# Ocean Reanalyses

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# Goals of Ocean Reanalysis

Goal of ocean reanalysis is to obtain best possible description of the ocean circulation by combining all available data with the dynamics of an ocean circulation model and use the results to:

- **Improve understanding** of past climate variability and climate sensitivities.
- **Improve climate forecasts** by merging coupled models with the **climate data base** (certainly relevant for SSH predictions).
- **Improve models** through parameter estimation**.**

# Ongoing Ocean Reanalyses

- Several global and regional ocean data assimilation products are available today that in principle can be used for climate applications.

- Those efforts having three different goals, all essential for WCRP, namely:

  – climate-quality hintcasts,
  – high-resolution nowcasts, and
  – the best initialization of forecast models.

- Underlying assimilation schemes differ vastly, ranging from simple and computationally efficient (e.g. optimal interpolation) to sophisticated and computationally intensive (e.g., adjoint and Kalman smoother, applied over long periods).

# Typical Applications

- THE OCEANS IN THE PLANETARY HEAT BALANCE:

(1) heat storage, (2) heat transports and (3) ocean/ atmosphere feedbacks.

- THE GLOBAL HYDROLOGICAL CYCLE:

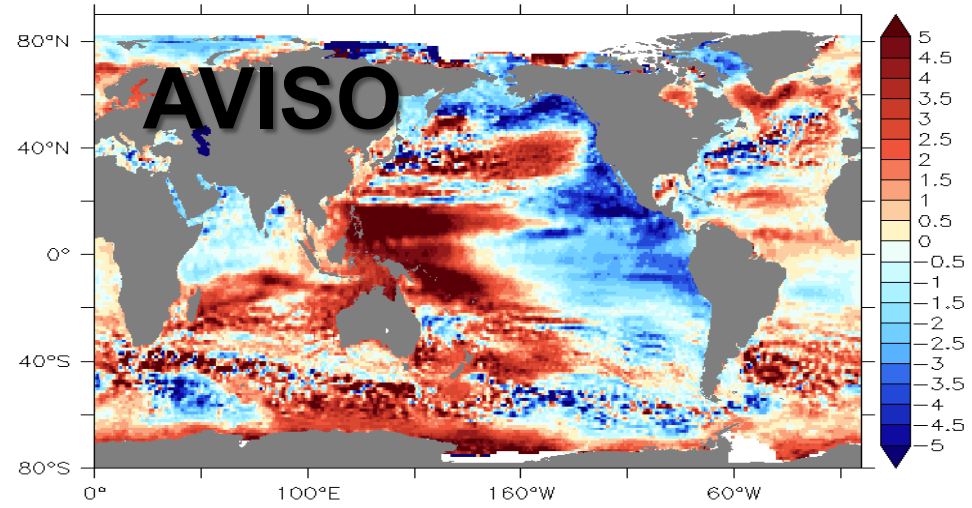
(1) water balance, (2) rainfall variability and (3) salinity and convection.

- SEA LEVEL:

(1) sea level rise and (2) sea level variability.

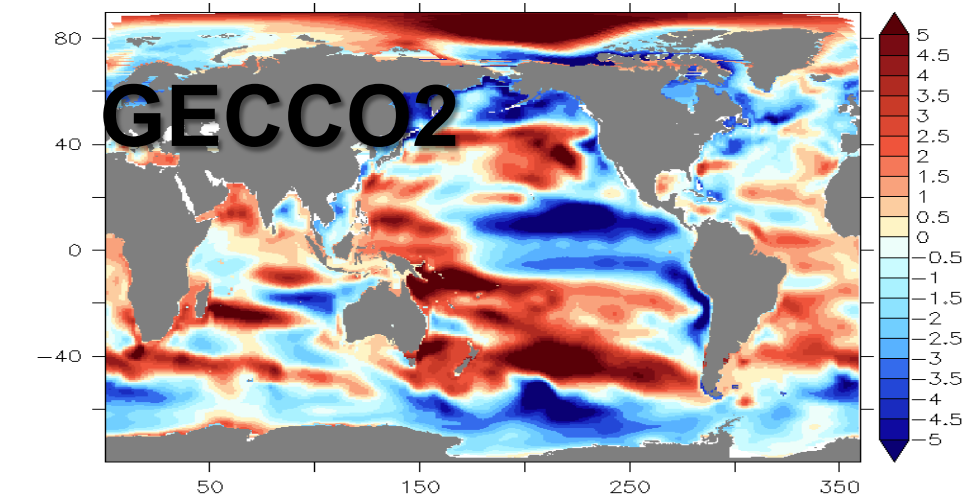
- CLIMATE MODEL INITIALISZATION

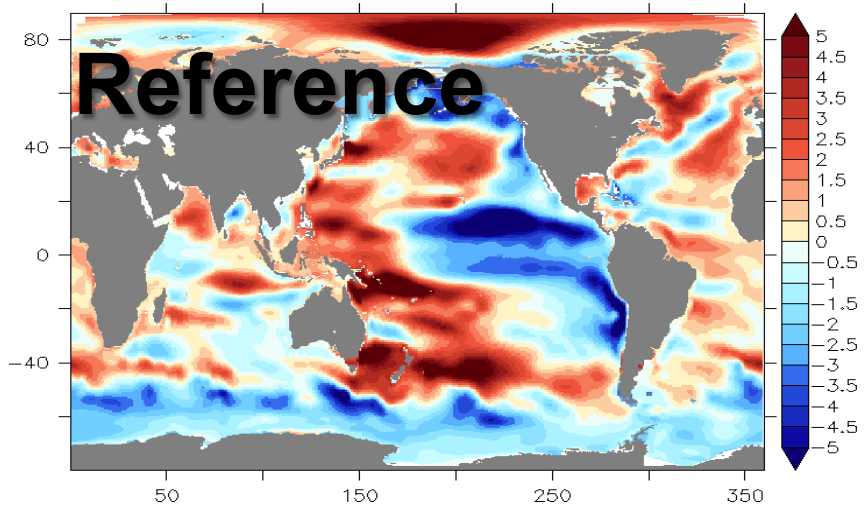
# Example: Sea Level Change 1993-2009 (cm/yr)



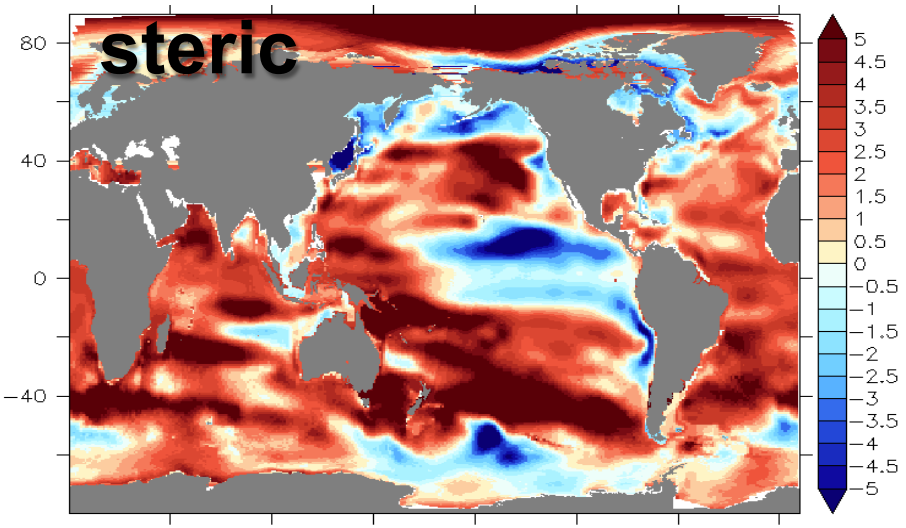

Sea level trend estimates in cm/yr from altimeter observations, GECCO2 and the reference for the period 1993-2009.

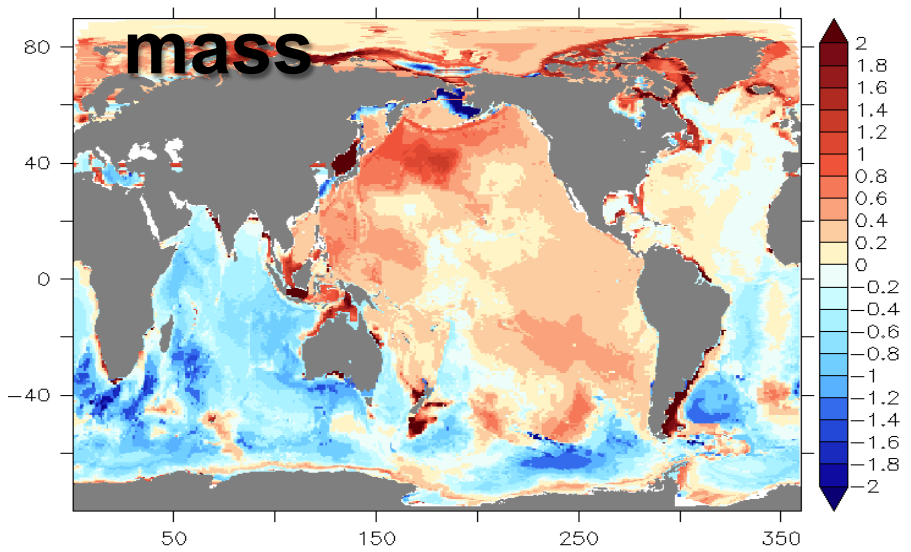
Global steric increase is 1.1 mm/yr for Reference and 1.9 mm/yr for GECCO2

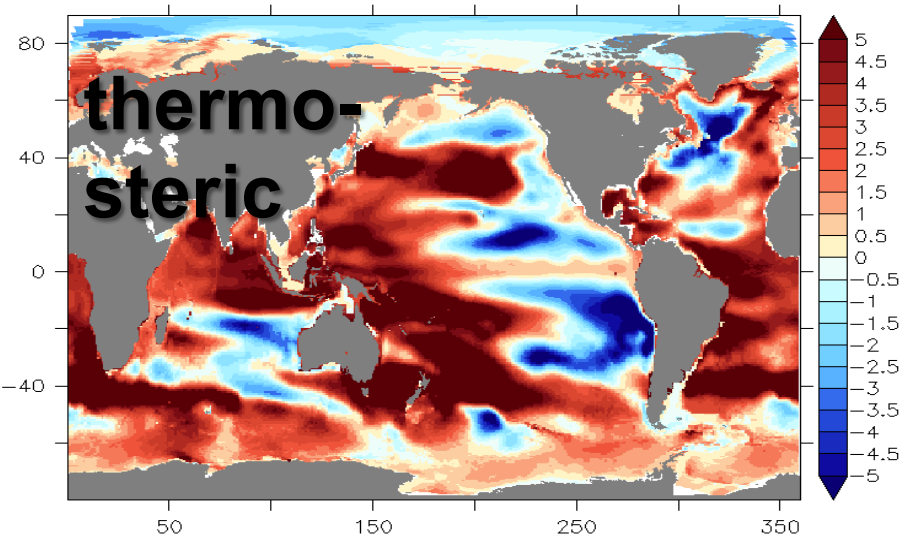


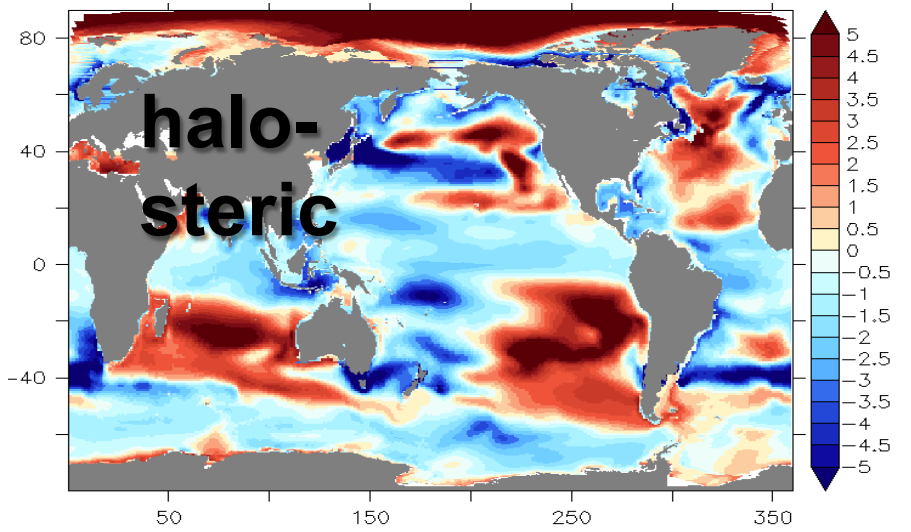



# Steric and mass changes 1993-2009 (mm/yr)



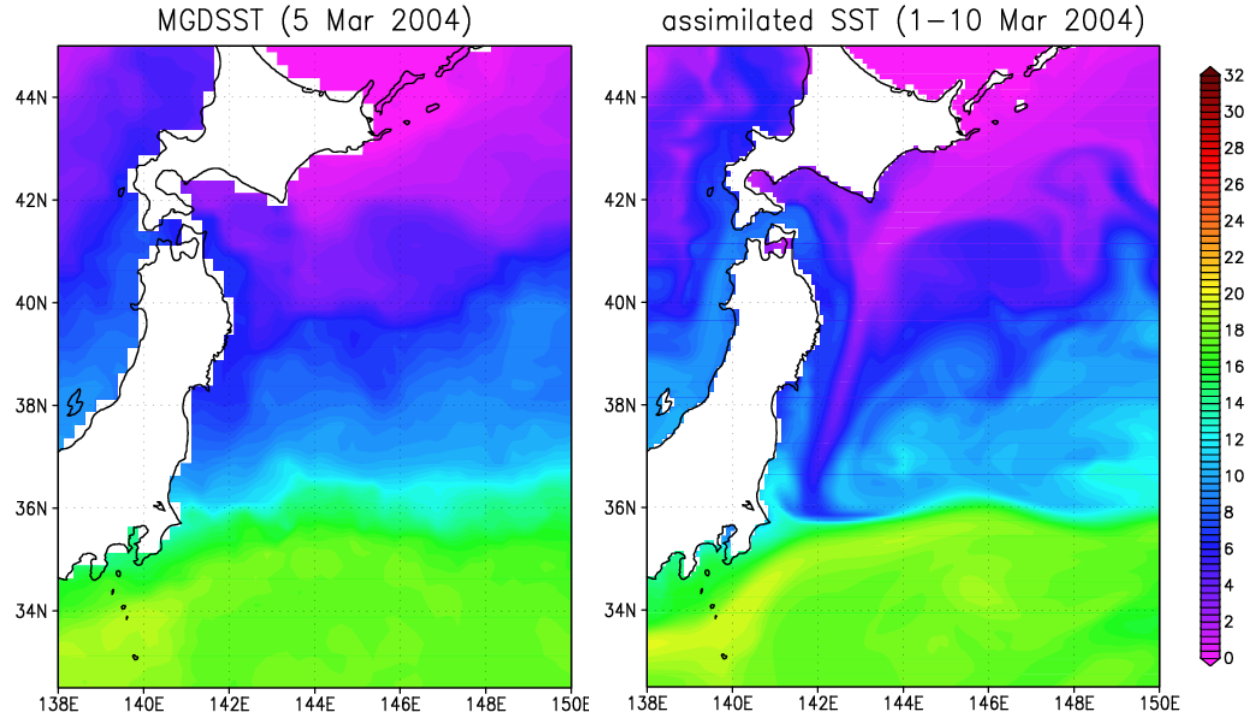



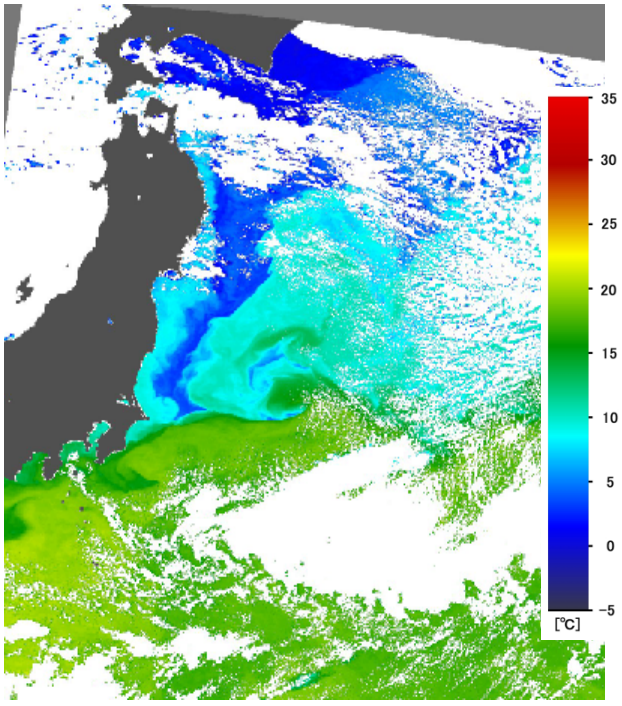
# Example: MOVE-WNP 3DVAR-RA

**JMA's GHRSST product**
(MGDSST; SST objective mapping data)

**MOVE-WNP 3DVAR-RA**
(Reanalysis by the data assimilation system)

**MODIS Satellite data**



# 1. GSOP/GODAE Synthesis Evaluation Activity

- Evaluate the quality and skill of available global synthesis products and determine their usefulness for CLIVAR.

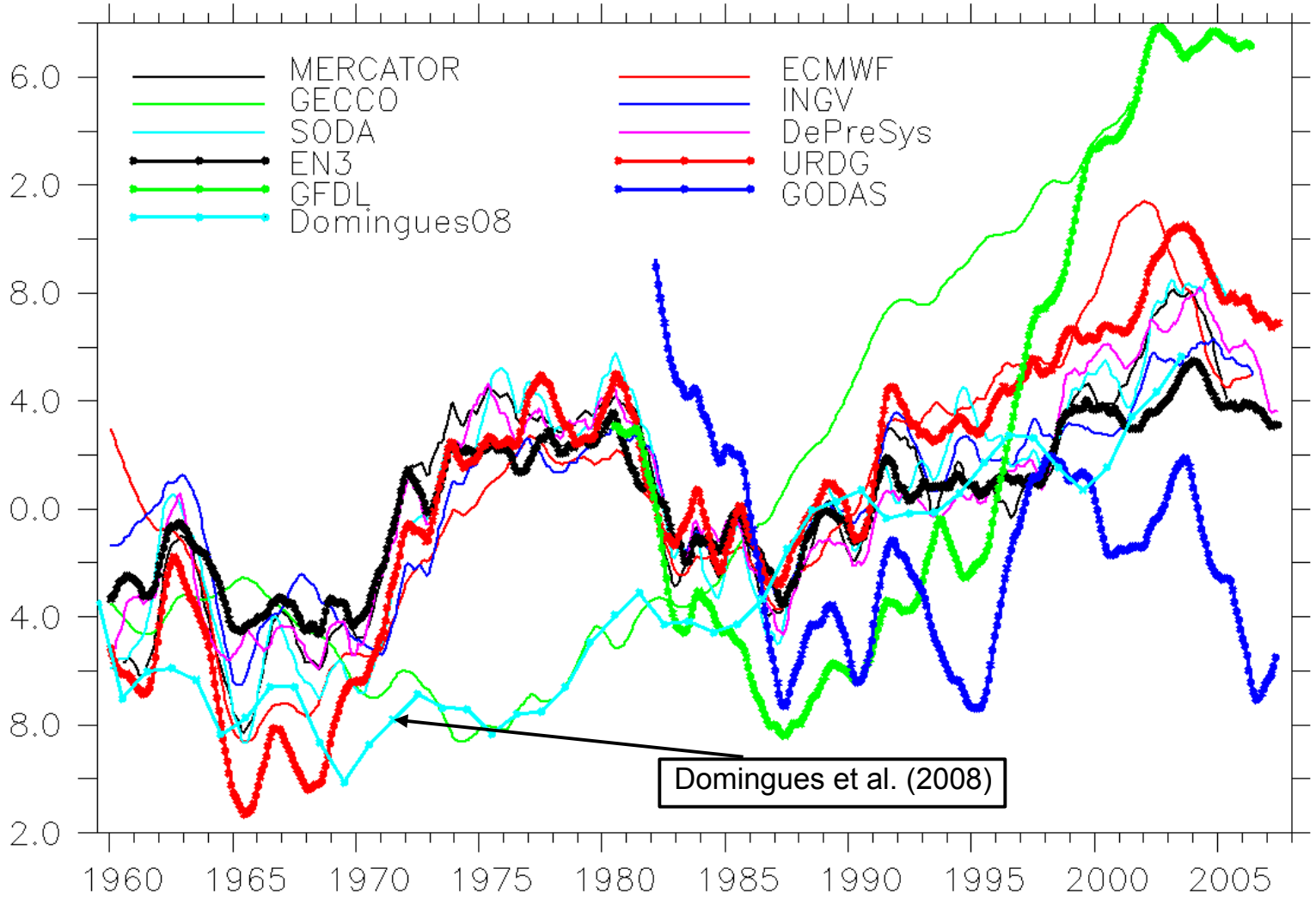
- Identify the common strength and weakness of these systems and the differences among them, as well as to identify what application can be best served by what synthesis approach.

- Define and test climate-relevant indices that in the future should be provided routinely by ongoing or planned synthesis efforts in support CLIVAR and of the wider community.

# Participating Groups

- ECCO
- GECCO
- SODA POP
- GFDL/NOAA
- NCEP/NOAA
- HYCOM
- GMAO/GSFC
- ECMWF
- INGV/ENACT
- CERFACS-LODYC/ENACT
- UK Met Office
- MERCATOR/MERSEA
- MOVE-G
- K-7
- BlueLink

# Global Heat Content Anomaly ($10^{22}$ J)



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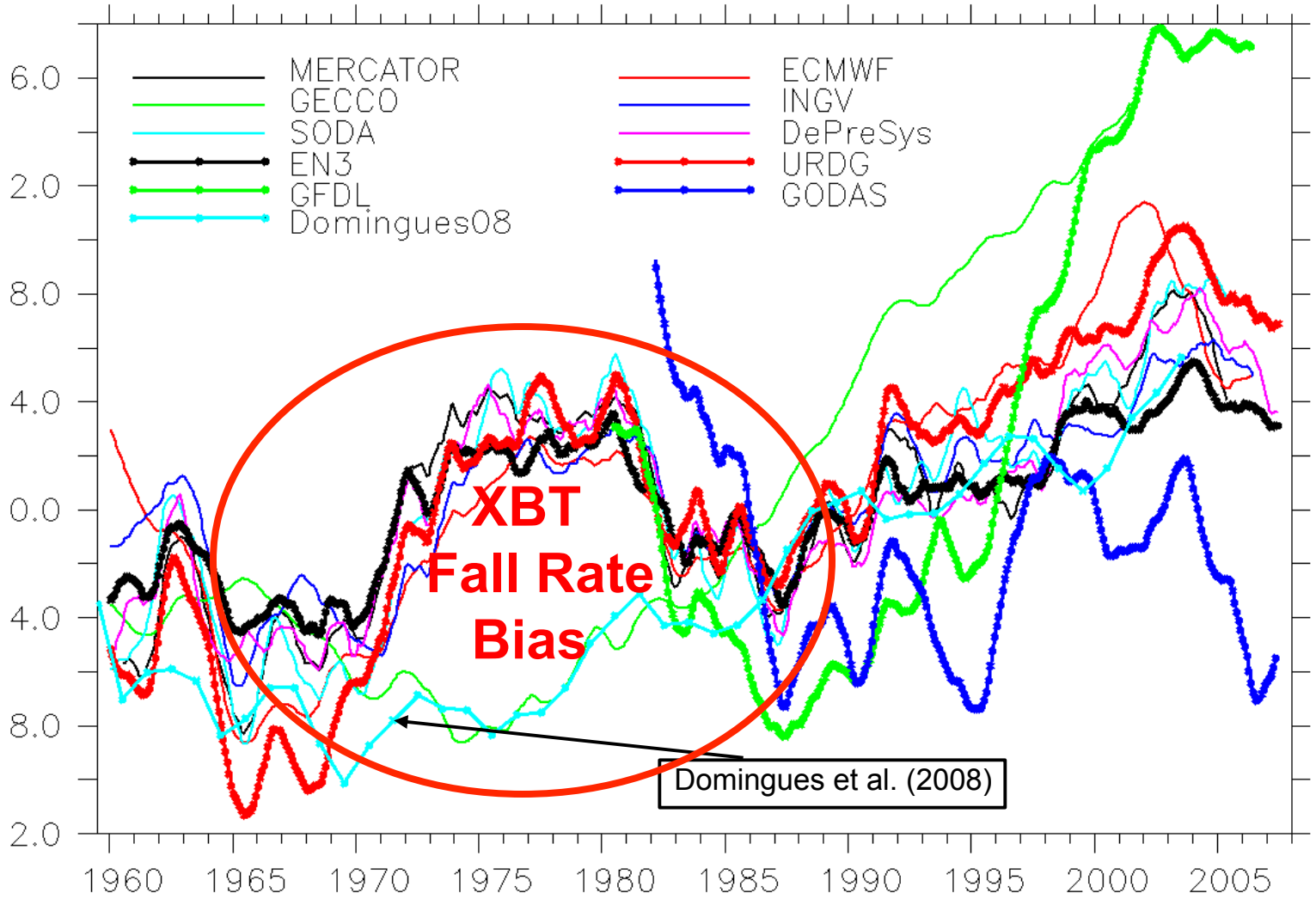
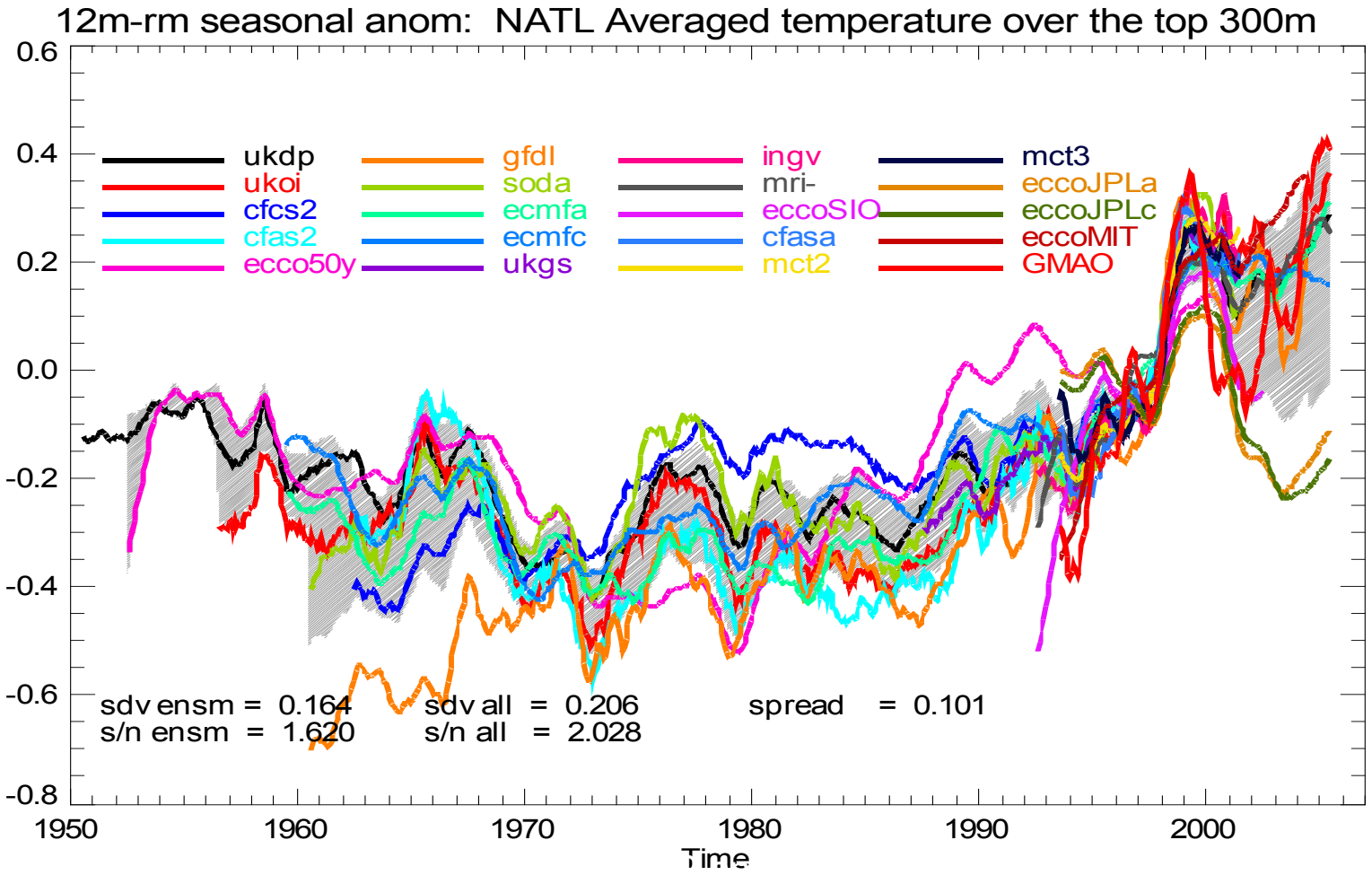


# N. Atlantic Temp (0-300 m)



# 2. GSOP/GODAE Intercomparison

- GSOP/GODAE Ocean View initiative of using multi-reanalyses products for climate monitoring and intercomparison.

- Goal to produce ensemble mean ocean reanalyses and uncertainty information.

# A Comparative Analysis of Upper Ocean Heat Content Variability from an Ensemble of *Operational* Ocean Reanalyses

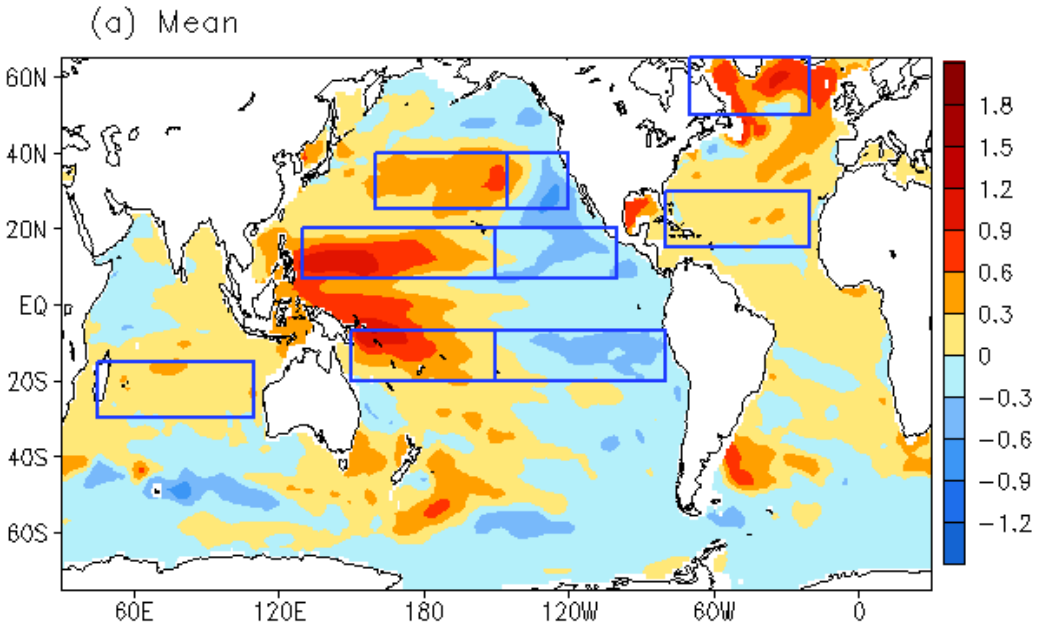
Yan Xue, Magdalena A. Balmaseda, Tim Boyer, Nicolas Ferry, Simon Good, Ichiro Ishikawa, Arun Kumar, Michele Rienecker , Anthony J. Rosati, Yonghong Yin

Table 1. A summary of the major features in each of the ten operational ocean reanalyses.

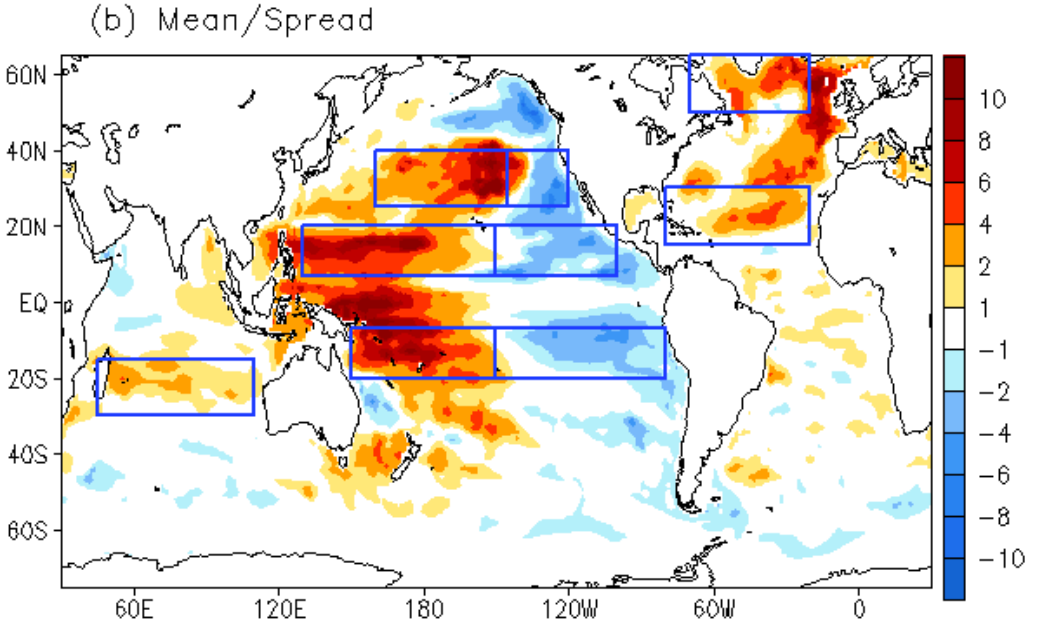
| Name (Reference) | Model and Resolution | Surface forcings | Method | Data | Period | Vintage |
|---|---|---|---|---|---|---|
| EN3.v2a (Ingleby and Huddleston 2007) | No Model 1°x 1° 42 Levels | Not required | Objective analysis using analysis correction scheme | Temperature profiles from WOD05, GTSPP, Argo, Arctic Synoptic Basin-wide Observations project | 1950-present | 2009 |
| NODC (Levitus et al. 2009) | No Model 1°x 1° 16 Levels | Not required | Objective analysis | Temperature profiles from WOD09, GTSPP and Argo | 1955-present | 2010 |
| GODAS (Behringer and Xue 2004) (Behringer 2007) | MOM3 1°x (0.3-1°) 40 Levels | NCEP/DOE reanalysis | 3D-VAR<br>No relaxation to climatology | Altimetry sea level since August 2006 Temperature profiles from XBT, CTD, buoys, Argo<br>Relaxation to OISST (5 day) | 1979-present | 2003 |
| ECMWF (Balmaseda et al. 2008) | HOPE 1°x (0.3-1°) 29 Levels | ERA40 until 2002 ECMWF operational analysis afterwards | 3-D OI with online bias correction<br>Relaxation to climatology (10 yr) | Altimetry sea level Temperature & Salinity profiles from XBT, CTD, buoys, Argo<br>Relaxation to OISST (3 day) | 1959-present | 2007 |
| JMA (Usui et al. 2006) | MRI.COM 1°x (0.3-1°) 50 Levels | JRA-25 | 3D-VAR Coupled Temperature–Salinity EOF<br>Relaxation to climatology (2.7 yr) | Altimetry sea level Temperature & Salinity profiles from XBT, CTD, buoys, Argo<br>Assimilate COBE-SST | 1979-present | 2009 |
| CFSR (Xue et al. 2011) | CFSv2/MOM4 0.5°x (0.5 -0.25°) 40 Levels | CFSR | 3D-VAR First guess from coupled model<br>No relaxation to climatology | Temperature profiles from XBT, CTD, buoys, Argo<br>Nudging to daily OISST in which obs have equal weight with the 1st guess (.5/.5). | 1979-present | 2009 |
| GFDL (Zhang et al. 2007) | CM2.1/MOM4 1°x (0.3-1°) 50 Levels | Coupled model fluxes | Ensemble Kalman Filter Fully coupled<br>No relaxation to climatology | NCEP/DOE Reanalysis winds, temperature and sea level pressure Altimetry sea level Temperature & Salinity profiles from XBT, CTD, buoys, Argo<br>Assimilate OISST | 1970-present | 2010 |
| GMAO (Vernieres et al. 2011) | GEOS5/MOM4 0.5°x (0.5 -0.25°) 40 Levels | MERRA | Multivariate EnOI First guess from coupled model | Altimetry sea level Temperature & Salinity profiles from XBT, CTD, buoys, Argo, WOA09 climatology<br>Assimilate daily OISST | 1980-present | 2010 |
| MERCATOR (Drevillon et al. 2008) | OPA8.2 2°x (0.5-2°) 31 Levels | ERA40 until 2002, ECMWF operational analysis afterwards, | KF-SEEK<br>Relaxation to climatology (3yr) | altimetry sea level Temperature & Salinity profiles from XBT, CTD, buoys, Argo<br>Assimilate OISST | 1979-present | 2007 |
| BOM (Yin et al. 2011) | MOM2 2°x (0.5-1.5°) 25 Levels | ERA40 until 2002 NCEP/DOE reanalysis afterwards | Ensemble Kalman Filter<br>Relaxation to climatology (2 yr) | Temperature and Salinity profiles from EN3<br>Relaxation to OISST (1 day) | 1980-present | 2009 |

# Linear Trend of HC300 anomalies, 1993 – 2009 C/decade

Ensemble Mean HC300 Trend

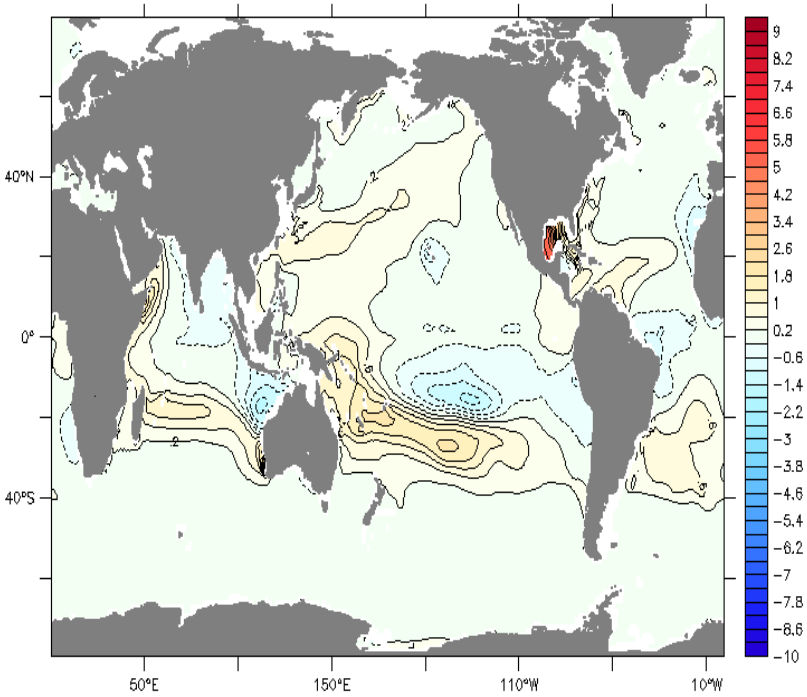



Ensemble mean/spread

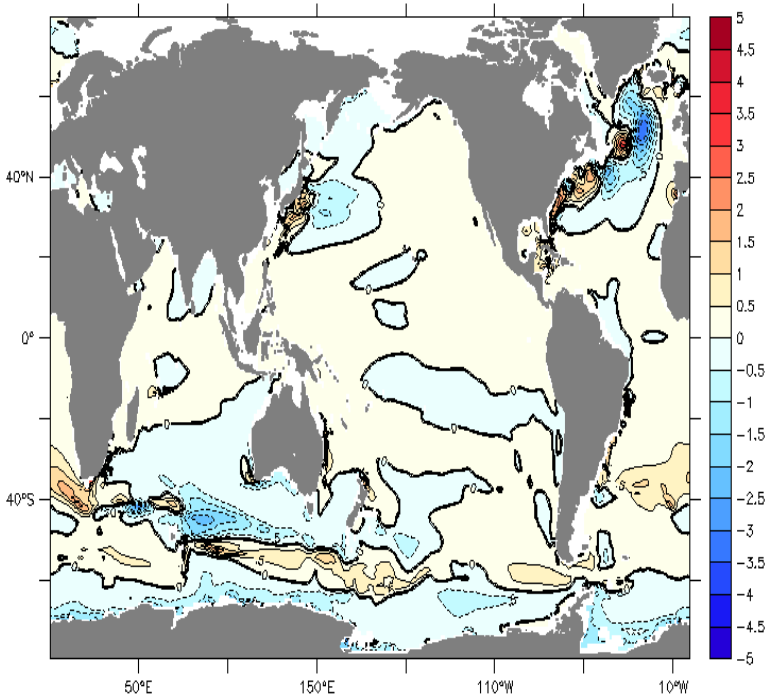


# Parameter Estimation: Mixing Coefficients

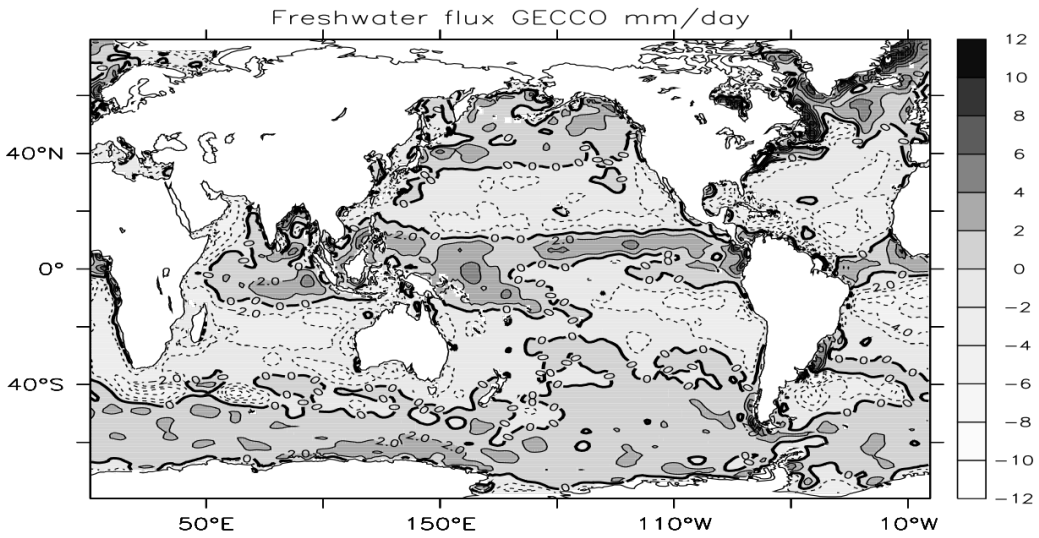
Vertical Diffusivity at 450 m

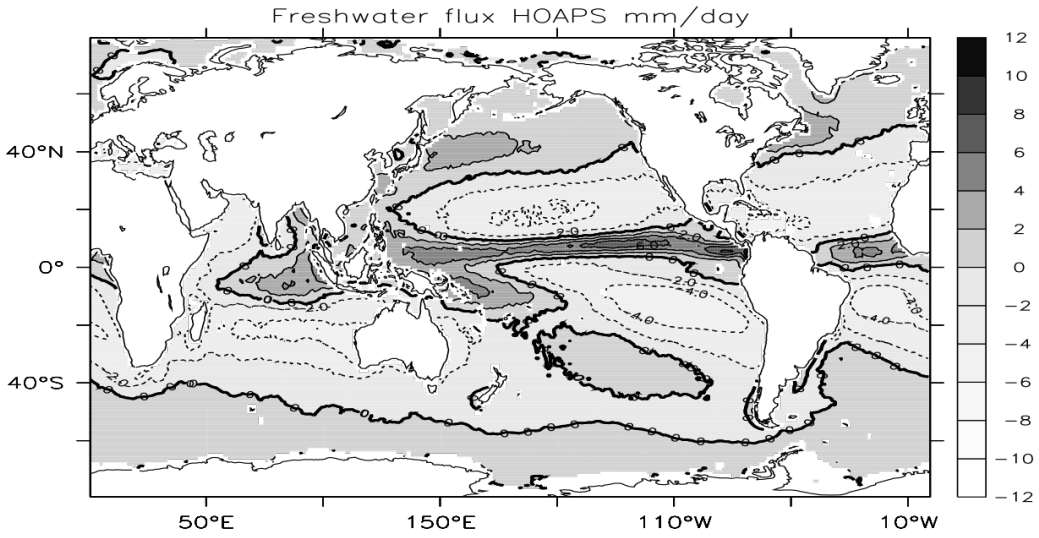



Improvements in Temperature at 450m

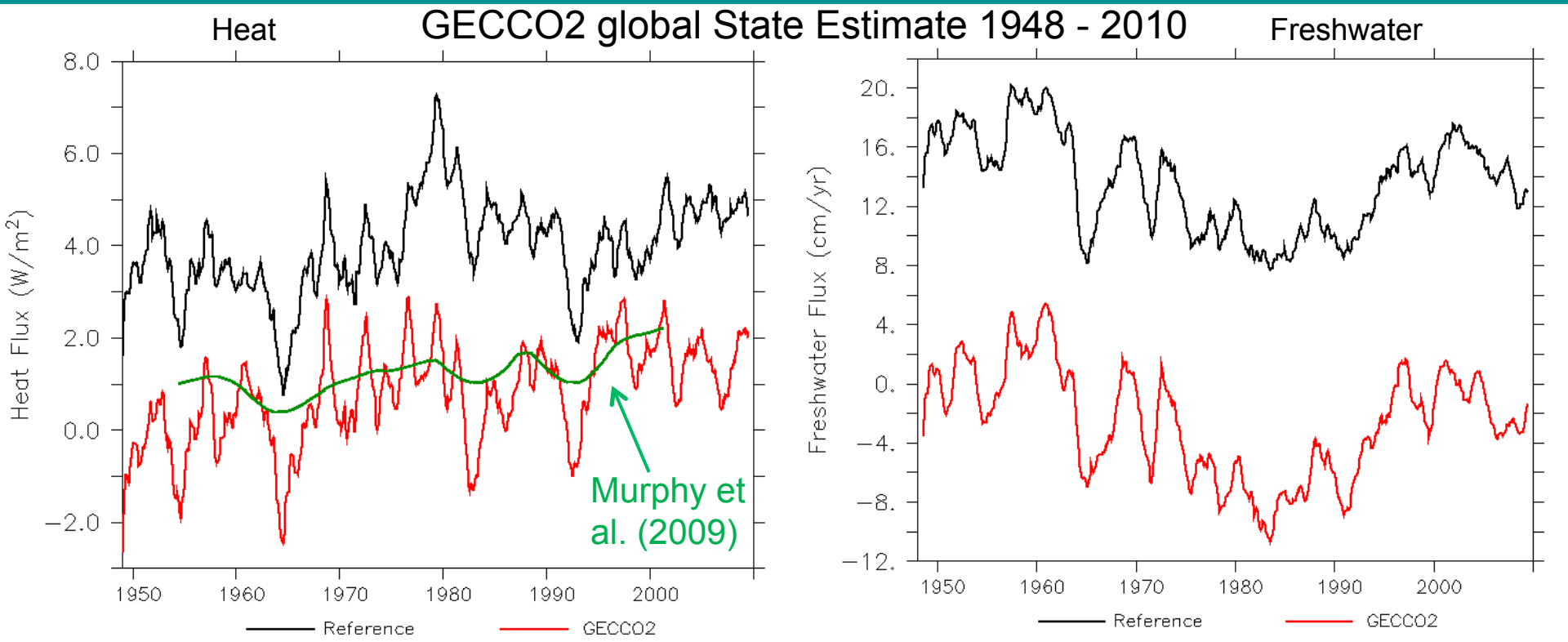


# Estimation of Surface Freshwater Forcing



# Globally averaged Surface heat and freshwater fluxes



# Climate Reference Data Sets

- Climate reference data sets and their error fields for the ocean and sea ice are required.

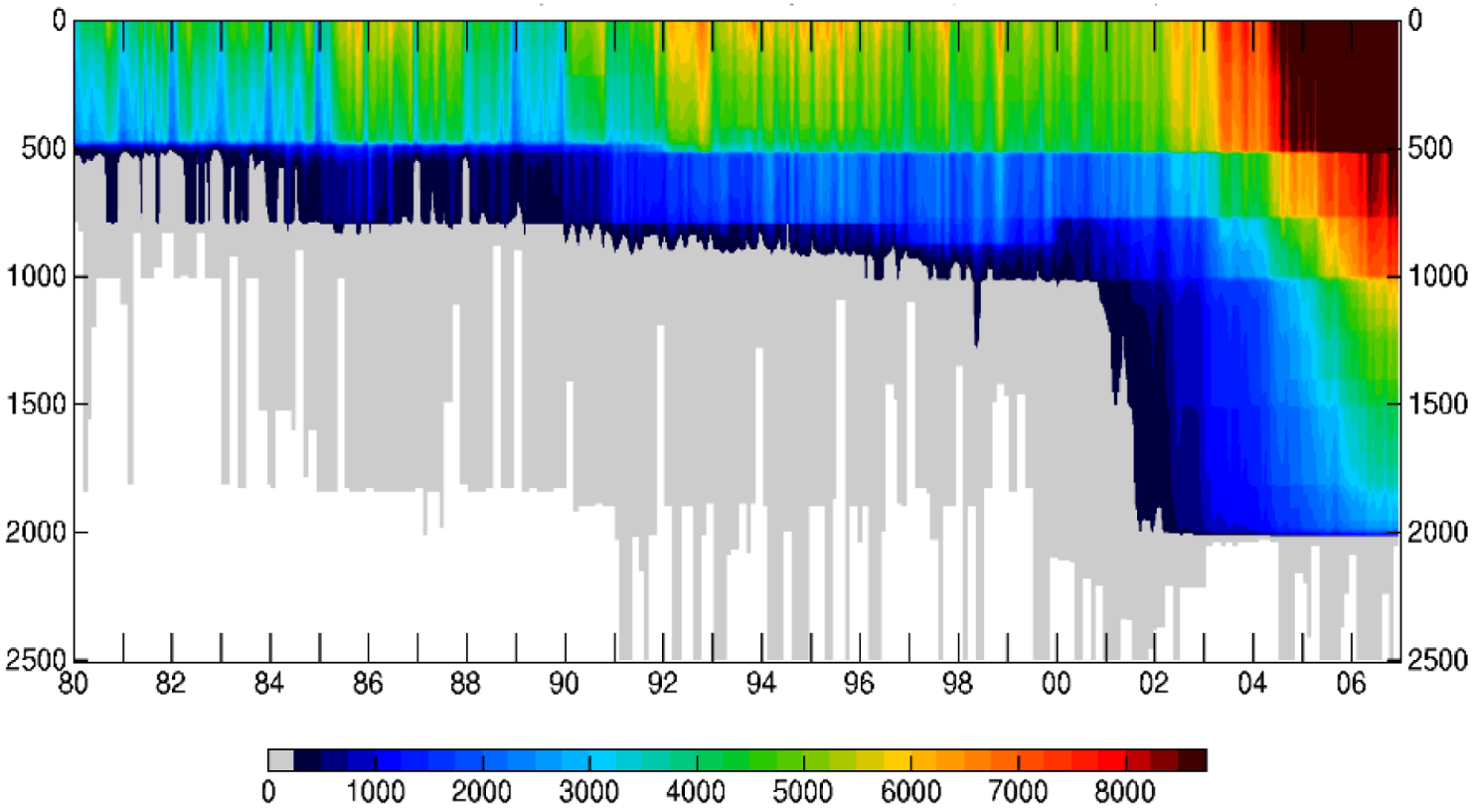
- Climate reference data sets include in situ and satellite data sets, as well as surface flux fields (run-off).

- They are available through data centers (NODC, Coriolis, Headly Center, MyOcean, etc)

- Requires continuous effort on data archaeology and QC to improve existing data sets.

- Requires also effort to improve observing system for future observations.

# Data Problems in the Ocean
# Example: Temperature Profiles




*Global number of temperature observations per month as a function of depth*

*1980-2006*

# New Data Opportunities

## GRACE: Bottom pressure data

## SMOS, Aquarius: SSS data

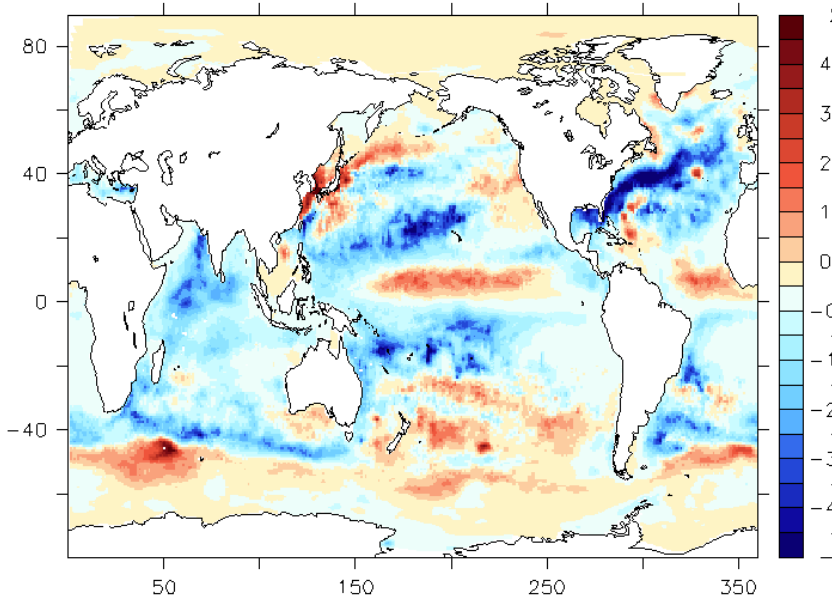
**Example: GECCO Assimilating** 2010 SMOS DATA in global model

Input Data: Argo and CTD T/S, XBT, Altimeter SLA, SST (HadISST, AMSR/E), mean SSH and SMOS Level 3 SSS

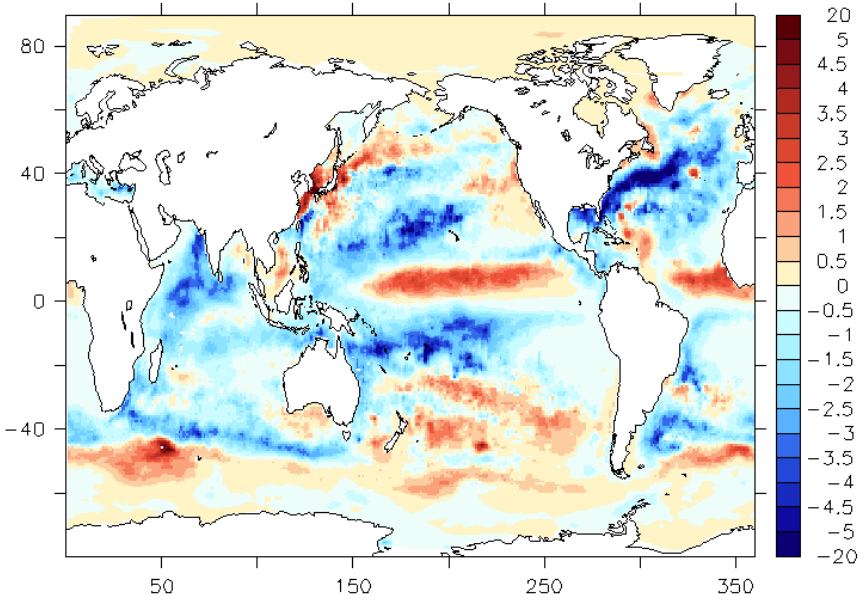
Optimized parameters include T/S initial conditions, wind, air temperature, humidity, precipitation.

# Mean Precipitation Changes (mm/d)

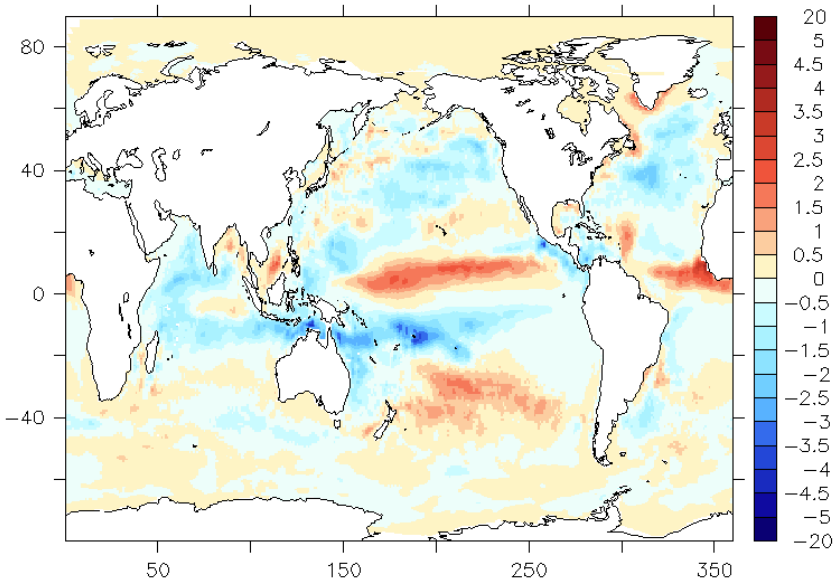
noSMOS



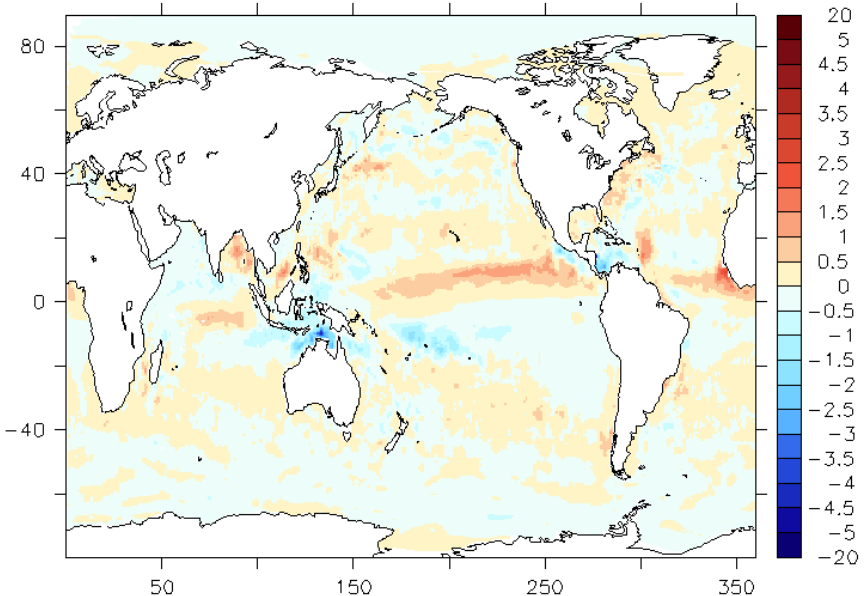

SMOS




SMOSonly




SMOS-noSMOS

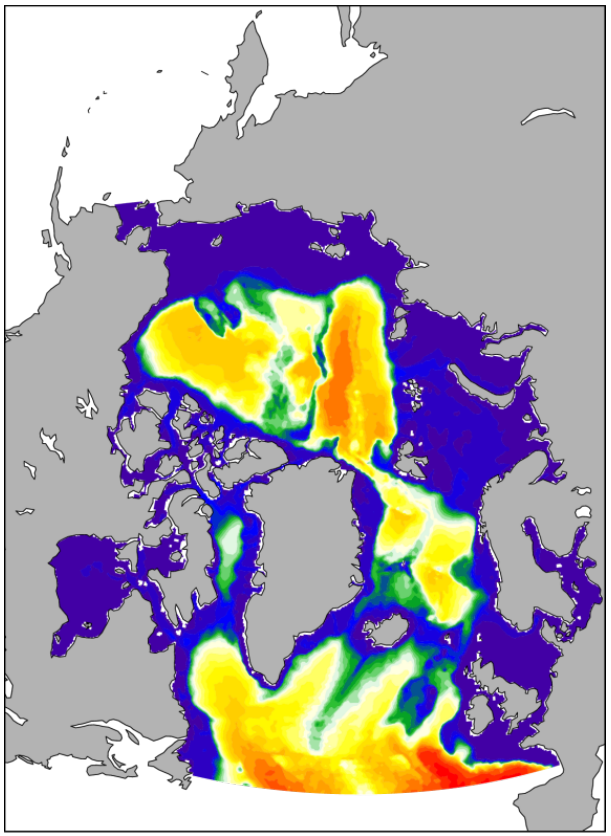


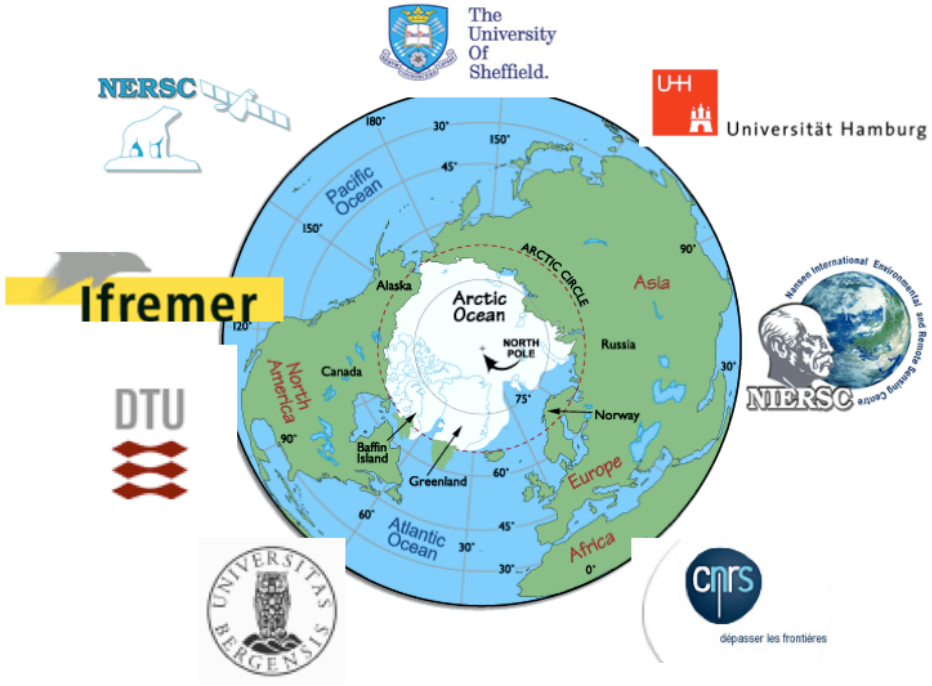
# Outlook

- Ocean reanalyses will continue and will continue to improve. Applications and use of results are still spinning up.
- Holds for regional and global scale, with more use being made for the production of ECVs.
- Activity toward coupled data assimilation is speeding up and more efforts toward initialization of climate forecasts through climate observations are emerging.
- A close collaboration with WCRP model development efforts is required for use of parameter improvements.

# Regional Coupled Arctic Ocean/Sea Ice Reanalysis

Monarch-A




Outcome:

- ECVs for the Arctic:
- Circulation and Transports
- Sea Level
- Sea Ice
- Run-off
- Ice melting from Greenland

# Continuation of Ocean Assimilation

Ocean state estimation with various degrees of sophistication, lengths and resolution; emphasis on the ocean and on initialization.

- SODA: centennial data assimilation
- ECMWF: to initialize monthly, seasonal and decadal forecasts
- UK Metoffice: EN3 objective analyses as part of monthly-seasonal forecasting
- MyOcean:

  Mercator: GLORYS2V1, reanalysis, Kalman Filter
  CMCC: C-GLORSv2, reanalysis, 3DVAR
  U-Reading: UR025.4 , reanalysis, OI
- K7: 1957-2009 synthesized run by using a quasi-global 4D-VAR ocean data assimilation system
- MOVE/MRI.COM: used in the ENSO, seasonal, and ocean state forecast in JMA
- BlueLink: Operational oceanography
- ECCO: sustained global multi-decadal climate analysis and development

# Emerging Coupled Assimilation Efforts

- JAMSTEC: K7 and CFES-LETKF (see poster)
- NASA/GMAO: uses a coupled atmosphere-ocean model and an ensemble optimal interpolation method to assimilate ocean and sea-ice observations while the atmosphere is constrained to MERRA.
- NCEP/GODAS: coupled forecast provides the first guess for data assimilation in the separate atmosphere, ocean and land components.
- BOM/POAMA: semi coupled assimilation where an ensemble of coupled models is run, but assimilation still takes place separately for the ocean and atmosphere
- SODA/OARCA: coupled reanalysis that will span the period from 1845 – present
- U-Reading/ECMWF: Joint project with ECMWF to develop a weakly coupled data assimilation system (run at ECMWF) with a focus on improving assimilation of near surface data.
- GECCO/THOR/NACLIM/MIKLIP: coupled data assimilation with focus on parameter optimization and decadal forecasting.

Thank You!

# ECMWF

At ECMWF we have a new ocean reanalysis product ORAS4, which replaces the previous ORAS3.

It is based on NEMO/NEMOVAR, it still has climate resolution (1 degree), and it is used to initialize monthly, seasonal and decadal forecasts (by EC-EARTH). It starts in 1957 09 and brought up to real time.

Apart from NEMO/NEMOVAR there are some other upgrades:-5 ensemble members, sampling uncertainty in forcing, deep ocean and observation coverage-Upgrades on the treatment of model bias, including the use Argo information to estimate the bias (this is a way of extrapolating Argo into the past).-

Upgrade in the quality controlled data set (EN3), with XBT corrected (and others)-Along-track assimilation of altimeter with revised multivariate formulation.-Forcing ERA40 until 1988, ERA-Interim 1989-2009, NWP

# UK Metoffice

- EN3 objective analyses (www.metoffice.gov.uk/hadobs/en3): These are monthly estimates of the temperature and salinity of the ocean and they run from 1950 up to the present (with updates produced at approximately one month lag).

- The Met Office also runs routinely ocean reanalysis as part of the operational monthly-seasonal forecasting systems.
- The main purpose is to provide initial conditions for the hindcast simulations.
- The latest reanalysis uses NEMOVAR at a resolution of 0.25 degree and 75 vertical levels. CICE is used for sea-ice, we assimilate concentration only.
- The temporal period covered is 1989 - present.

# MyOcean

GLORYS objectives in the next years are:- to assimilate new observations like sea ice concentration and drift- to extend (from 1979-present) the reanalysis time period- to produce eddy resolving reanalyses at 1/12° resolution- to produce 1/4° biogeochemical simulation forced by 1/4° reanalysed ocean physicsMyOcean global ocean reanalysis effort:

In the framework of EC funded MyOcean project, a global ocean reanalysis effort has been coordinated between Mercator (F), CMCC (It), LEGI (F), University of Reading (UK) and CLS (F) to produce a unique set of eddy permitting description of the ocean sate at the meso scale covering the 1992-2009 time period.

This data set consists of 3 ocean reanalyses at 1/4° (same model configuration, same forcing: ERA-Interim, data assimilation of SST, SLA, T & S profiles) differing by the assimilation methods used, 1 reference simulation at 1/4° with no data assimilation, 1 ocean state estimation based on observations only (SST, SLA, T & S profiles):

# MyOcean

Mercator: GLORYS2V1, reanalysis, Kalman Filter

CMCC: C-GLORSv2, reanalysis, 3DVAR

U-Reading: UR025.4 , reanalysis, OI

LEGI: MJM95, reference simulation, no data assimilation

CLS: ARMOR3D, multivariate ocean state reconstruction with observations only

Common validation diagnostics have been implemented to rigourosly assess and validate the reanalyses according to Mersea/GODAE/CLIVAR/GSOP/ MyOcean metrics.

MyOcean project will continue in the next 2,5 years with MyOcean2 project with a WP dedicated to reanalyses. The objectives are :(i) to produce user oriented assessment of reanalyses, (ii) to reprocess delayed time observations (iii) to produce in a coordinated way global and regional reanalyses physical / biogeochemical reanalyses.

# ECCO

•The ECCO consortium is presently engaged in two core efforts jointly among MIT, AER, and JPL partners: (1) A sustained global multi-decadal climate analysis called "ECCO-Sustained Production" (ECCO-GODAE follow-on), and (2) A modeling and estimation development effort called "ECCO-Ocean & Ice Interactions" targeting eddy resolving scales and coupling the ocean to other Earth system components, notably the cryosphere (ECCO2 follow-on).

•(1) The "ECCO-Sustained Production" project is currently revising the version 3 ECCO Central Production solution in a forthcoming version 3.1 product. The estimate is an extension of the ECCO-GODAE adjoint-based system with improvements in model and data constraints (updated data sets, improved model and data treatments, new data types) in addition to extending the estimation period to the present. In particular, the model employs a prognostic sea-ice model and bulk air-sea flux formulations. New constraints include global mean sea level rise and ocean bottom pressure changes. The ECCO Near Real-Time Kalman filter, which remains operational, is also being ported to this new analysis so as to extend the estimate in near real-time.

•A new-generation version 4 ECCO Central Production system is also currently being developed. The version 4 system combines a cubed-sphere and dipolar grid in a fully global rendering of the ocean that includes the Arctic, features scale-sensitive treatment of observational constraints, and estimation of model parameters as additional controls. We anticipate the version 4 estimates to be adopted as the new ECCO Central Production analysis within this coming year. All ECCO-Central Production estimates remain at nominally 1 degree

# ECCO

•(2) The "ECCO-Ocean & Ice Interactions" project is a continuation of the ECCO2 project and it aims to develop coupled ocean, sea ice, and ice sheet data assimilation capabilities and to incorporate these capabilities in the GEOS-5 Earth System Model, towards enabling next-generation ECCO estimation products. The specific science objectives of this project are to study (i) the origin and evolution of water masses near polar ice sheets from high-resolution state estimates, numerical simulations, and adjoint sensitivity computations, (ii) the scientific basis for decadal climate predictability, and (iii) the reduction of uncertainties in sea level projections through improved modeling of ice sheets and ocean-ice interactions.

•The "ECCO-Ocean & Ice Interactions" project also produces shorter (2-4 year), higher-resolution (18-km horizontal grid spacing), adjoint-model-based ocea and sea ice state estimates, which are being used for a variety of science applications that require higher resolution than is possible for the longer-period "ECCO-Sustained Production" state estimates.  These applications include ecosystem modeling, biogeochemistry, sea ice kinematics, and acoustic propagation studies.

# K7

- K7 long-term ocean state estimation: 1967-2006 ocean synthesized dataset is now available.

- At present, we are executing a 1957-2009 synthesized run by using a quasi-global 4D-VAR ocean data assimilation system for surface to bottom ocean state estimation.

- Our tentative future plan (next 5yr): Construction of a tri-polar global 4D-VAR data assimilation system for higher-accuracy estimation of heat, mass, material (e.g., carbon) transports in the global ocean (now preparing; 0.25(?) - 1 degree). Sea Ice data assimilation is another target although we have no clear strategy, yet.

# University of Reading/ECMWF

- Joint project with ECMWF to develop a weakly coupled data assimilation system (run at ECMWF) with a focus on improving assimilaiton of near surface data (funding by ESA)Hope thats usefulbest regards

# NASA GMAO Ocean reanalysis

**GEOS5odas-4.0**

- The GMAO ocean retrospective analysis GEOS5odas-4.0 spans 52 years from 1960 to the present day. The reanalysis uses a coupled atmosphere-ocean model (MOM4 for the ocean and CICE for the sea-ice, GEOS-5 atmospheric model) and an ensemble optimal interpolation method to assimilate ocean and sea-ice observations while the atmosphere is constrained to the GMAO's Modern-Era Retrospective analysis for Research and Applications (MERRA).
- The ensemble used for estimating the background error covariances consist of the 20 leading EOFs of an ensemble of 900 ocean states consisting of temperature, salinity, velocities, sea surface height, sea-ice concentration and sea-ice thickness.
- The observations assimilated consist of sea surface temperature retrievals, temperature and salinity profiles from XBT, CTD, Argo, along-track sea level anomalies from the AVISO merged product and sea-ice concentration from NSIDC (CMIP5 prior to 1979). Prior to the Argo period, the model biases are corrected by assimilating 10% of the climatological profiles of temperature and salinity, randomly selected, from WOD09 every 10 days. GEOS5odas-4.0 is available online at http://dp6.nccs.nasa.gov/las/getUI.do
- **GEOS5odas-5.0**
- A revised analysis is currently running, geared towards seasonal forecast. By mid-May 2012 it will span 32 years from 1979 to present. Some of the major changes include:
- Updated static ensemble that uses the 20 leading EOFs of forecast anomalies initialized from GEOSodas-4.0.
- Revised assimilation of sea-ice concentration. Multivariate assimilation of sea level anomalies. Better dynamical balance of the increments
- 
- **Long term goals**
- Consistent atmosphere and ocean analyses by assimilation into the GEOS-5 AOGCM.

# GODAS/NCEP

- Built on MOM3, forced by the NCEP-DOE atmospheric reanalysis, and using a 3dvar data assimilation, remains in operations.
- It runs on a 1-degree quasi-global grid (no Arctic, no ice model) with 40 levels and assimilates temperature and salinity profiles, SST and SSS, and TOPEX-Jason class altimetry.
- The starting date for the reanalysis is 1979.NCEP's new Climate Forecast System v.2 (CFSv2) became operational in March 2011. It couples NCEP's GFS atmosphere with a fully global MOM4p0 at 1/2-degree resolution and 40 levels, an ice model and a land surface model.
- The coupled forecast provides the first guess for data assimilation in the separate atmosphere, ocean and land components. Again, the starting date for CFSv2 reanalysis is 1979.
- Currently in development is a new version of GODAS upgraded to MOM4p1. It is running uncoupled on NCEP's Power6 system and on a Linux cluster where we are validating its performance and testing a method for controlling model bias.
- Also, in collaboration with the University of Maryland, we are developing a new assimilation system for MOM4p1 based on UMD's Local Ensemble Transform Kalman Filter (LETKF).Dave

# SODA

- At Texas A&M we have been working on historical reanalyses. i.e. reanalyses that span the entire 20th Century.

- Complete two historical runs using the conventional SODA framework (i.e. pop model, 25 km resolution in the mid-latitudes, 40 vertical levels):
- SODA 2.2.4 which spans from 1871 - 2010 forced with 20CR ensemble mean forcing. Observations for this run include SST and hydrography, but not satellite data.

- SODA 2.2.6 spans from 1865 - 2010 and is an 8-member ensemble using ensemble member forcing from 20CR. SODA 2.2.6 assimilates only SST data (not hydrography).

- Our future plans include developing OARCA (Ocean Atmosphere Reanalysis for Climate Applications). OARCA is a coupled reanalysis that will span the period from 1845 - present.Ben

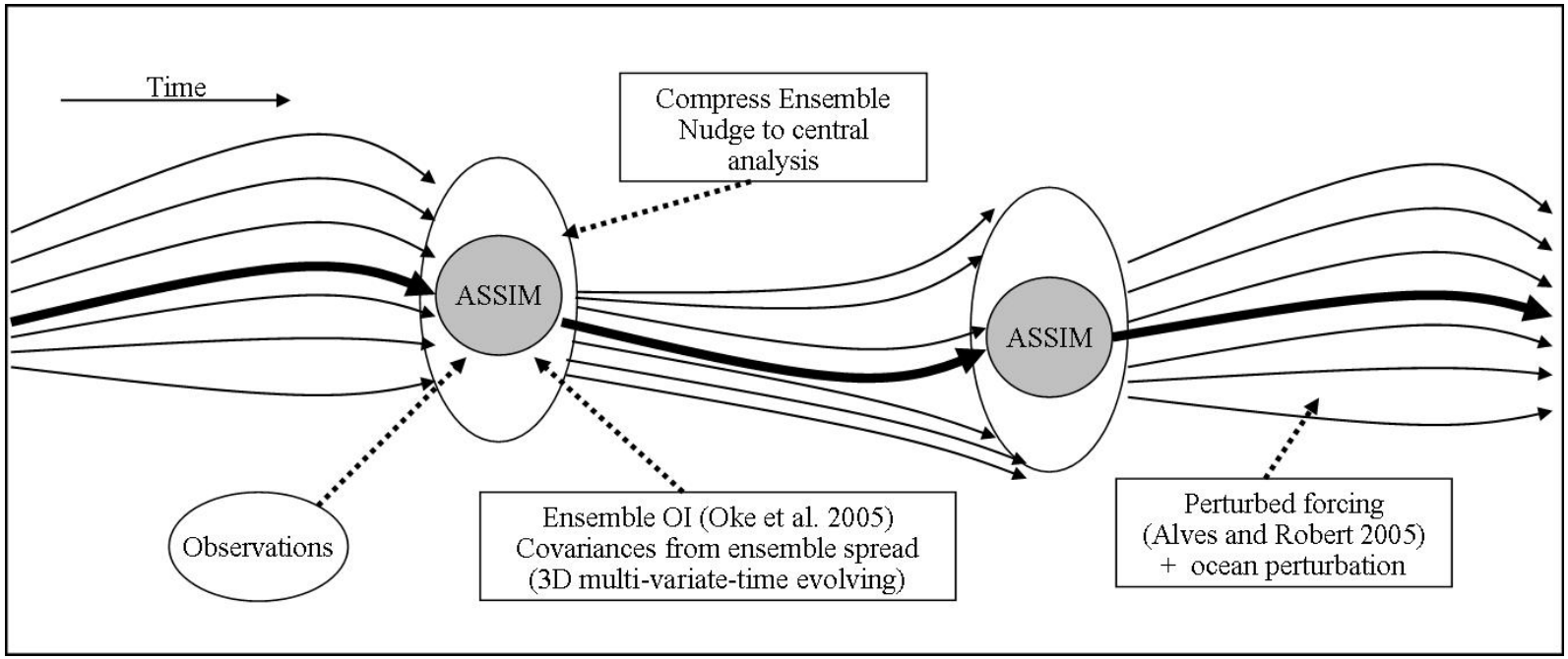
# BOM, AU

- Ensemble Kalman Filter called PEODAS (POAMA Ensemble Ocean Data Assimilation System) for the ocean (Yin et al 2011 MWR) which is now run operationally for our seasonal predictions (http://poama.bom.gov.au).

- Around this we have developed a coupled breeding technique that generates coupled bred vectors to perturb the ensemble forecasts. We have generated a re-analyses from 1960-present.

- We have now converted PEODAS into a semi coupled assimilation where an ensemble of coupled models is run, but assimilation still takes place separately for the ocean and atmosphere, but coupled pertubations are generated and these coupled perturbations are also used to generated the covariances for the EnKF.

# PEODAS (Yin et al 2011)




Pseudo Ensemble Kalman Filter – (Based on extension of BLUElink system; Oke et al)

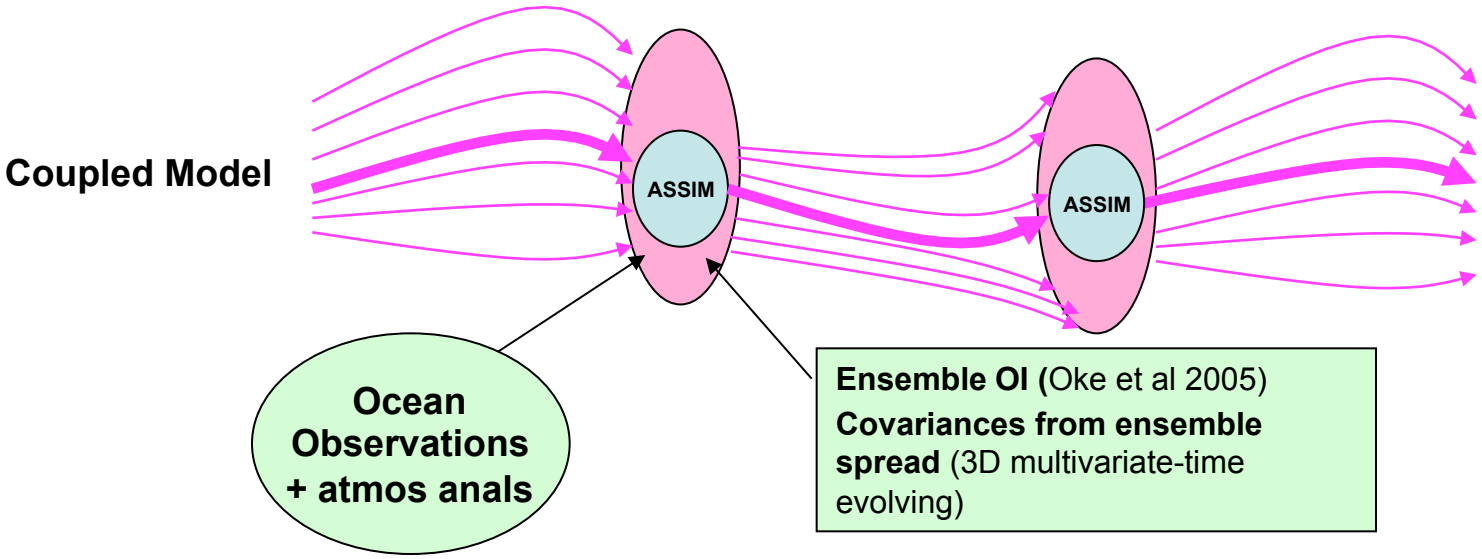
11 member ensemble but used lagged set for covariances (100 member)

Compression to central rather than assimilation into each

Constant background/obs error ratio (not using ensemble)

Background covariance only used from ensemble

# Coverting PEODAS to Fully Coupled Assimilation




- Assimilate ocean obs and atmos re-analyses
- Cross-covariances between ocean and atmos (&ice & land)
- Initial version ocean and atmosphere assimilation separate
- This will be done with the next version of our model based on UKMO UM coupled to MOM4

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