- Australia: BLUElink project
  - Australian region focus
- Europe: Mersea consortium - *global*
- France: MERCATOR
  - N. Atlantic, Medit., global
- Japan: J-GODAE
  - Pacific + Earth Simulator project global
- MFS (Medit. Forecasting System)
- Norway – TOPAZ
  - N Atlantic + global
- UK – FOAM
  - Global and regional; interest in Indian Ocean
- US – HYCOM, ECCO, and others
  - N Atlantic, Pacific, global; global climate

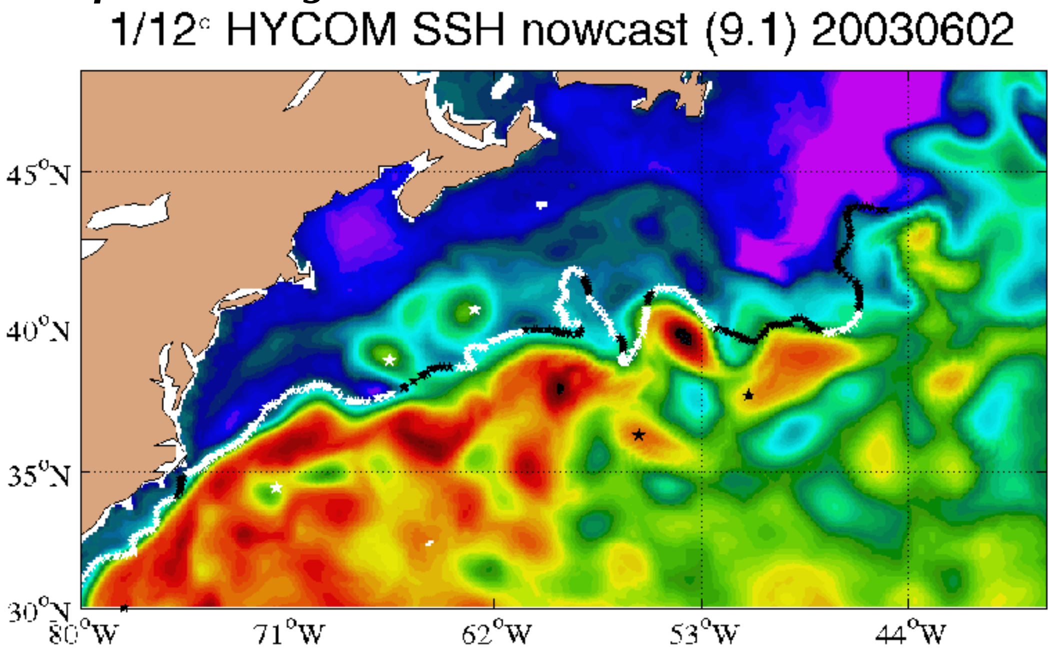
Many plan reanalyses ~ 1992-present.

Some do already 50 yr reanalyses.

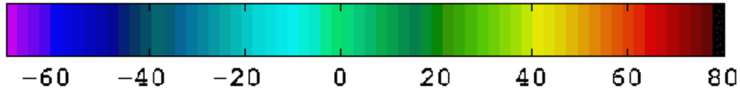
HYCOME

- ? Partnership to develop and demonstrate the application of eddy-resolving, real-time ocean prediction systems using HYCOM (global and basin-scale).
- ? NOAA/Navy cooperation ranging from research to the operational level. To be transitioned for operational use by the U.S. Navy at NAVOCEANO and FNMOC and by NOAA at NCEP.
- ? Global outputs available to the community at large. Strong participation of the coastal community in using and evaluating boundary conditions from the global and basin-scale ocean modeling prediction systems
  - **Assimilates the satellite altimeter analysis from the MODAS operational system at NAVOCEAN.**
  - **Vertical projection via the Cooper and Haines technique (1996, JGR)**
  - **Relaxation to the MODAS SST analysis**

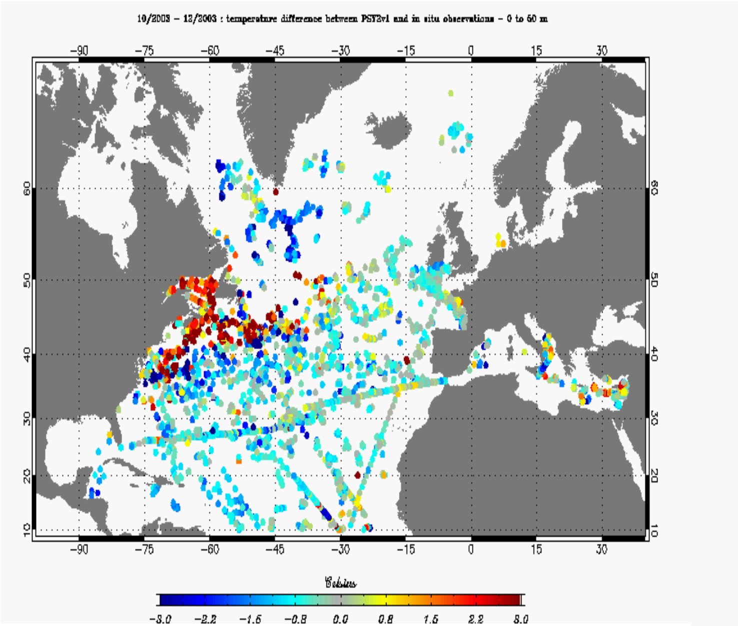
SSH in Gulf Stream region



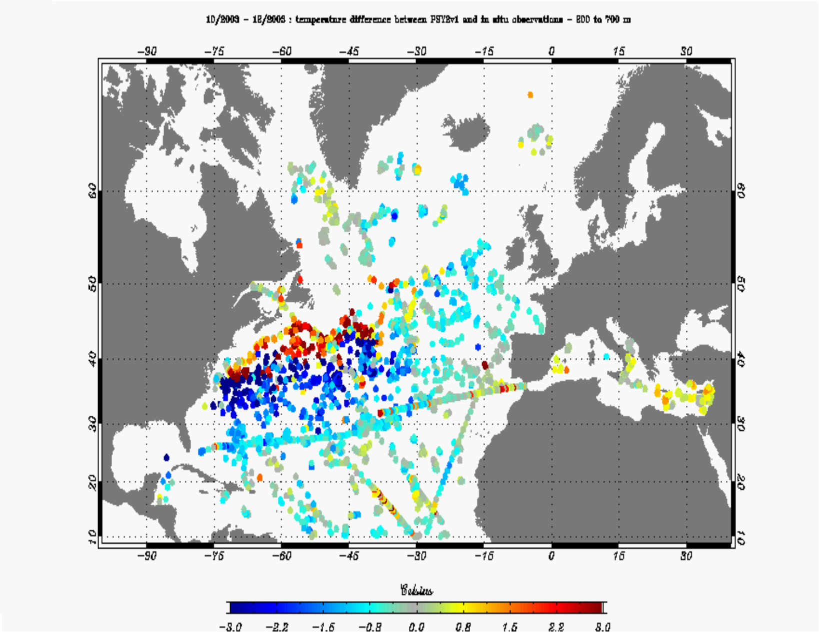
White/black line is the frontal analysis of MCSST observations performed at NAVOCEANO. Black line represents data more than four days old.



Temperature differences between MERCATOR best estimates and in situ data (Oct-Dec 2003)



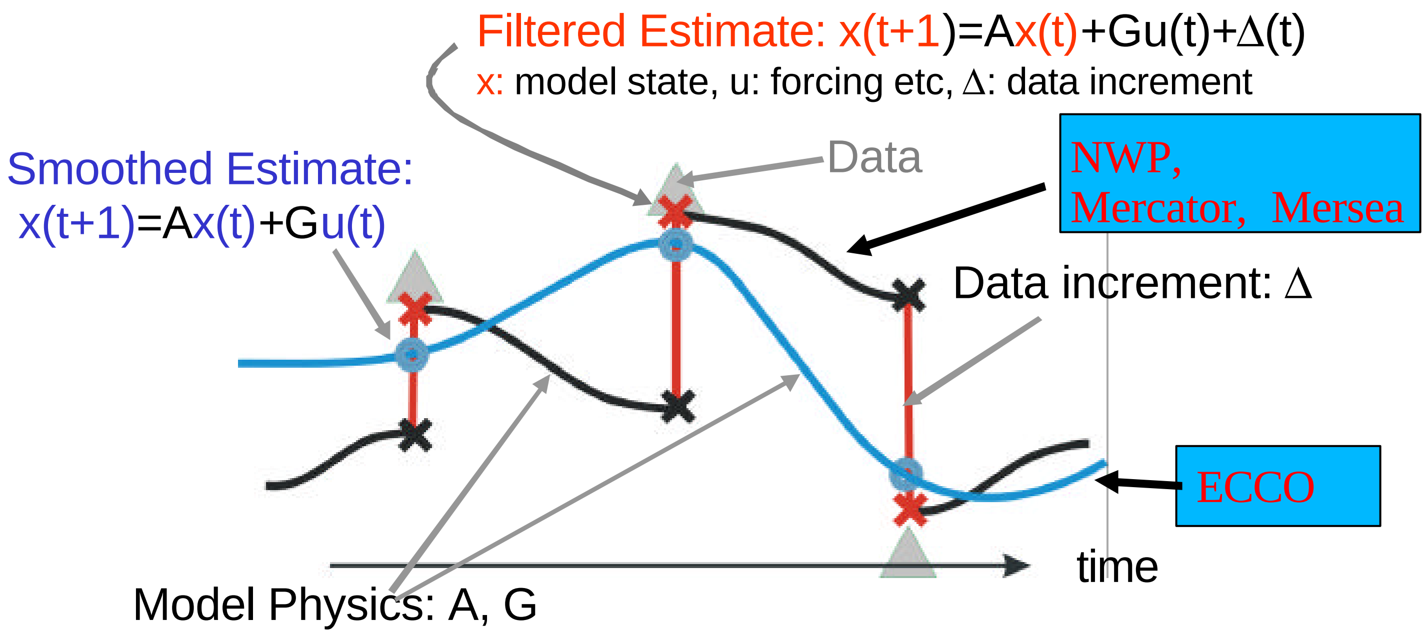
between 0 and 50 m



between 200 and 700 m

Consistency of Assimilation

The temporal evolution of data-assimilated estimates is physically inconsistent (e.g., budgets do not close) unless the assimilation's data increments are explicitly ascribed to physical processes (i.e., inverted).



(I. Fukumori)

“Estimating the Circulation and Climate of the Ocean” (ECCO)

Describes the global ocean circulation at time scales of days to decades. Employs sustained ocean/data syntheses in support of GODADE and CLIVAR.

- **Status: Employs most available observations as constraints: Uses ECCO/MIT ocean adjoint model and Kalman filter/smoother.**

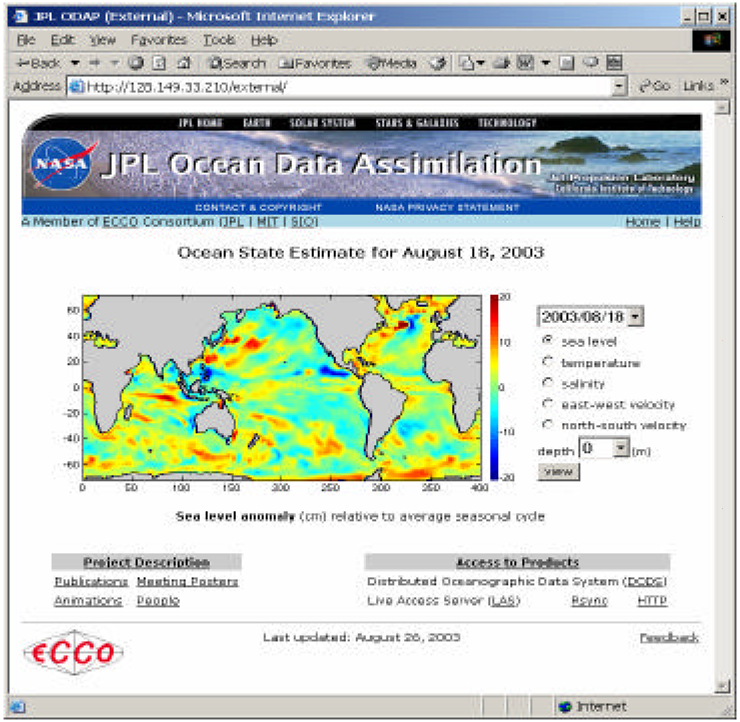
Ongoing:

- **50yrs with 1 degree resolution ongoing (RA).**
- **Near-realtime estimates: 1-1/3 degree from 1992 to present; every week provided through ECCO LAS.**
- **Working toward goal of ¼ degree global near-real time smoother solution.**

- **http://www.ecco-group.org**

www.ecco-group.org/las

ECCO Near Real-Time Analysis



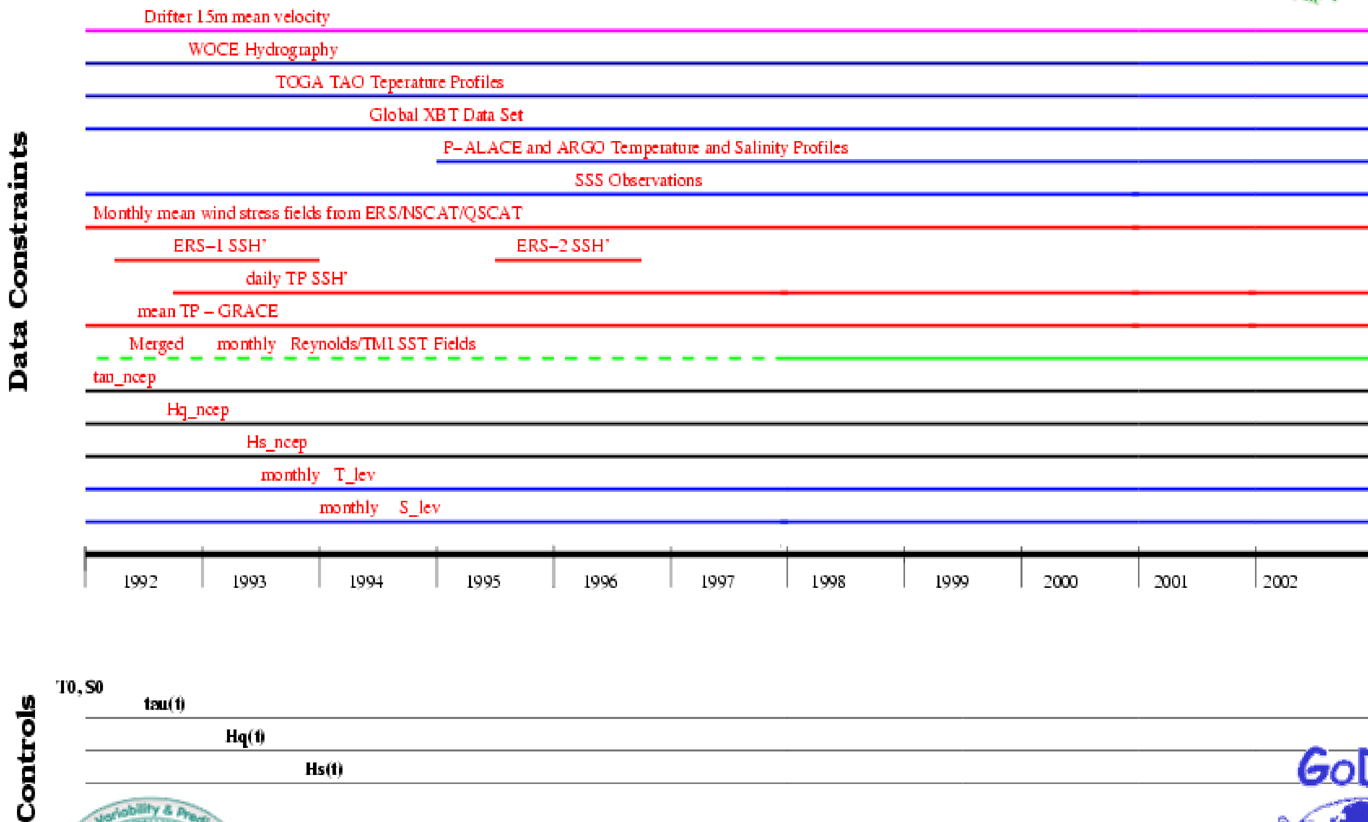
Near real-time global nowcasts every 10-days since October 2002.

Highlights @ http://ecco.jpl.nasa.gov/external

SSH (T/P, Jason-1), Temperature profiles (XBT, TAO, ARGO, etc), & time-mean sea level (drifters, GRACE) are assimilated.

Estimated controls: external time-variable & time-mean forcing (winds, heat & fresh water fluxes) and mixing parameters.

ECCO 1 degree global Synthesis 1992 – 2002



The Methodology

Cost Function

$$J = \sum_t (\mathbf{y}(t) - \mathbf{E}(t)\,\mathbf{x}(t))^T \mathbf{R}^{-1}(t)\,(\mathbf{y}(t) - \mathbf{E}(t)\,\mathbf{x}(t)), \quad (1)$$

Model

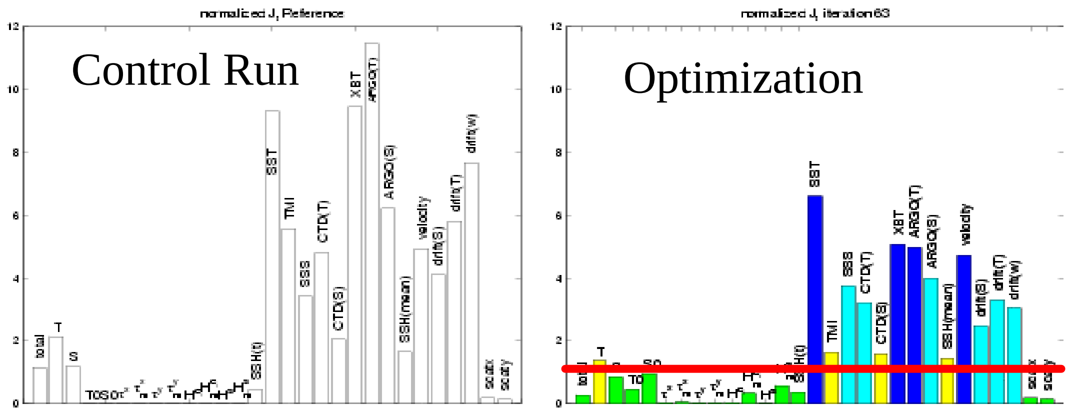
$$\mathbf{x}(t+1) = \mathcal{F}[\mathbf{x}(t), \mathbf{q}(t), \mathbf{u}(t), \varepsilon(t), t], \quad (2)$$

Penalty-function type cost function

$$J' = \sum_t \left[(\mathbf{y}(t) - \mathbf{E}(t)\,\mathbf{x}(t))^T \mathbf{R}^{-1}(t)\,(\mathbf{y}(t) - \mathbf{E}(t)\,\mathbf{x}(t)) + \varepsilon(t)^T \mathbf{Q}^{-1} \varepsilon(t)\right] (3)$$

The model can be imposed upon the objective function either by using Lagrange multipliers (constrained optimization), or in an unconstrained optimization form with a penalty-function type of formulation.

11-year 1 deg. Synthesis 1992-2003

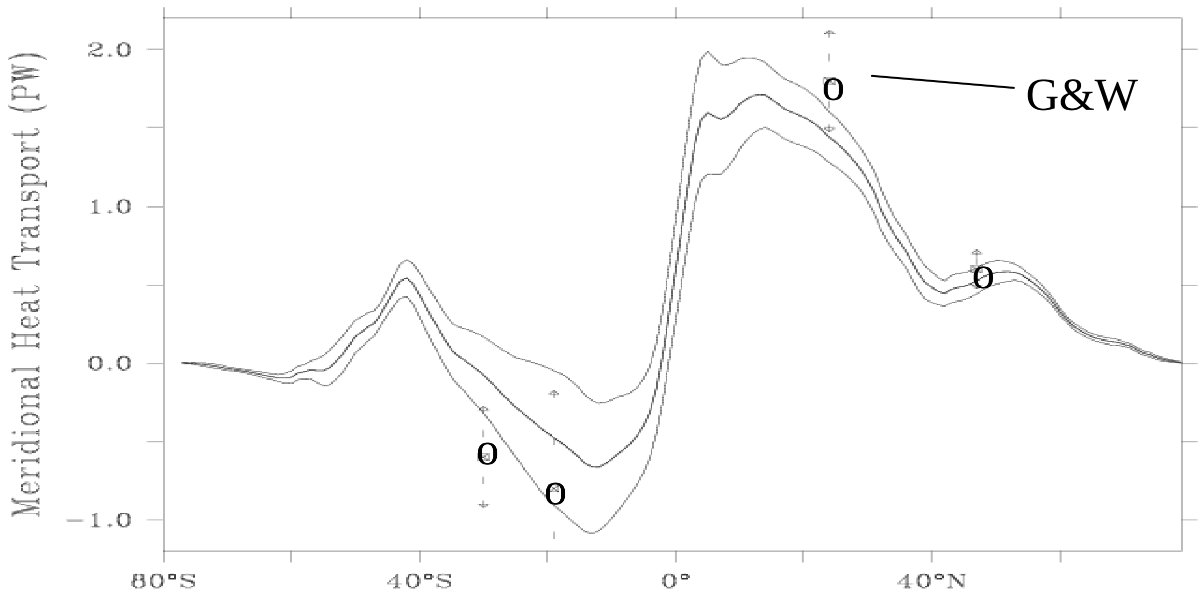


ECCO synthesis is a hole-domain approach over 11+ years.

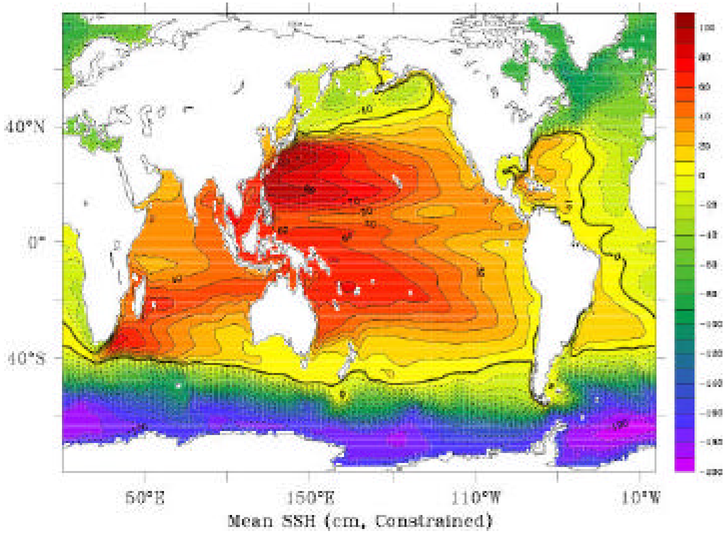
Contributions to cost function from individual data sets.

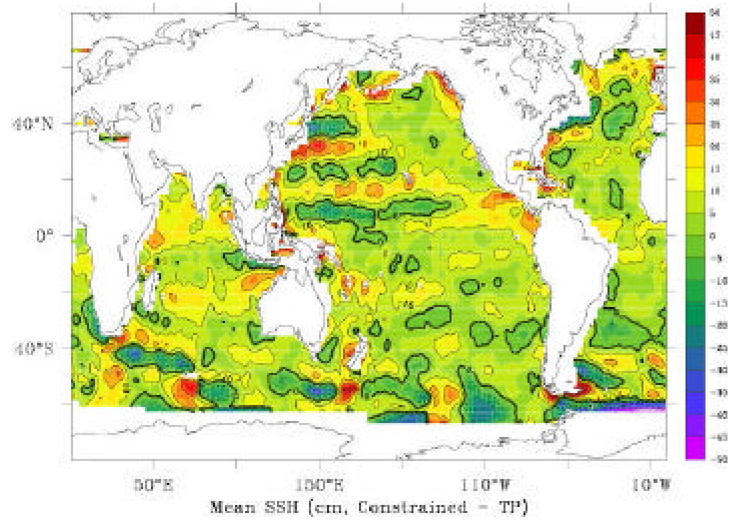
Estimates of un-observables:
Global Ocean Heat and Freshwater Transports

Heat Transport



The Mean Ocean Circulation, global



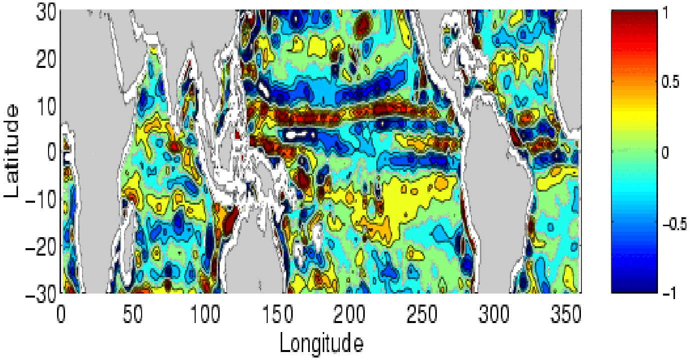


Residual SSH values decrease significantly with use of GRACE geoid:
Ocean state estimation helps in determining geodetic information.

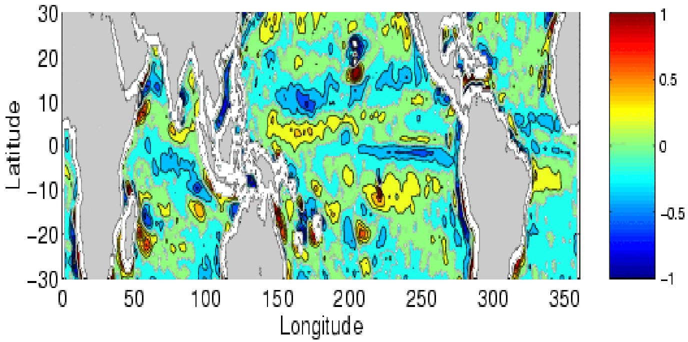
Surface Wind Stress Estimates

Wind Stress Curl

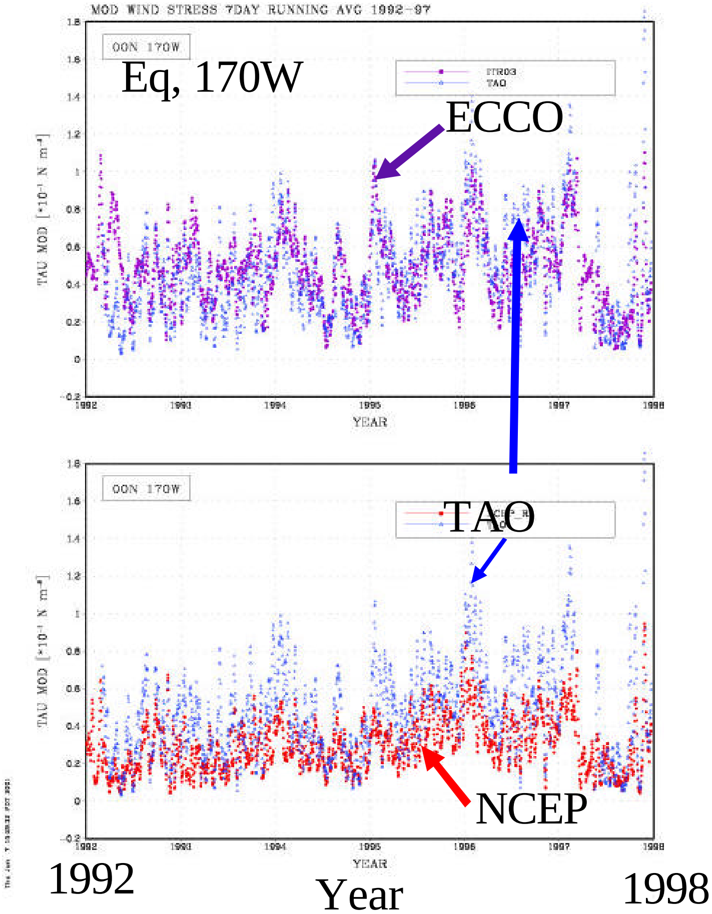
ECCO-NCEP



SCAT-NCEP

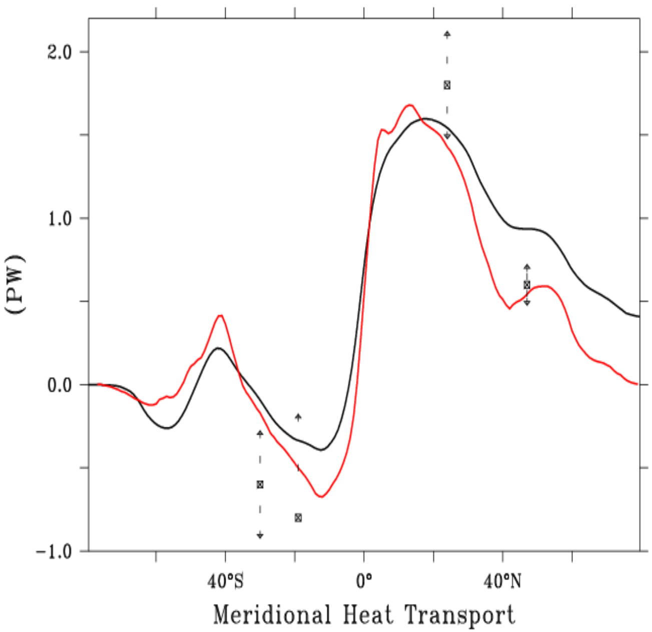


Zonal Wind Stress

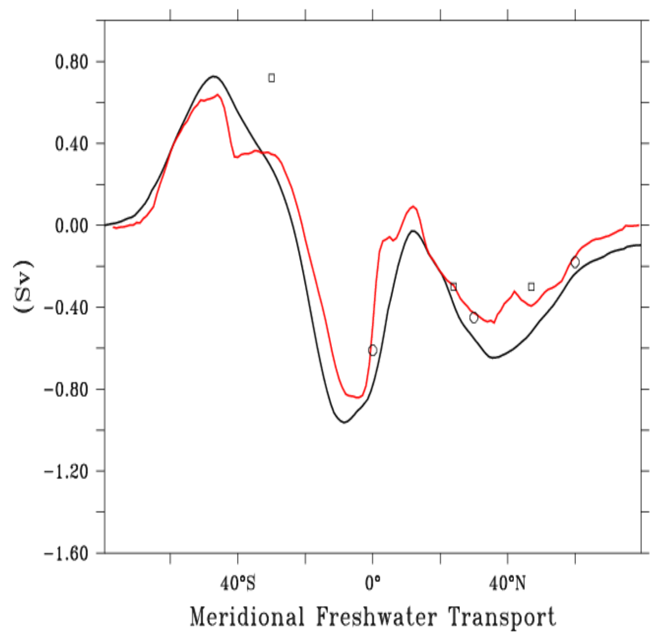


Global Ocean Heat and Freshwater Transports

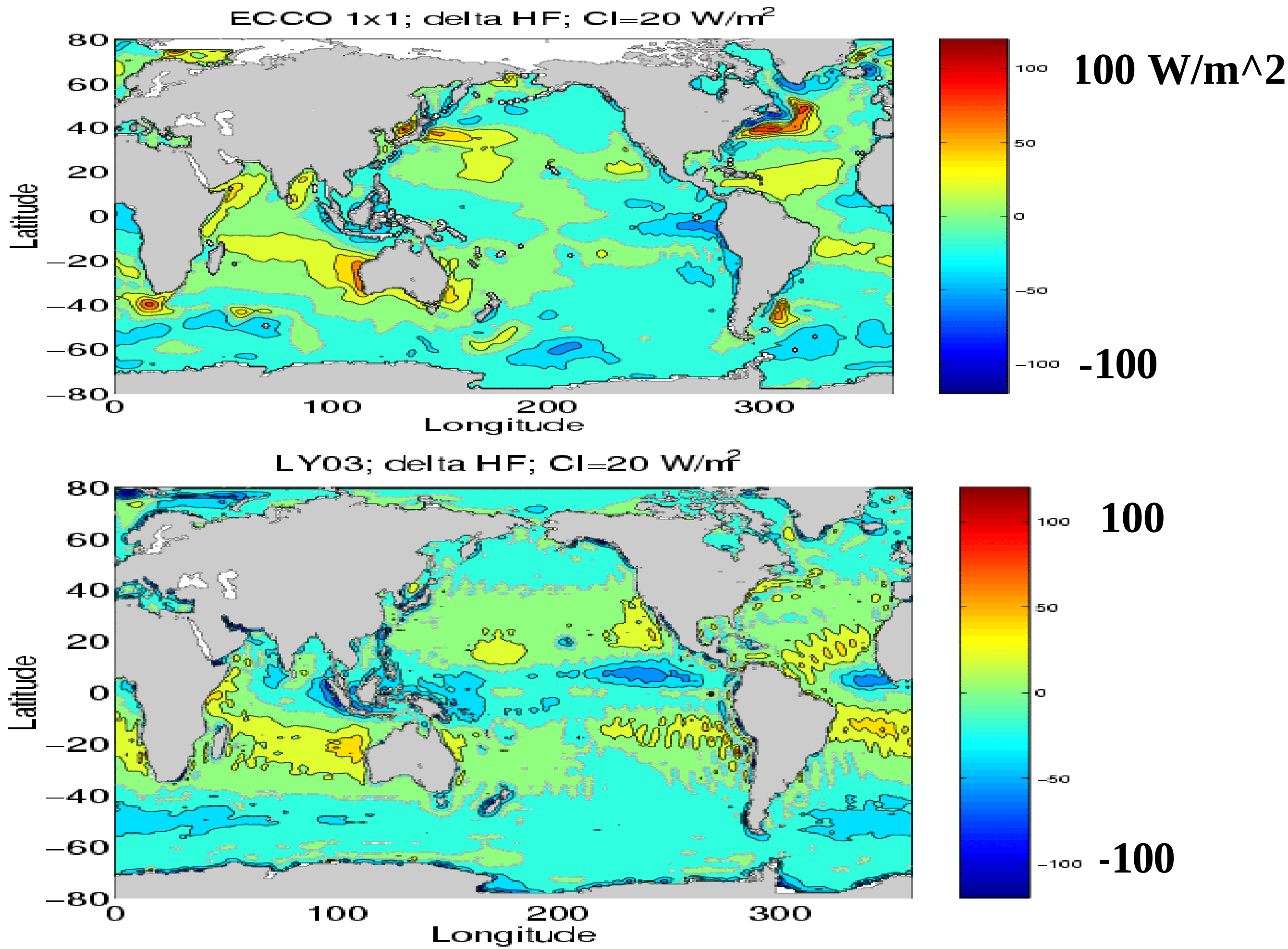
Heat Transport



Freshwater Transports



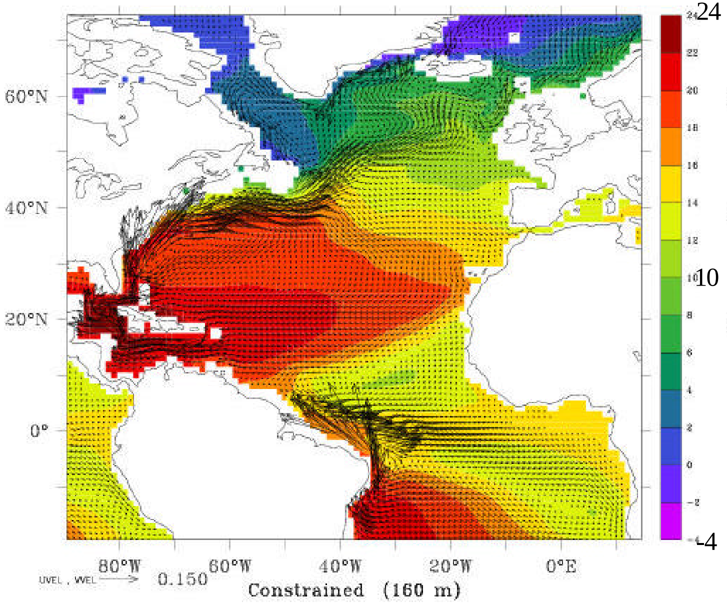
Surface Heat Flux Estimates



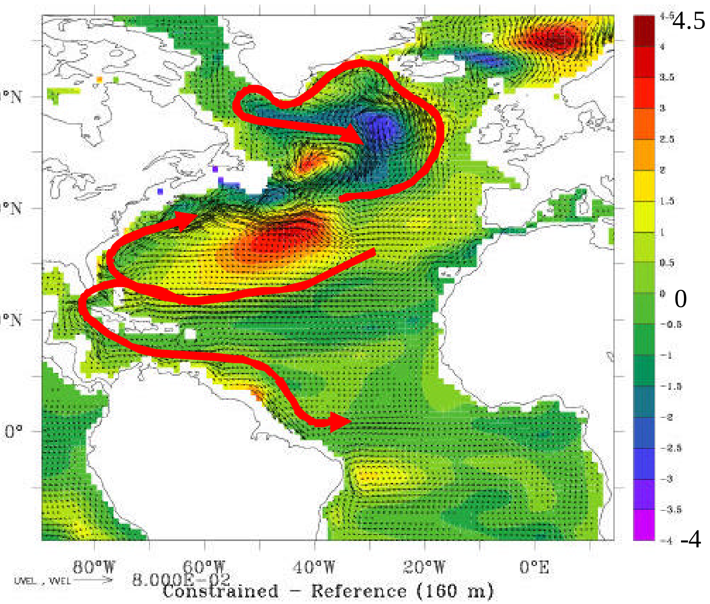
The Mean Circulation, Atlantic

Velocity and temperature, 160 m

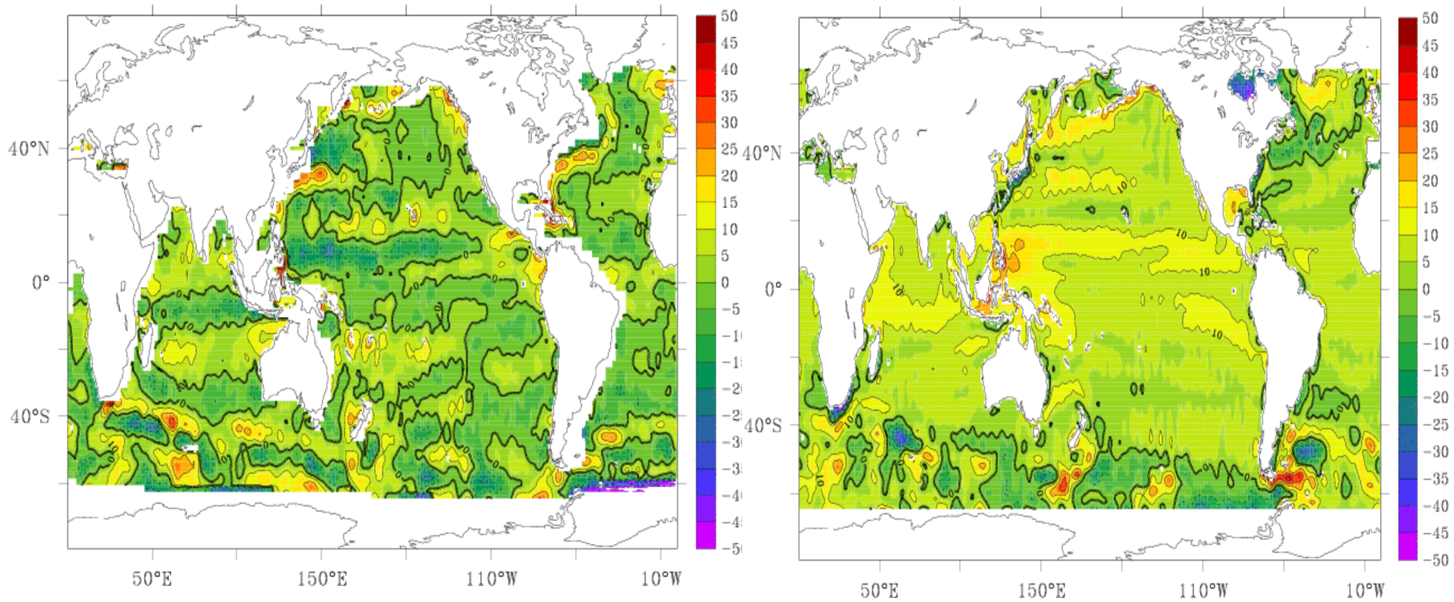
Constraint



Constraint - Ref.



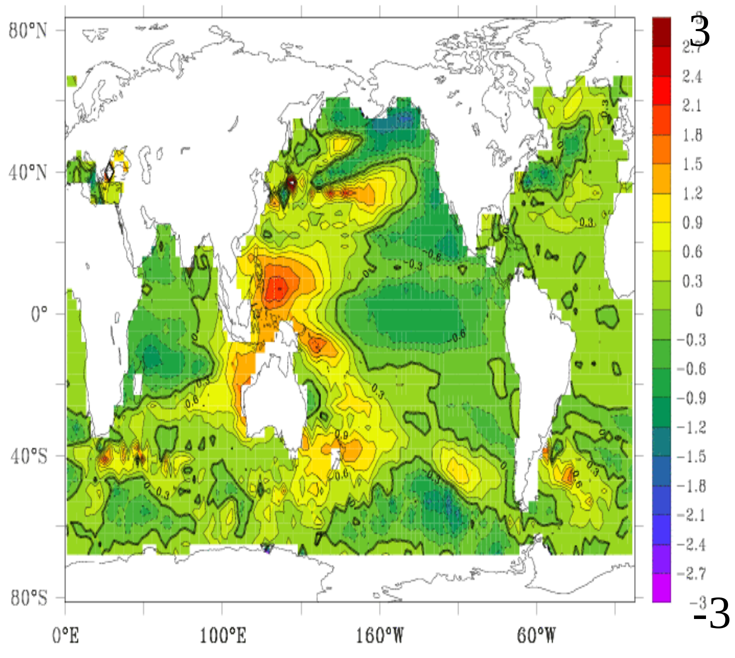
The Mean Ocean Circulation, global



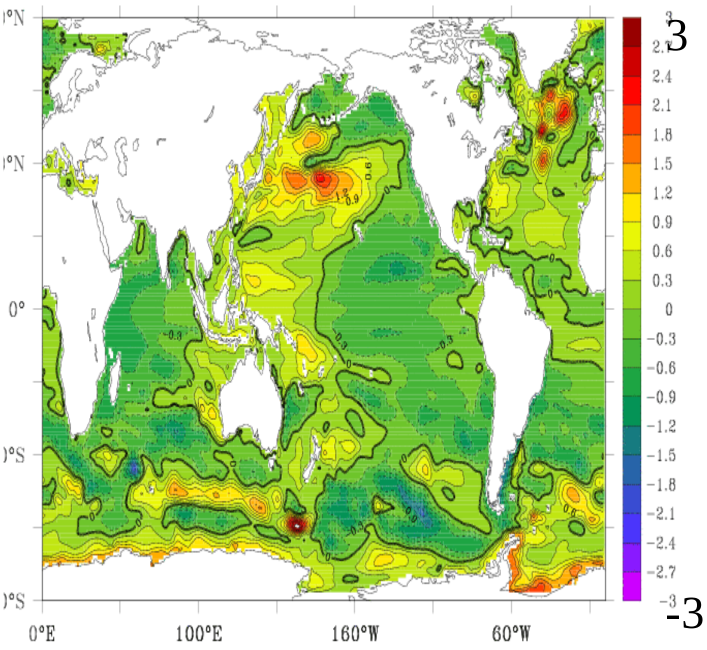
Residual SSH values decrease significantly with use of GRACE geoid:
Ocean state estimation helps in determining geodetic information.

SSH Drift 1993 – 2002

ECCO Estimate (cm/yr)

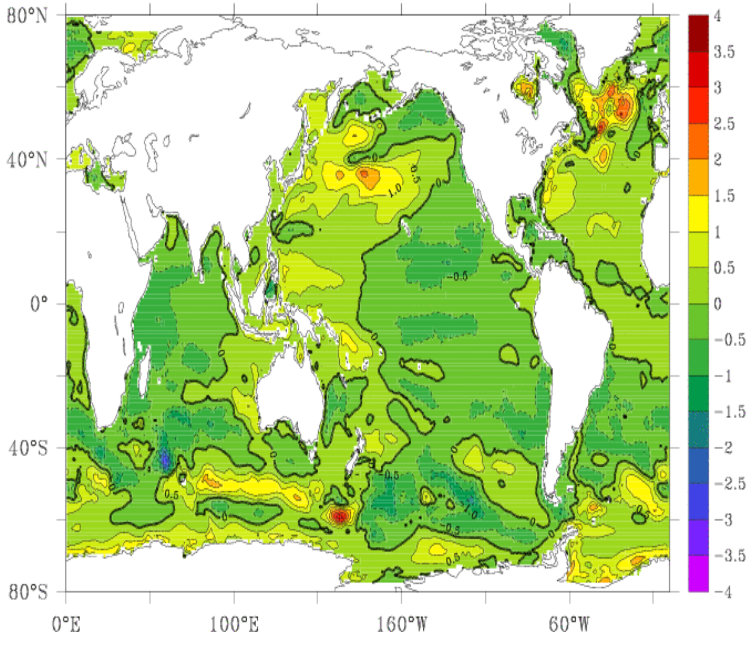


T/P Observations (cm/yr)

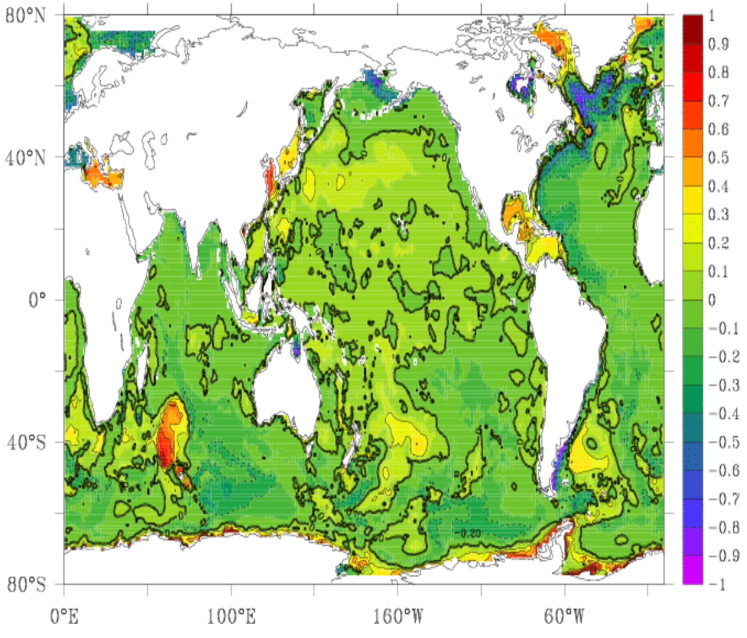


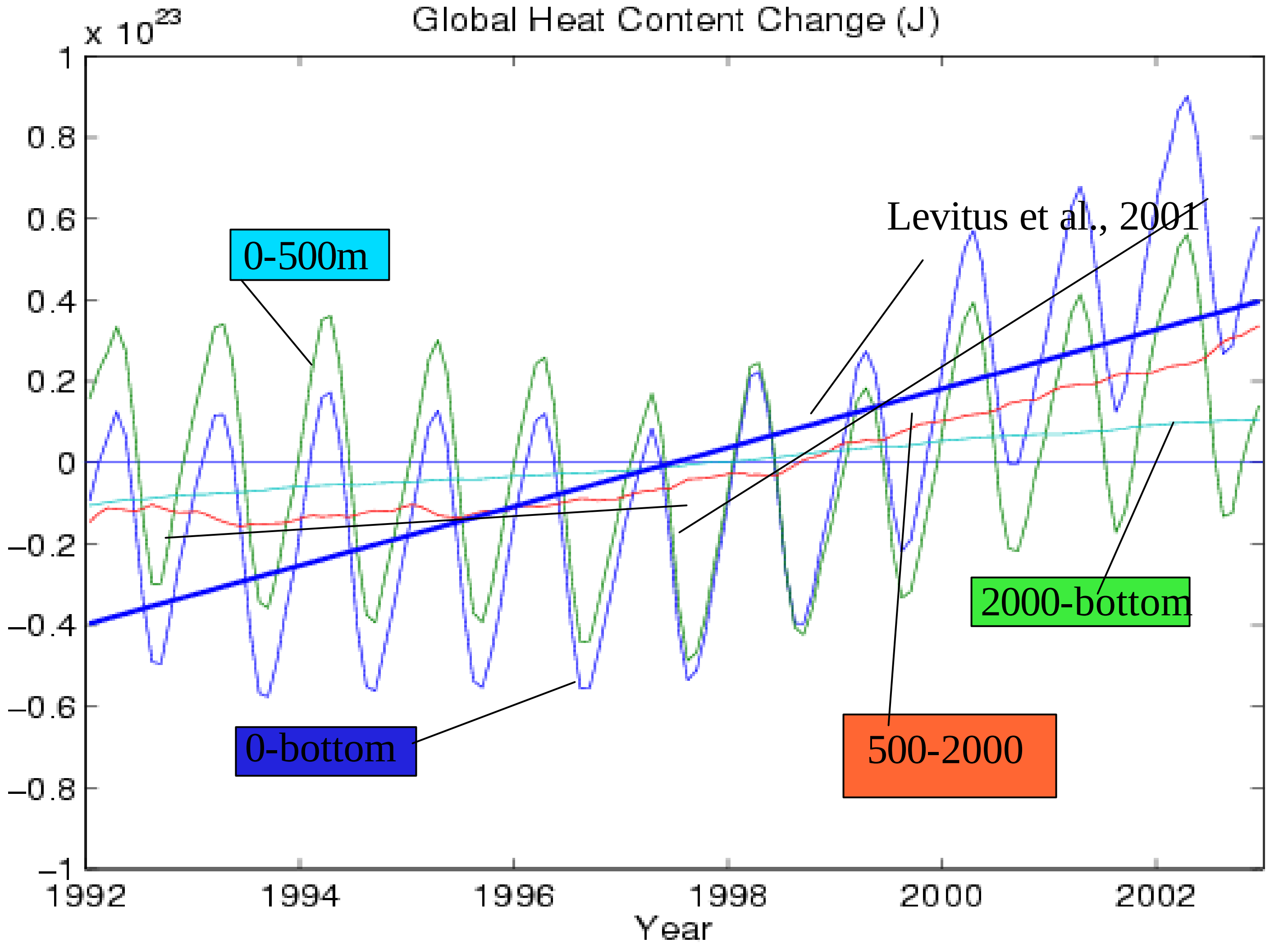
SSH Drift 1993 – 2002

ECCO Steric SSH Changes (cm/yr)



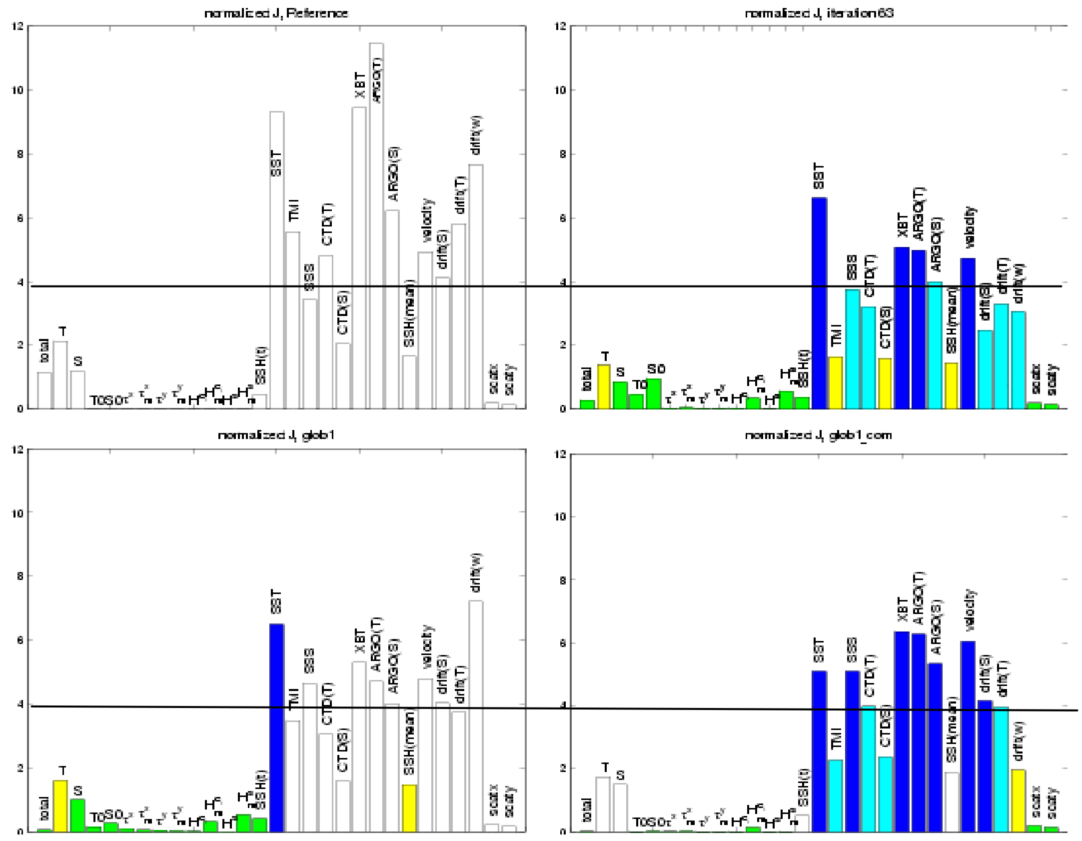
ECCO Mass Redistribution (cm/yr)





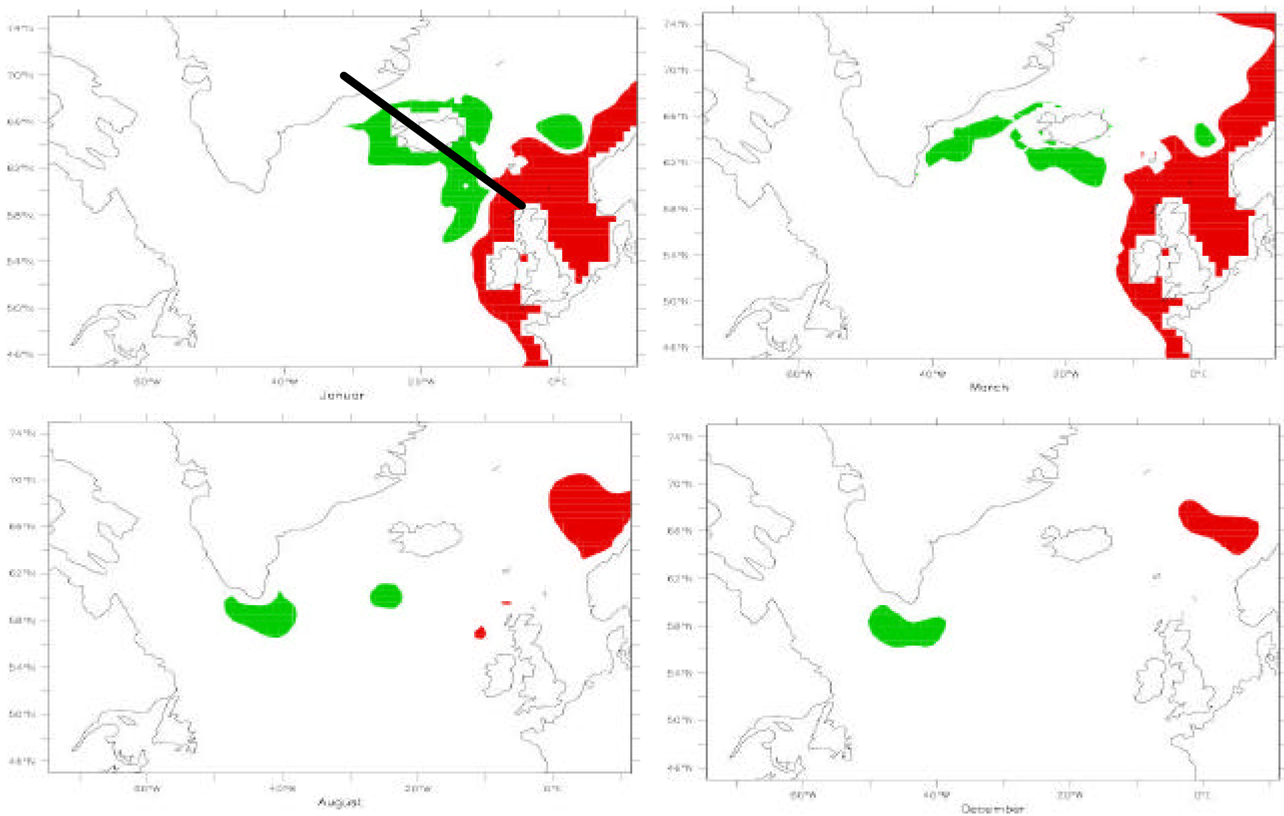
Global Heat Content Change (J)
x 10^23
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
1992
1994
1996
1998
2000
2002
Year
0-500m
Levitus et al., 2001
2000-bottom
0-bottom
500-2000

Data Sensitivity Study



Observing System Design: Optimal Observations

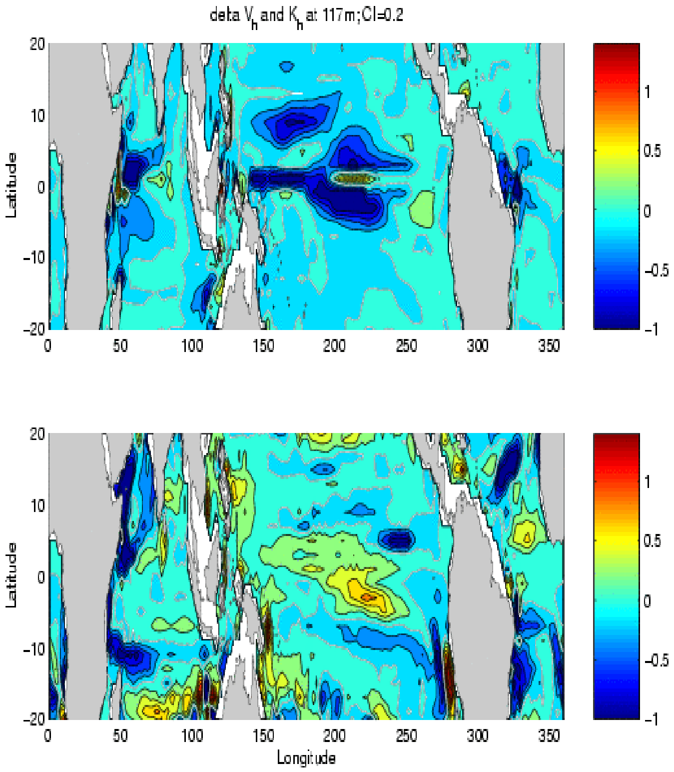
Where does SSH need to be observed to reproduce the Febr. Heat Transport??



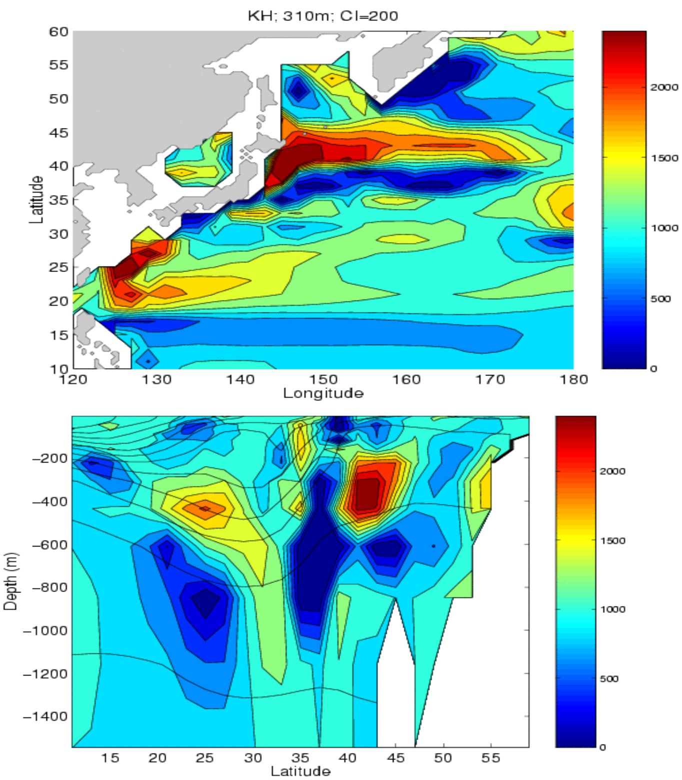
(Koehl and Stammer , 2003)

Extended Control Vector: Ocean Mixing

Delta Horiz. Mixing, 117m

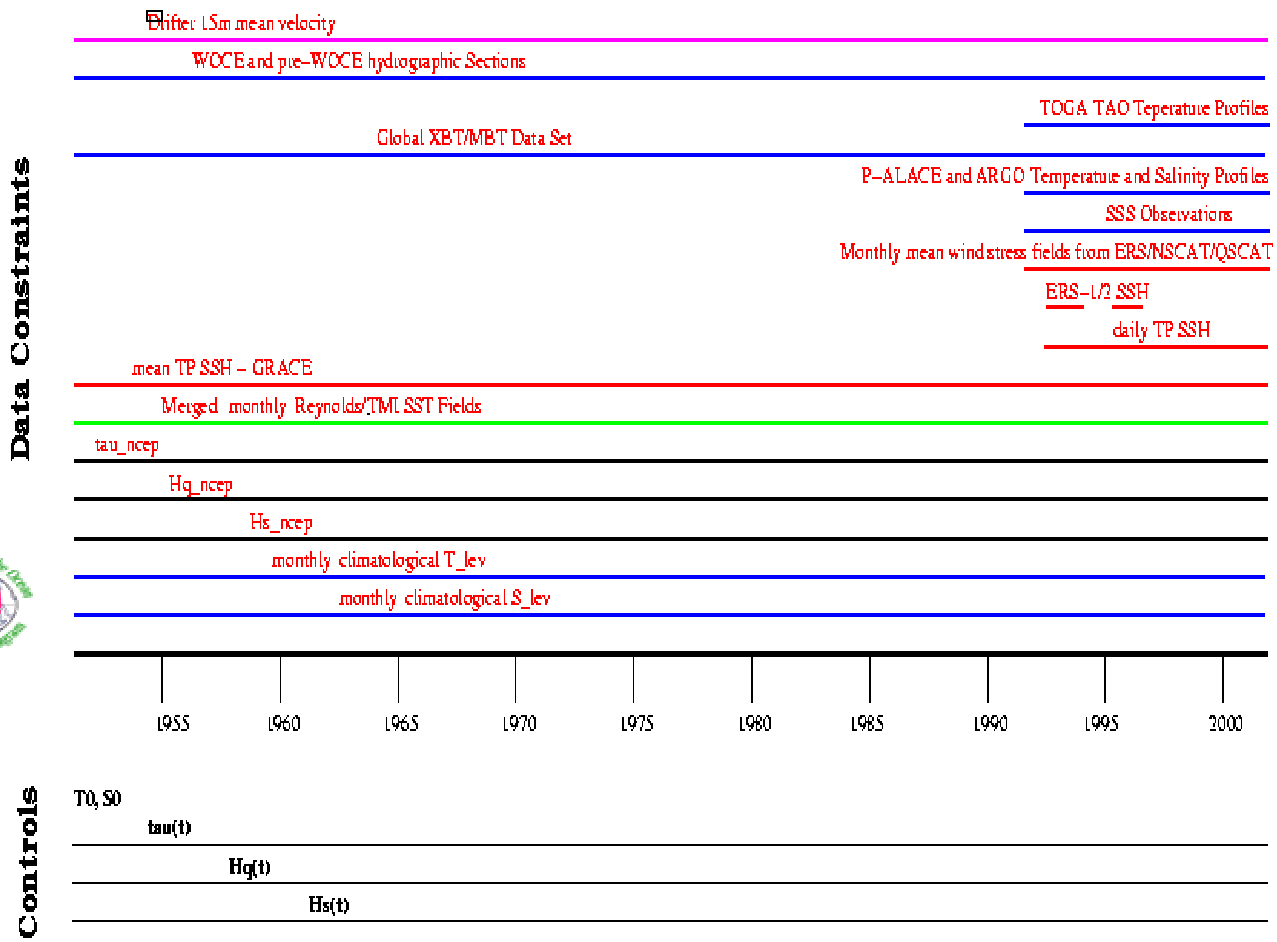


Delta Horiz. Diffusivity



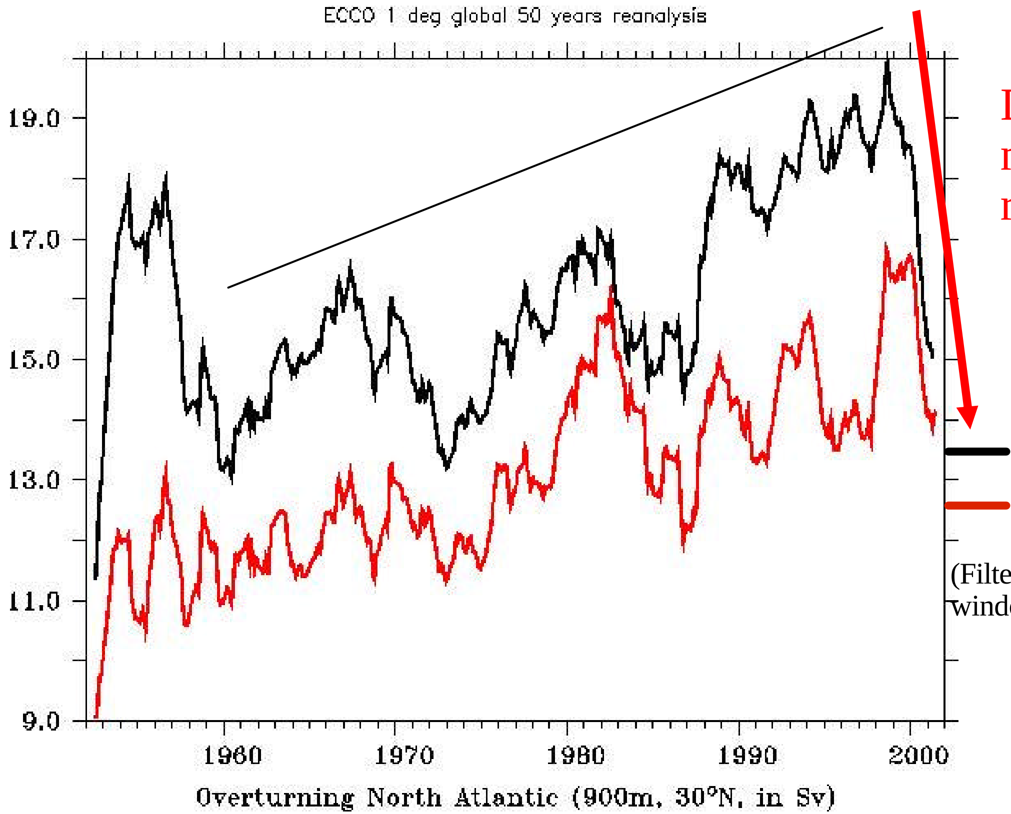
(Stammer, 2003)

Global 1° WOCE Synthesis 1952 through 2002



Koehl and Stammer (2004)

Overturning in the North Atlantic at 30°N in 900m depth



Drop present in
many models;
robust climate signal?

Reference

Optimized

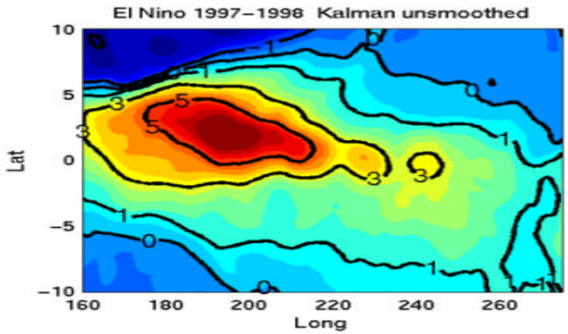
(Filtered with 12-month window)

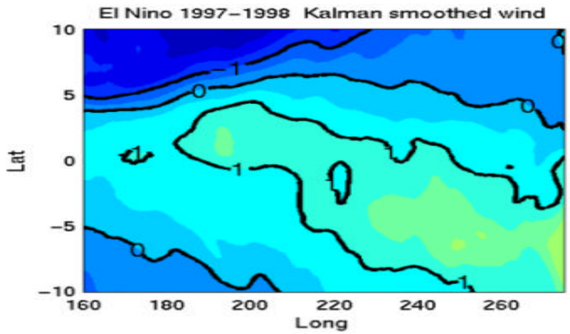
Sensitivity of CO2 Sea Air Flux

The unrealistically large CO2 flux during ENSO present in the filtered solution (left) due to anomalous vertical advection is corrected in the smoothed estimate (right) consistent with observations.

Filtered Estimate

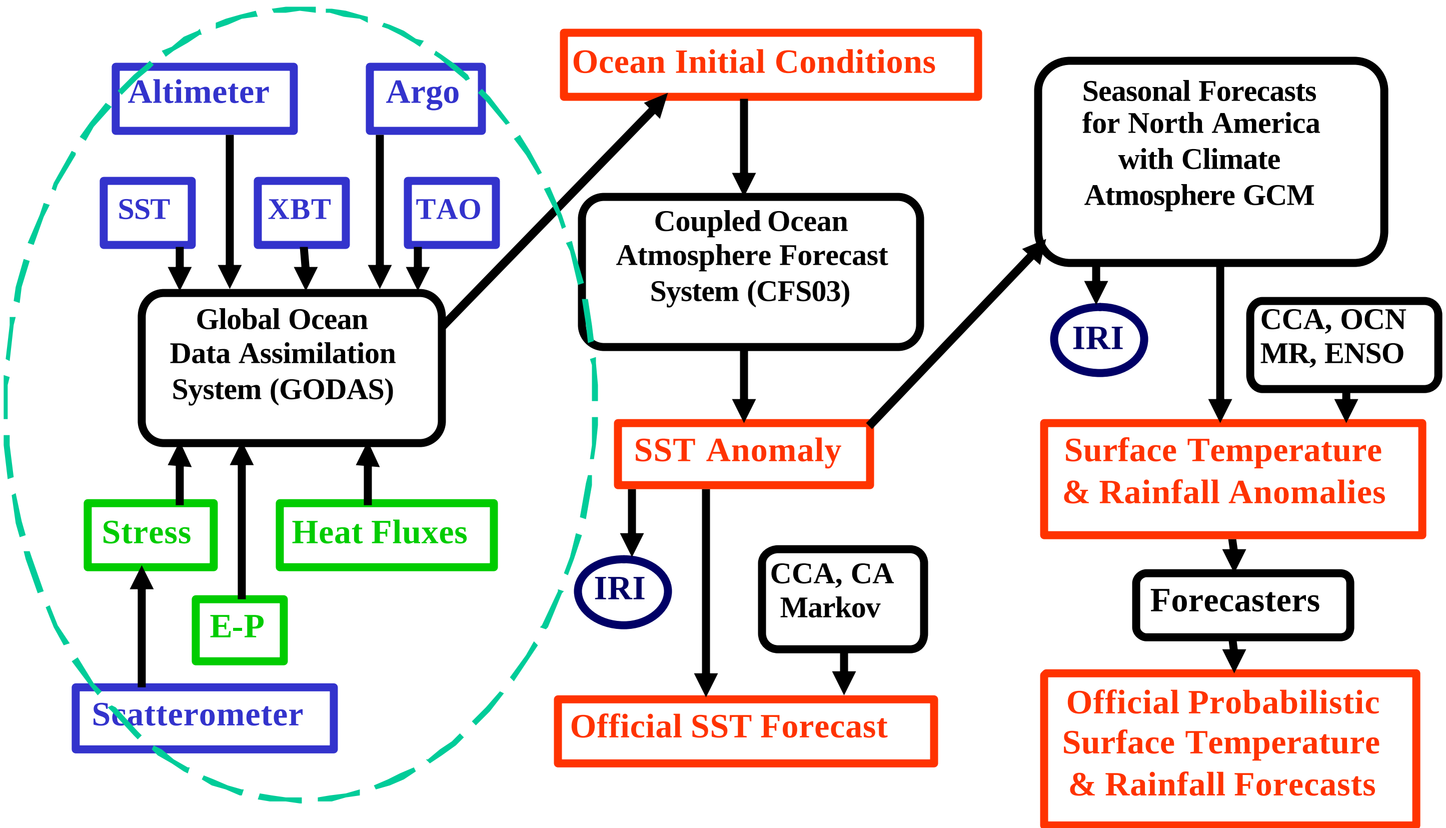
Smoothed Estimate





(G.McKinley, 2002)

Seasonal to Interannual Forecasting (ODASI, ENACT) At NCEP:

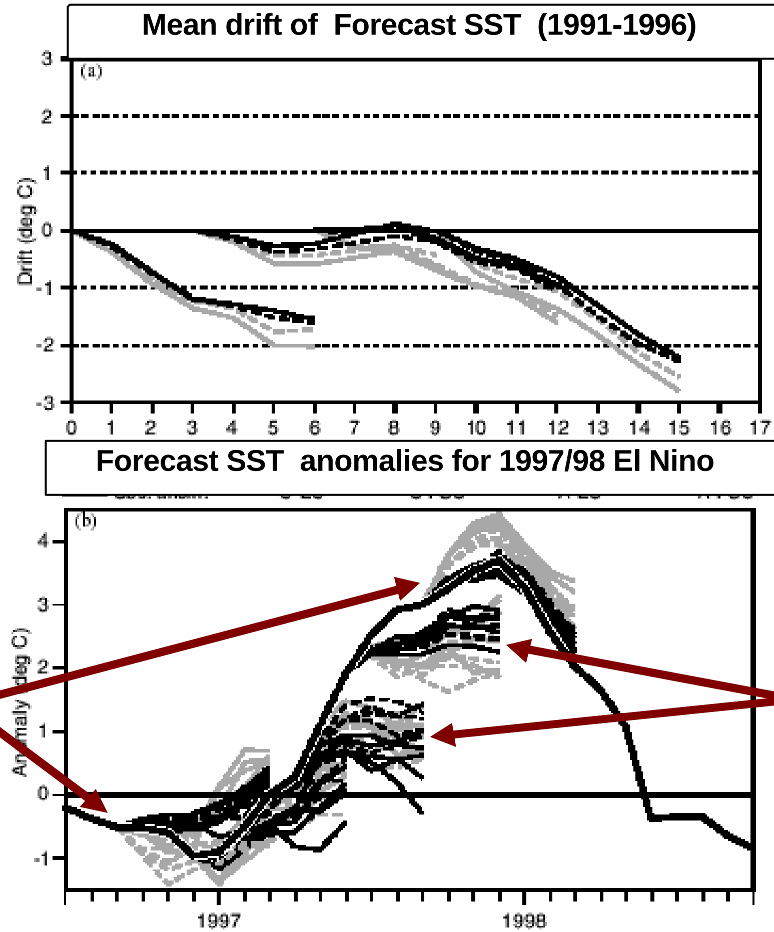


Steve Lord, Hua Lu Pan, Dave Behringer

IMPACT of ASSIMILATION and SURFACE FORCING on NINO-3 SST FORECASTS

ECMWF: Alves, Balmaseda, Anderson & Stockdale: QJRMS 2004

Legend:
No-assimilation cases
Assimilation cases



- **Drift is larger for non-assimilation cases**
- **Assimilation compensates for forcing uncertainties**

Sensitivity to initial conditions - Assimilation initialization performs better

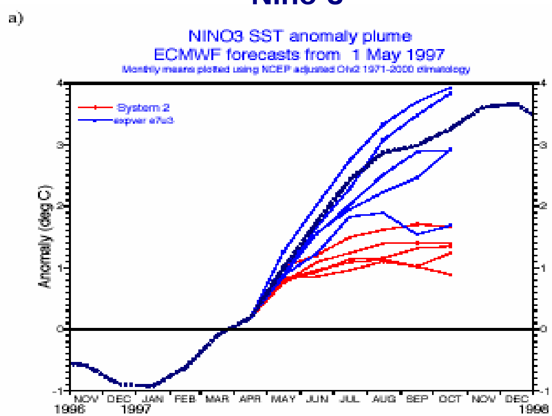
Under-prediction of anomaly due to model error

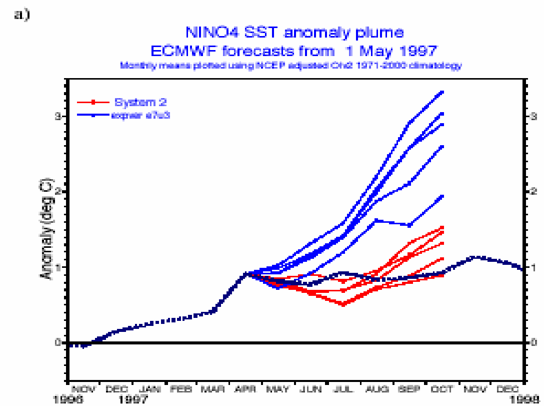
IMPACT of DIFFERENT OCEAN ANALYSIS SYTEMS on SST FORECAST

ECMWF & Met Office

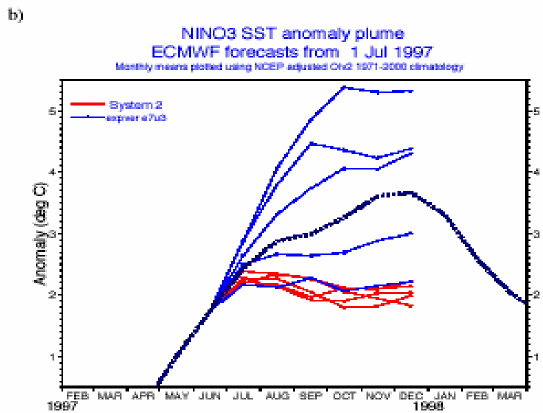
Nino-3 | **Nino-4**

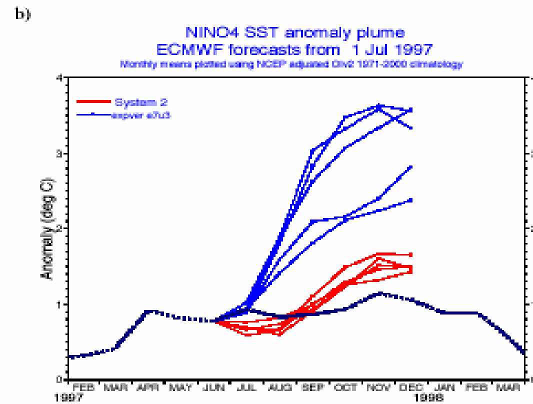
Initialized 1 May 1997





Initialized 1 July 1997





Challenges: Climate Data Assimilation

? Assimilation models need to be global in the future and need to include full ice modes to simulate properly the global hydrological cycle, ice feedback and and global sea level rise.

?Imperfect knowledge of error covariances (model and data), and especially of multivariate error covariances requires the close collaboration of the observational and modelling communities.

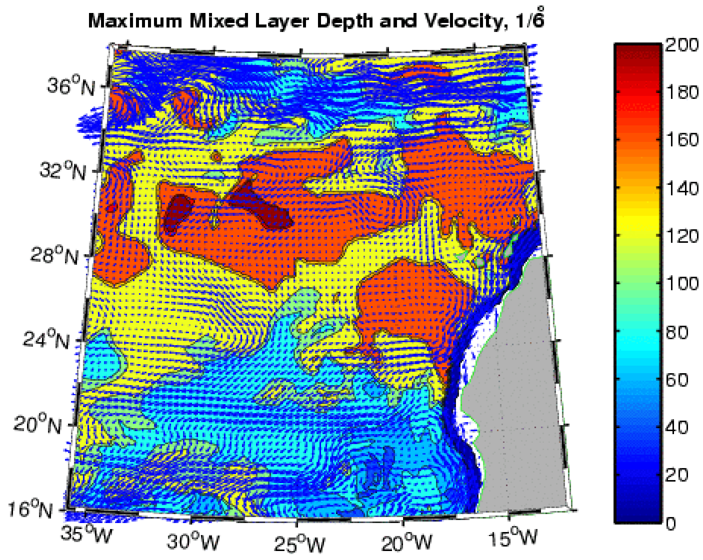
?Estimation uncertainties have yet to be provided.

?For ocean state estimation in general, resolution is a major limitation. The role of large-scale to small-scale coupling in general circulation models needs to be established (coastal and biogeochemical applications).

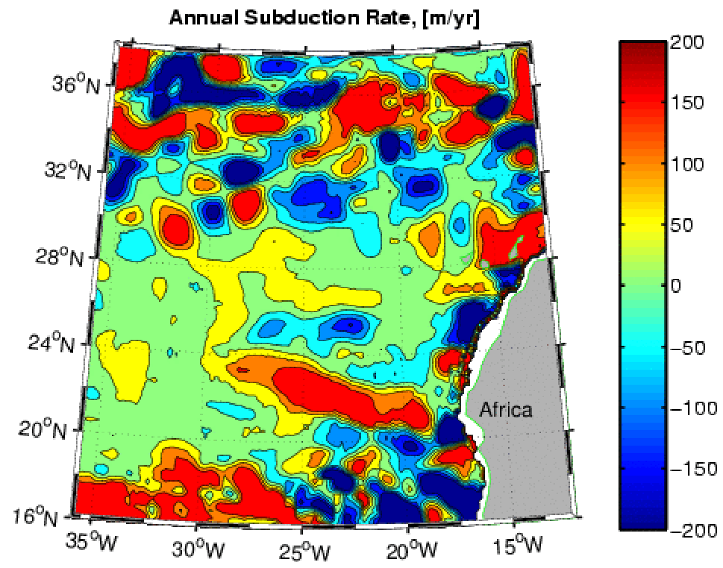
High-Resolution Estimations

Eddy-permitting Estimation in Subduction region (1/6 degree); nested into global results.

Maximum MLD



Subduction Rate

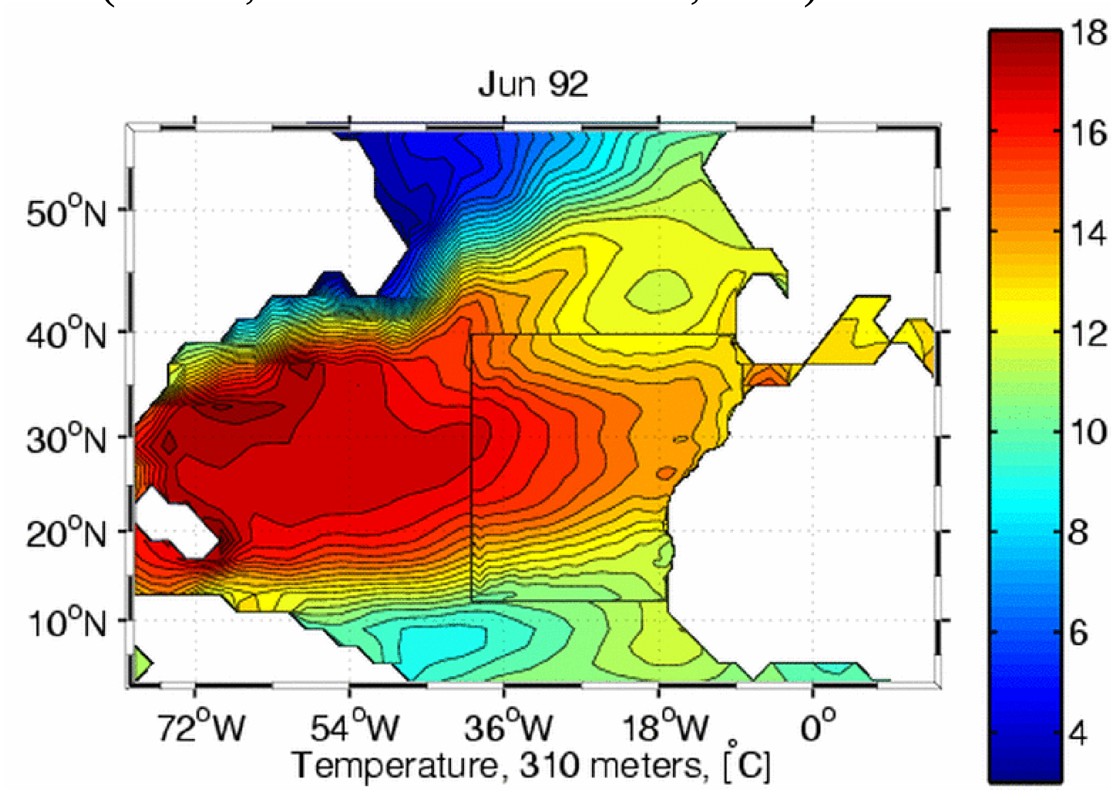


(Gebbie and Wunsch, 2003)

Multi-Resolution Assimilation

(Gebbie, Wunsch and Heimbach; 2004)

2degee



1/6 degree

Chalanges for Seasonal-to-Interannual Analysis and Prediction

- ? **Ocean data assimilation improves S-I forecasts, compensating for model biases and for forcing errors.**

- ? **Different methods vary in skill. BUT coupled model error dominates forecast error, so it is difficult to discriminate between methods. We need improved coupled models!!**

- ? **For sequential methods, multivariate error covariances are important and needed.**

Conclusions

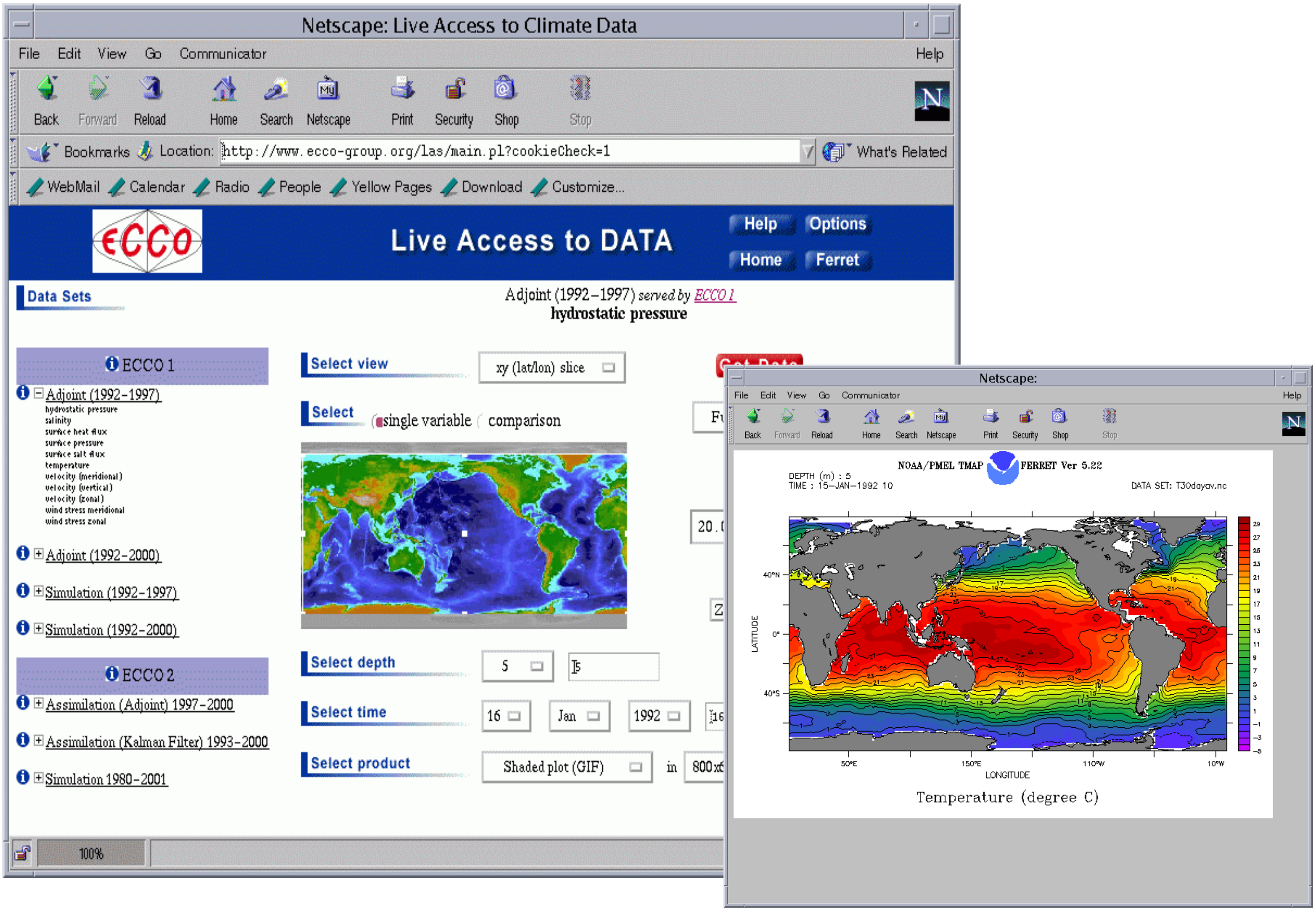
?**Biggest challenge remains completion of the global ocean observing system and maintaining and refining it for future scientific generations.**

?**Three applications of ocean data assimilation: mesoscale now-and forecasts; SIP initialisation; ocean reanalyses and decadal forecasts. Optimum methods have not yet been established for any of these applications. It is recognized that parallel infrastructure development is required to support all three applications for the foreseeable future.**

?**Resolution remains an issue for assimilation, especially climate-related. There remains a gap between routine estimates and predictions the ocean eddy field and the high-quality products that are required for climate research. But ...**

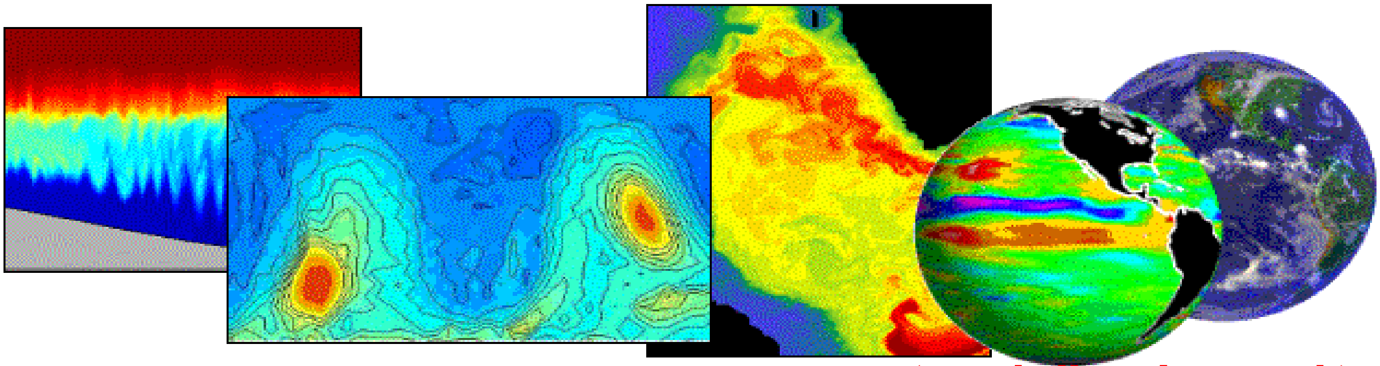
Live Access Server (LAS)

http://www.ecco-group.org/las



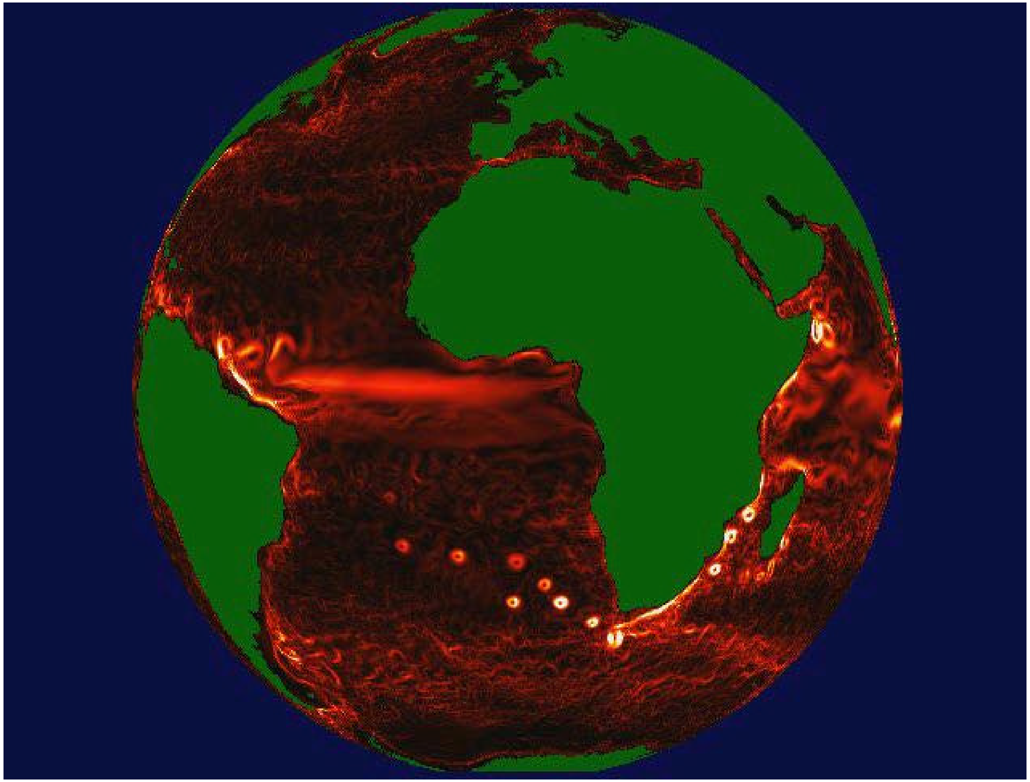
MIT Model Development

- Used to study atmospheric and oceanic circulation.
- Non-hydrostatic capability.
- Finite volume treatment (lopped cells).
- Wide range of physical parameterizations (KPP, GM).
- Compatible with tangent linear and adjoint compiler.
- Exploits parallel computers.
- Designed to address the estimation problem.
- Includes ice model.



(Marshall et al, 1997a,b)

¼ degree **global** Filter/Smoother with ice
(Menemenlis, Fukumori, Lee)



Outlook:

For ENSO and mid-latitude decadal predictions, the scientific community is looking for using assimilation products for coupled-model initialisation and improvements. We have to look beyond simple initialization to more sophisticated use of the ocean data to:

- ?generate ensembles and
- ?provide estimates of uncertainty
- ?more effectively use multivariate datasets.

We have to improve coupled models and use them in an assimilation-initialization mode to approach seamless weekly-seasonal-interannual-to-decadal forecasts.

Future Earth system research will require a significant demand for computing resources.

CLIVAR Global Synthesis and Observations Panel (GSOP)

- **Develop strategies for a synthesis of global ocean, atmosphere and coupled climate information. Initial emphasis will be on global ocean synthesis efforts.**

- **Responsible for the definition and fulfilment of CLIVAR's global needs for sustained observations (in collaboration with relevant observational groups).**

- **Promote activities to develop the surface flux data sets required by CLIVAR in liaison with the WGNE, global atmospheric reanalysis efforts and the WCRP Working Group on Surface Fluxes.**

- **Provide an overview of and directions to CLIVAR data management and information activities in collaboration with other WCRP projects and in liaison with CLIVAR-relevant data centres and DACS and the ICPO.**

CLIVAR Reanalysis Workshop

November 8 -10, 2004 at NCAR (Boulder)

Objectives:

- ***Establish the requirements for ocean reanalysis within the remit of CLIVAR.***
- ***Review the state and usage of ongoing and planned ocean reanalysis efforts.***
- ***Stimulate new applications of existing ocean reanalyses for ocean studies, surface flux analyses, and initialization of coupled models.***
- ***Review the synergy between ocean and atmospheric reanalysis activities.***
- ***Review long-term observing system strategies, and designs.***
- ***Identify model improvements required for ocean and coupled reanalyses, including surface fluxes and its ice component.***

Adjoint Model Compiler

Source-to-sources differentiation tool.
Adjoint model from a FORTRAN forward model.
Allows easy addition of model improvements and new data.
Available tools are TAMC, TAF (Giering and Kaminski, 1998)

New open-source tool underway (NSF ITR project;
PI: C. Wunsch).