Introduction to the Estimating the Circulation and Climate of the Ocean (ECCO) project

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Origins of ECCO

In the 80's and the 90's, several major world-wide efforts to observe the global ocean were initiated, including the World Ocean Circulation Experiment (**WOCE**), the Tropical Ocean Global Atmosphere (**TOGA**) program, the Joint Global Ocean Flux Study (**JGOFS**), and the launch of the **TOPEX/Poseidon** satellite altimeter in 1992.

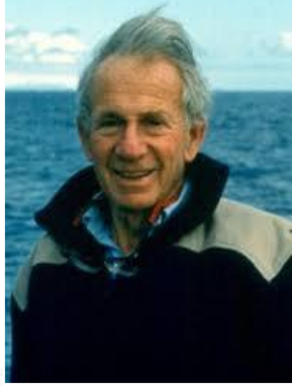
But the most important consequences of the ocean for climate, e.g., transports of heat and energy, the uptake of carbon from the atmosphere, and interactions with sea ice and ice sheets are not directly measurable.

Furthermore, the set of available ocean observations is extremely diverse, including in situ observations of temperature, salinity, velocity, and biogeochemical properties, and satellite-based observations of sea level, temperature, wind stress, etc.

These observations are connected to each other and to the desired derived quantities via the equations of fluid dynamics.

For understanding of the present-day climate, the extent to which it is changing, the places in which nutrients are being moved, and a host of other scientific questions, we need systematic syntheses of the observations with our best understanding of the physical principles determining ocean circulation.

An early vision of ocean state estimation from Wunsch (1982) in honor of Munk’s 65th birthday



Acoustic Tomography and Other Answers

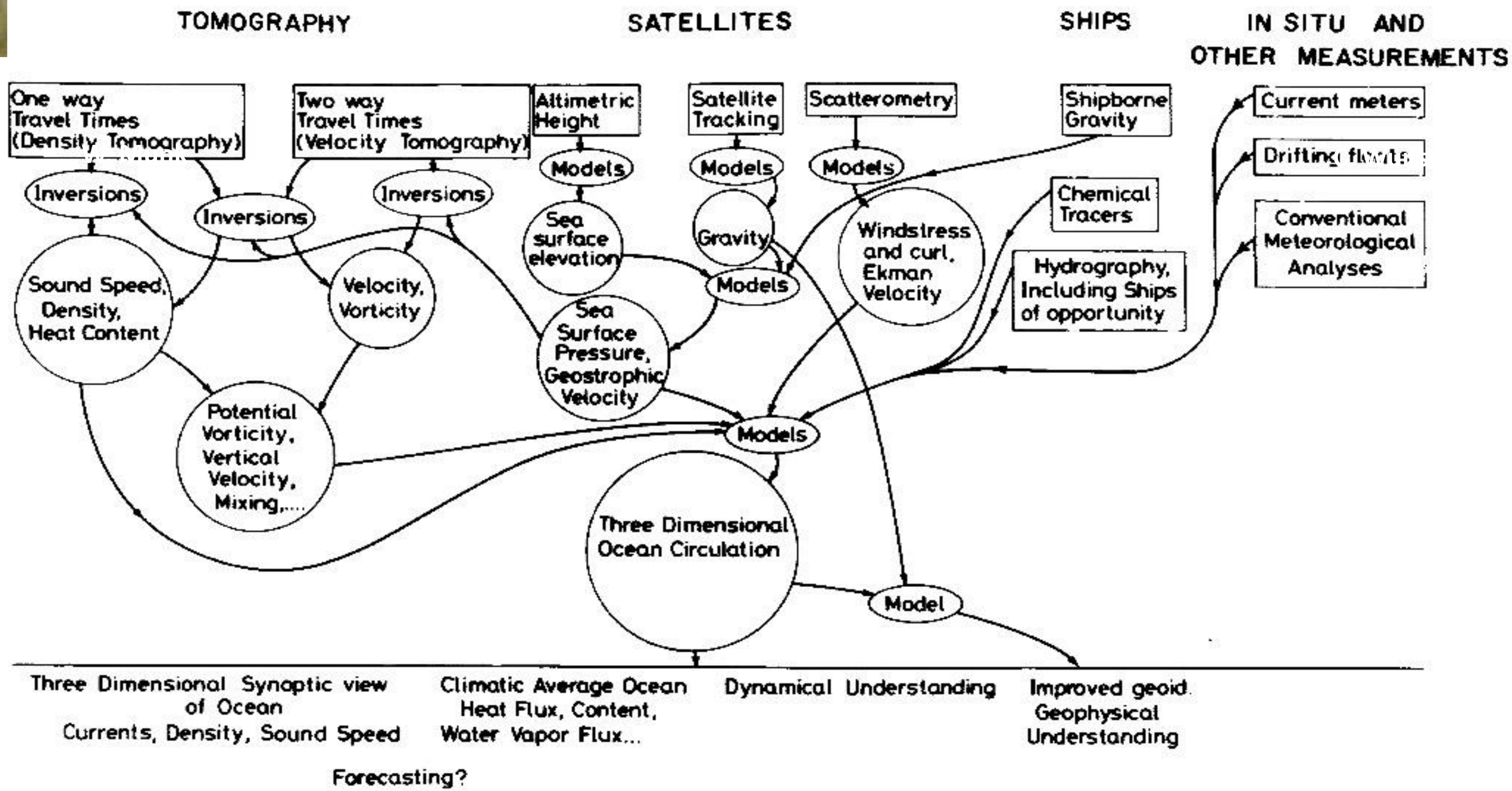


Figure 26. All measurements and models of the ocean can be interconnected to provide global estimates of the state of the three-dimensional ocean. Some side benefits accrue — e.g. improved estimates of the earth's gravity field.

June 1999: A Consortium for Ocean Circulation and Climate Estimation
National Ocean Partnership Program (NOPP) proposal led by Detlef Stammer

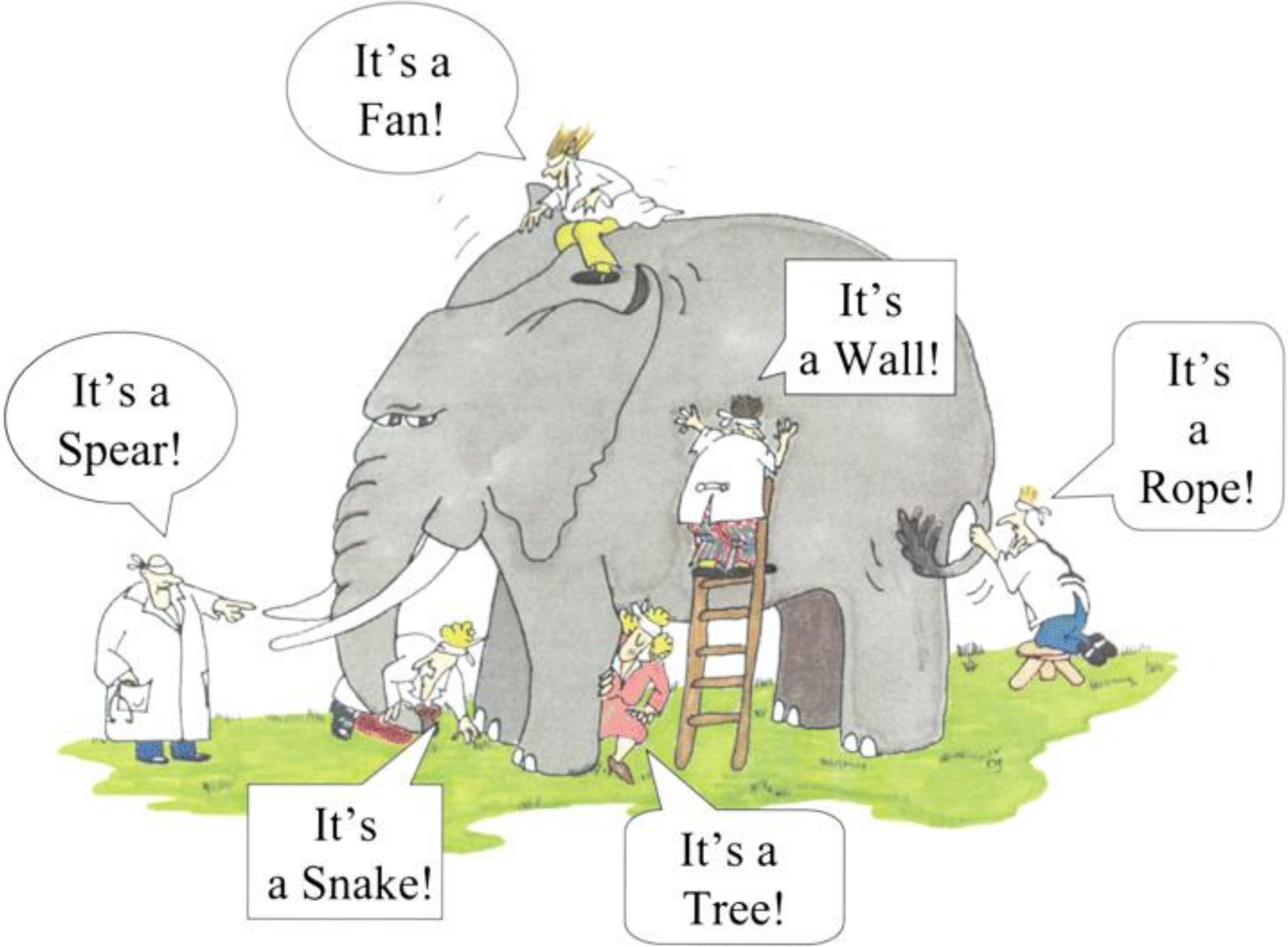
A consortium of scientists at the Massachusetts Institute of Technology, the Jet Propulsion Laboratory, the Scripps Institution of Oceanography, and the Max Planck Institut für Meteorologie of Hamburg proposes a five-year NOPP "node" to bring ocean state estimation from its current experimental status to a practical and quasi-operational tool for studying large-scale ocean dynamics, designing observational strategies, and examining the oceans role in climate variability.

August, 1999: First ECCO Consortium Meeting at Scripps Institution of Oceanography

A consortium name was discussed. D. Stammer presented a straw man **OCCE** (Ocean Circulation and Climate Estimation), taken from title of proposal. The later suggestion of **EGOS** (Estimation of the Global Ocean State) was rejected in favor of OCCE. However, there was a suggestion after the meeting (C. Eckert) to change OCCE into: **ECCO** (Estimation of the Circulation and Climate of the Ocean). The consortium voted for ECCO after the meeting.

The ECCO acronym soon morphed to:
"**Estimating the Circulation and Climate of the Ocean**".

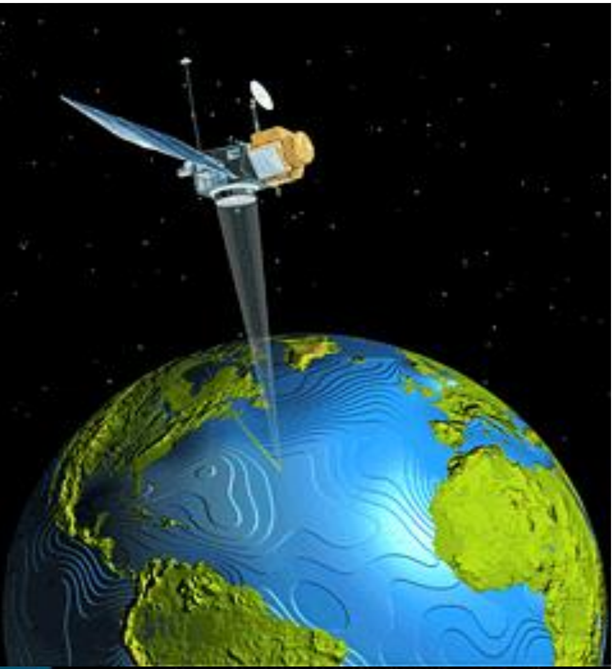
Observing the ocean is like blind men observing an elephant.

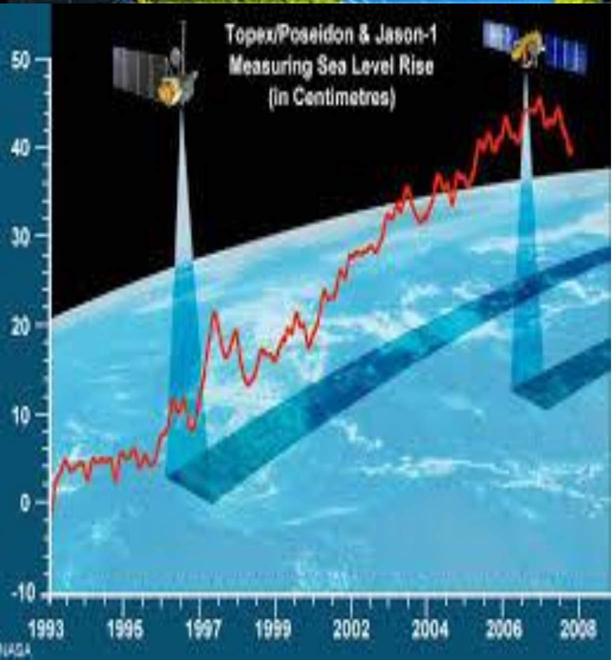


Strengths and limitations of in-situ observations

- ❖ **Closest to ocean truth ☺**
- ❖ **… but very limited spatiotemporal coverage ☹**
  - ➢ point measurement in time and space is not necessarily representative of large-scale, long-period average
  - ➢ contamination by geophysical and instrument noise
  - ➢ possibility of aliasing

Strengths and limitations of satellite observations



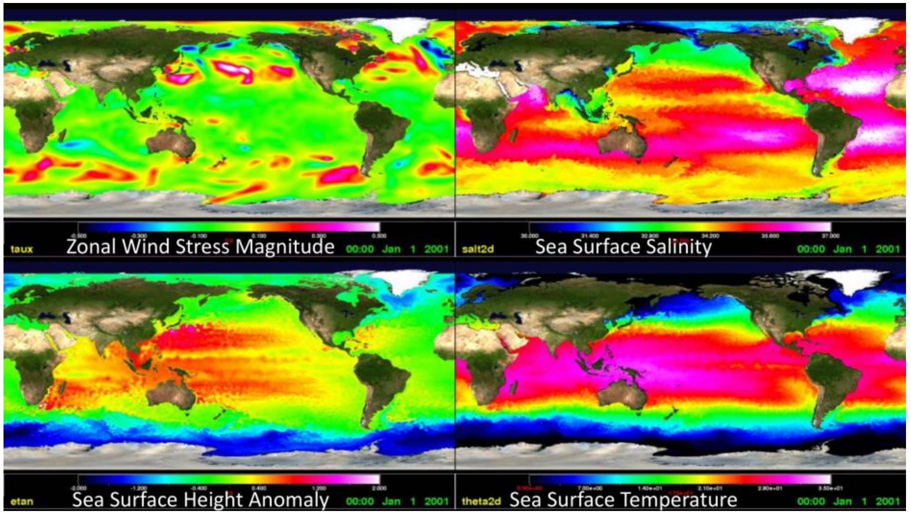


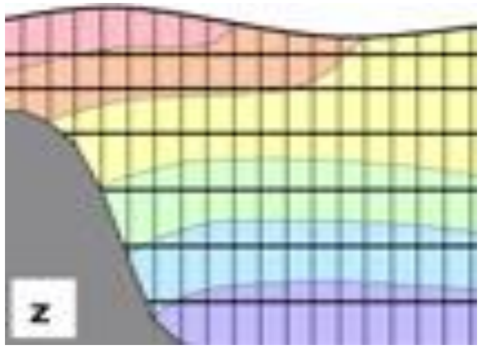
- **Global coverage ☺**

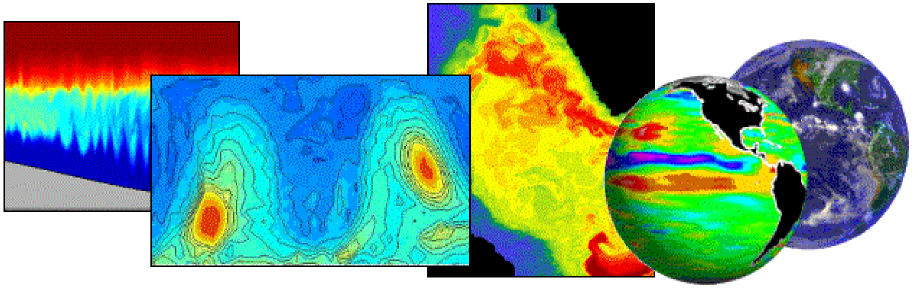
- **… but indirect observation of limited oceanographic variables ☹**

  - limited to near-surface or depth-integrated observables
  - errors due to, e.g., atmospheric variability and retrieval algorithms
  - sampling issues due to, e.g., footprint size and episodic sampling

Strengths and limitations of numerical models







- ❖ **Complete space-time description ☺**
- ❖ **… but imperfect representation of truth ☹**
  - ➢ discretization errors
  - ➢ subgrid-scale parameterization errors
  - ➢ boundary condition errors

How can we get a description of global ocean circulation that is as complete and as close to truth as possible?

1. Observe ocean circulation using satellite and in-situ instruments.

2. Construct numerical ocean models based on primitive equations and empirical parameterizations.

3. Use the observations to improve the numerical ocean circulation model and to adjust empirical parameterizations and boundary conditions.

4. Make practical and scientific predictions.

5. Acquire new observations to evaluate and constrain model predictions.

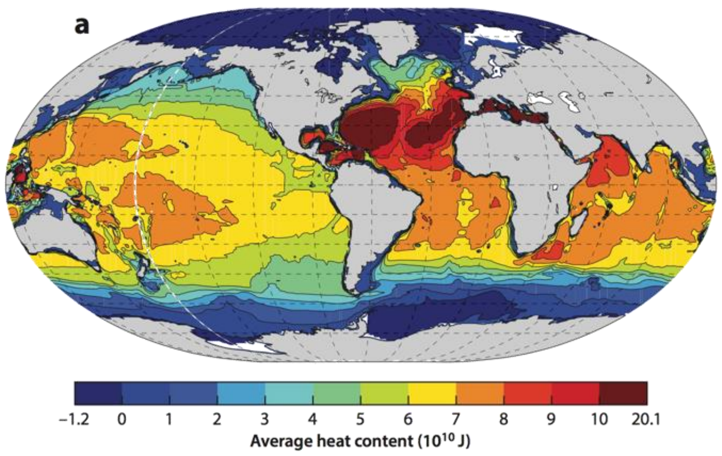
ECCO PRODUCTS AND TOOLS

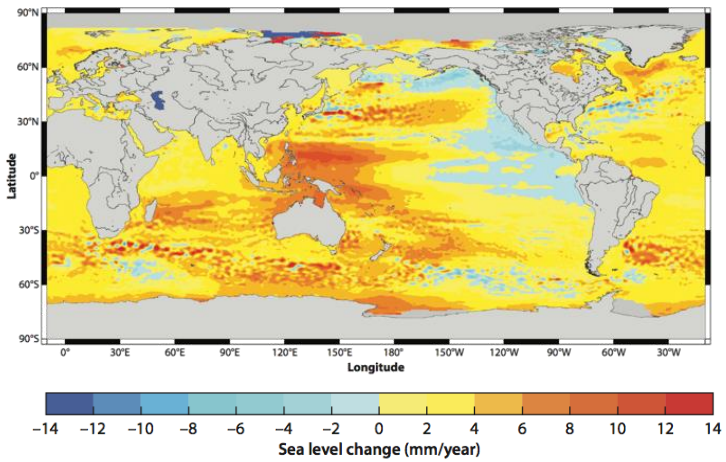
- *The “Estimating the Circulation and Climate of the Ocean” (ECCO) consortium endeavors to produce the best possible estimates of ocean circulation and its role in climate.*
- ***Solutions are obtained** by combining state-of-the-art ocean circulation models with global ocean and sea-ice data in a physically and statistically consistent manner.*
- ***Products are being utilized** in studies on ocean variability, biological cycles, coastal physics, water cycle, ocean-cryosphere interactions, and geodesy*

$$J = \sum_{t=0}^{t_f} (y_t - \Gamma_t x_t)' P_t (y_t - \Gamma_t x_t)$$

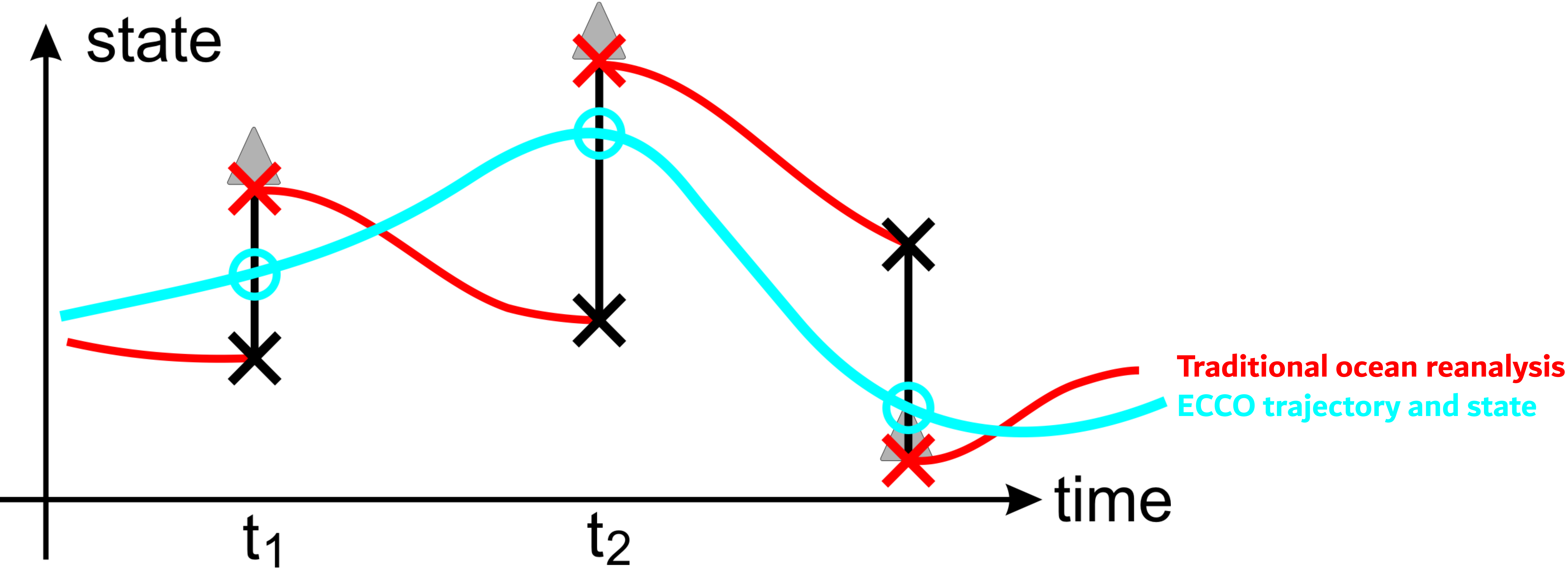
$$L = J(x_{[0,t_f]}) + \sum_{t=0}^{t_f-1} \lambda_t' \left(x_{t+1} - M(p_t, x_t)\right)$$

$$\lambda_0 = \sum_{t=1}^{t_f-1} \left\{ A_1' A_2' \cdots A_t' G_{t+1} \right\} + G_1$$





ECCO state estimates are ***physically-consistent*** *solutions of free-running models that are made* ***consistent with observational data*** *and their uncertainties.*



Inverse problem:

Solve for a set of *model initial conditions*, *atmospheric boundary conditions*, and *ocean mixing parameters* such that residuals between the **model solution** and the **observations** are minimized in a least-squares sense.

Automatic differentiation tools developed and used by ECCO

TAMC and TAF

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TAF: Transformation of Algorithms in Fortran

OVERVIEW:

TAF is a source-to-source translator for Fortran 77-95 code, i.e. TAF accepts Fortran 77-95 code as input, applies a semantic transformation, and generates Fortran 77-95 code as output. TAF supports several semantic transformations. The most important one is Automatic Differentiation (AD), i.e. generation of code for evaluation of the first-order derivative (Jacobian matrix). This generated code can operate in forward or reverse mode (tangent linear or adjoint model). TAF can generate code to evaluate Jacobian times vector products or the full Jacobian. Higher order derivative code is generated by applying TAF multiple times.

Another TAF transformation is Automatic Sparsity Detection (ASD), i.e. efficient determination of the sparsity structure of the Jacobian matrix. This transformation is important, because the Jacobian's sparsity pattern can be exploited to render the evaluation of the Jacobian more efficient.

HIGHLIGHTS:

Analyses:
TAF normalises the code and applies a control flow analysis. TAF applies an intraprocedural data dependence and an interprocedural data flow analysis. Given the independent and dependent variables of the specified top-level routine, TAF determines all active routines and variables and produces derivative code only for those.

Directives:
TAF accepts several kinds of directives. Using the reverse mode automatic storing/reading of required values is triggered by directives. Multi level checkpointing can be generated by splitting a loop and inserting directives. Generating memory efficient adjoint code for iterative solvers can be triggered by inserting a directive. Black box (library) routines are handled by specifying flow information via directives.

Readability:
TAF generated code is structured an well readable.

Parallelisation:
TAF offers basic support of OpenMP and MPI.

APPLICATIONS:

There are an overview and a list of references for some of TAF's applications.

AVAILABILITY:

TAF is a commercial product. Contact us to obtain a TAF licence.

***Fast*Opt**

http://www.fastopt.com/

OPENAD

Summary

1. Toy Problem
2. Technical Essentials
3. Download Test Binaries
4. Case Studies
5. OpenAD Bibliography
6. Future Plans

Technical Details

- Components Overview
- Why "Open"AD?
- AD Transformation Engine
- XAIF
- Front Ends
  - Fortran
  - C/C++
- Code Analysis
- Documentation
- Getting started
  - Download/Build
  - Testing the Build
  - Use
- Bug Tracking
- OpenAD wiki
- Mailing List

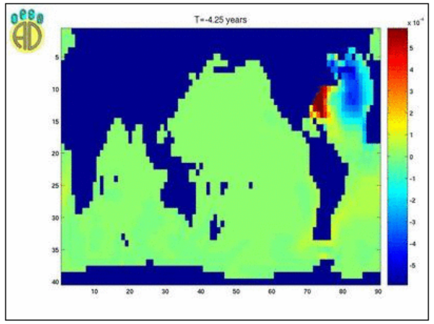
Institutions & Research Projects developing and using OpenAD

OpenAD is a tool for automatic differentiation (AD) of numerical computer programs. The initial development was part of the ACTS (Adjoint Compiler Technology & Standards) project funded by the NSF Information Technology Research (ITR) program. Current research and development is supported by

- ECCO2 under the NASA Modeling, Analysis, and Prediction (MAP) program
- CSCAPES under the DOE (Office of Science) Scientific Discovery through Advanced Computing (SciDAC) program
- Uncertainty Quantification in Geophysical State Estimation (Part I / Part II) under the NSF's ITR program.

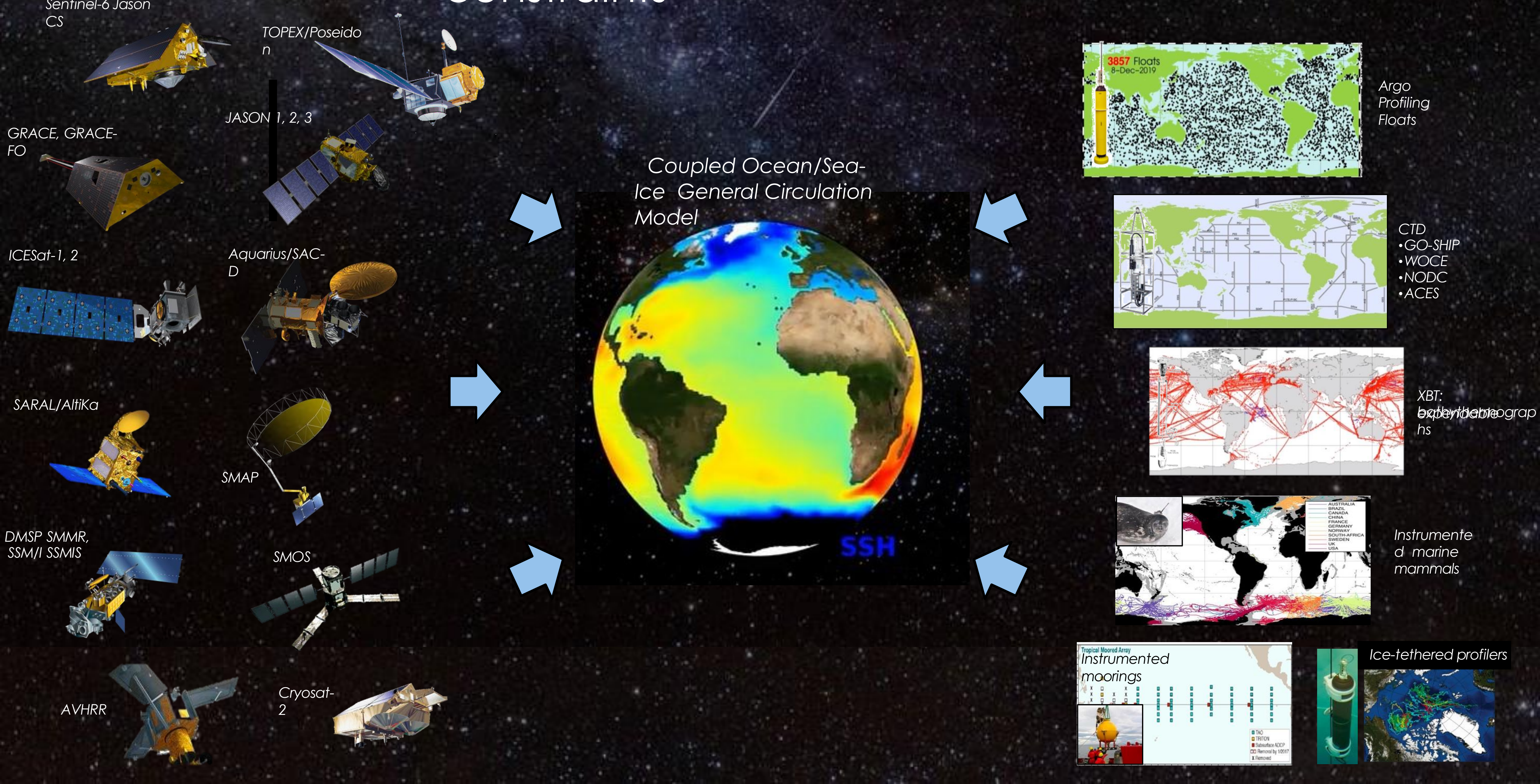
The main goals for OpenAD initially defined for the ACTS project are:

1. Develop a ***flexible, modular, open source*** tool that can ge`nerate adjoint codes of numerical simulation programs,
2. Establish a platform for easy implementation and testing of source transformation algorithms via a language-independent abstract intermediate representation
3. Support for source code written in C and Fortan,
4. Generate an adjoint for the MIT general circulation model. The example on the right (animated gif) shows a sensitivity map of the heat transport in the north atlantic to temperature in a depth of 1590 meters over a period of 10 years going backwards in time. There are also results of a 100 year simulation at three depth levels.



http://www-unix.mcs.anl.gov/~utke/OpenAD/

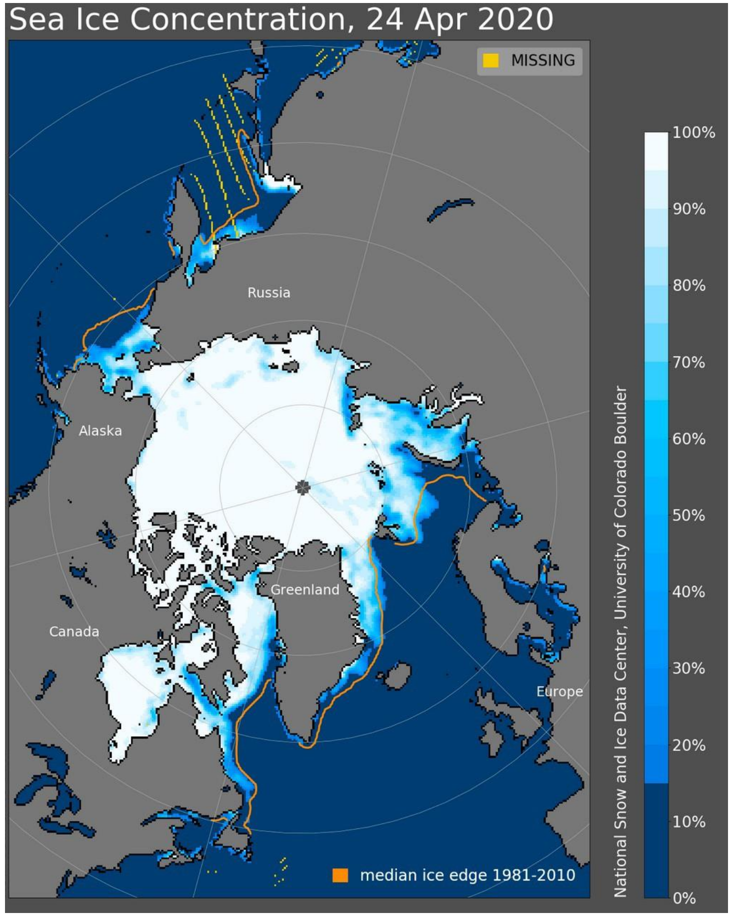
ECCO Version 4 data constraints



Constraining the state estimate to satellite sea-ice concentration data

ECCO V4 now includes an adjointable thermodynamic sea-ice model

- Previous ECCO V4 ocean state estimates included a dynamic/thermodynamic sea-ice model whose adjoint was unstable.
- We incorporated an new adjointable thermodynamic sea-ice model and added daily sea-ice concentration data constraints.
- Experiments demonstrate substantial and rapid reduction of model-data misfit using the new sea-ice model and data constraints



Arctic sea ice concentration. Credit: NSIDC

Constraining the state estimate to Antarctic ice-shelf basal melt data

ECCO V4 now includes a data-constrained thermodynamic Antarctic ice-shelf model

"3 equation" ocean/ice melt model

(1) linearized version of the seawater freezing point

$$T_B = a\underbrace{S_B}_{\text{S dependence}} + b + c\underbrace{p_B}_{\text{P dependence}}$$

+S → -T_b
+P → -T_b

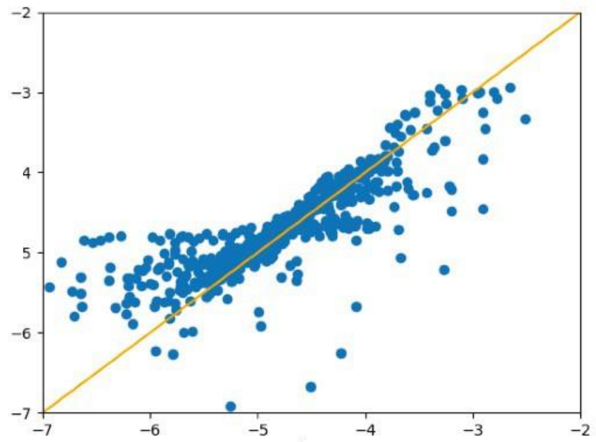
(2) Heat conservation

$$\underbrace{C_{pW}\rho_w\gamma_T(T - T_B)}_{\text{Turbulent heat flux from 'far field' to boundary layer}} + \underbrace{\rho_I C_{pI}\kappa\frac{(T_{ice} - T_B)}{h}}_{\text{Conductive heat flux from boundary layer into ice}} = \underbrace{-L_f q}_{\text{Latent heat flux to melt ice}}$$

(3) Salt conservation

$$\underbrace{\rho_w\gamma_S(S - S_B)}_{\text{Turbulent salt flux from 'far field' to boundary layer}} = \underbrace{-q(S_B - S_{ice})}_{\text{Freshwater flux from melting ice}}$$

Time-mean basal melt rate
Observations vs. New ECCO



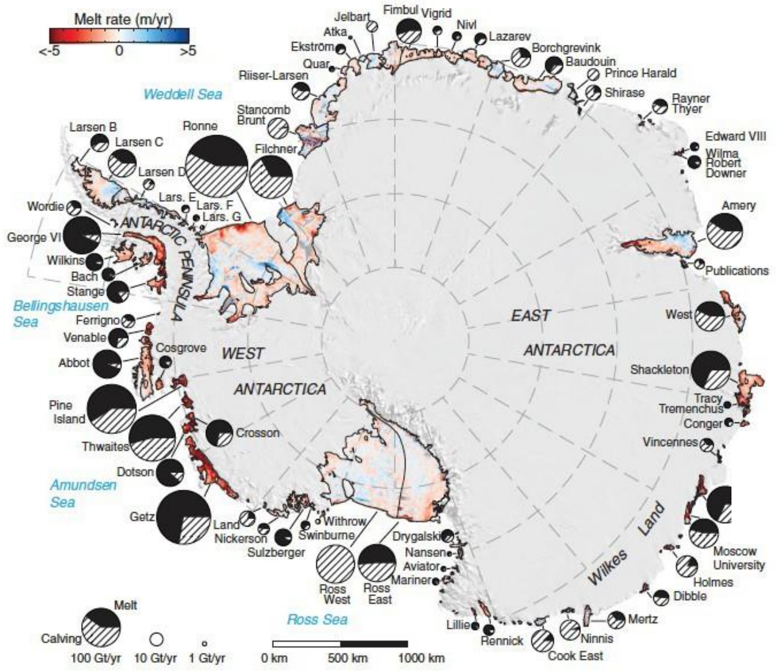
New ECCO

Log10 kg m-2 s-1

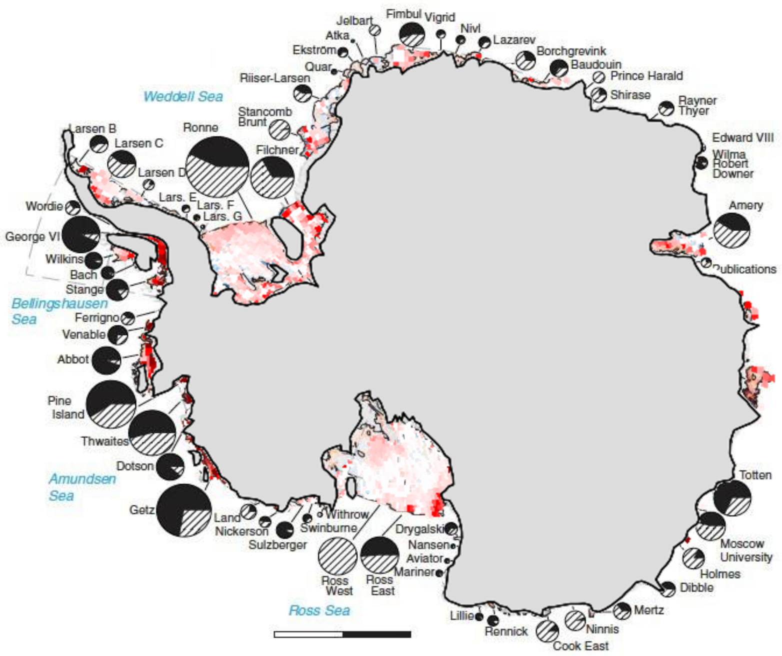
Rignot et al., 2013

Time-mean basal melt rate

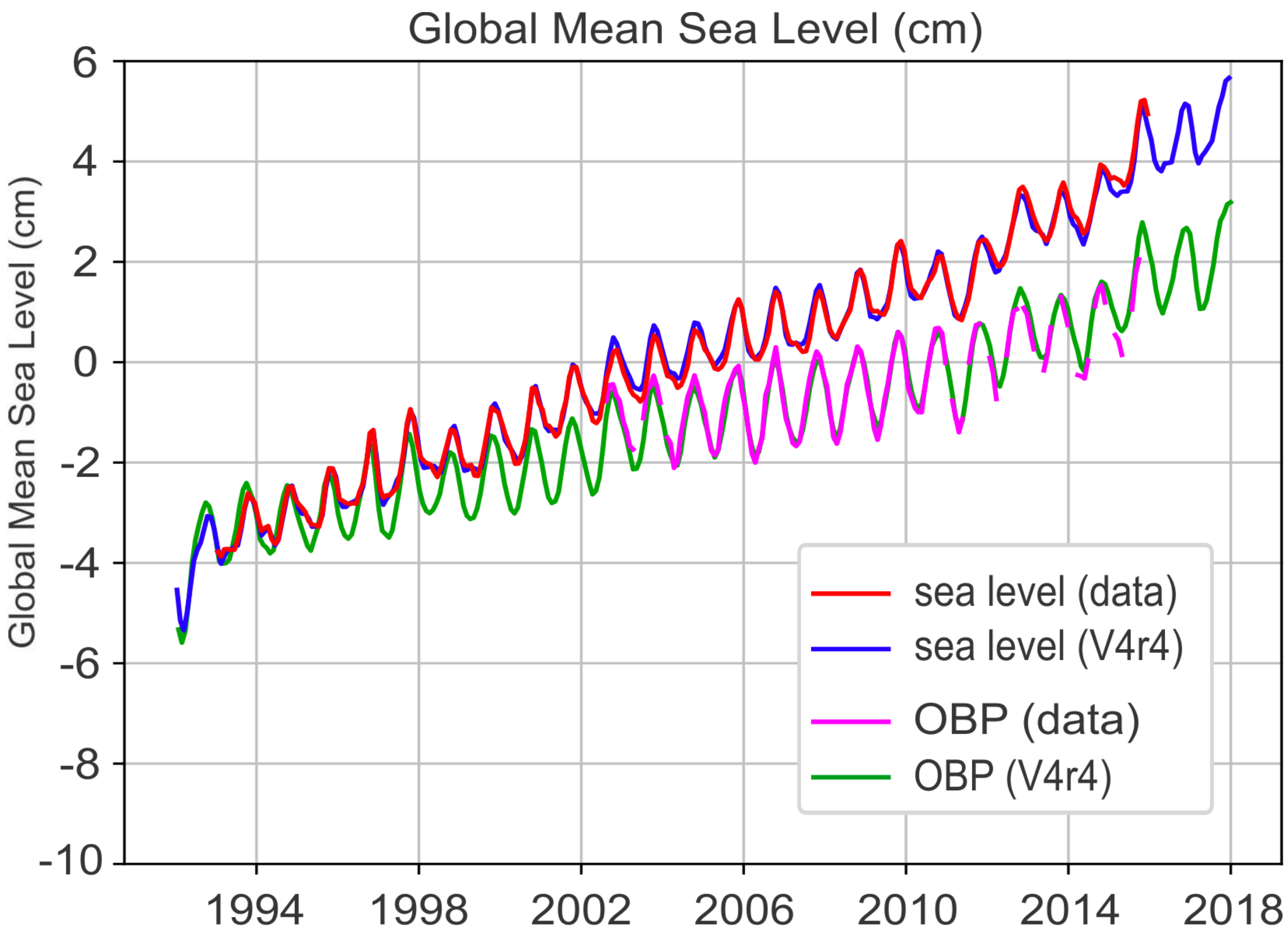
Observations



New ECCO estimate

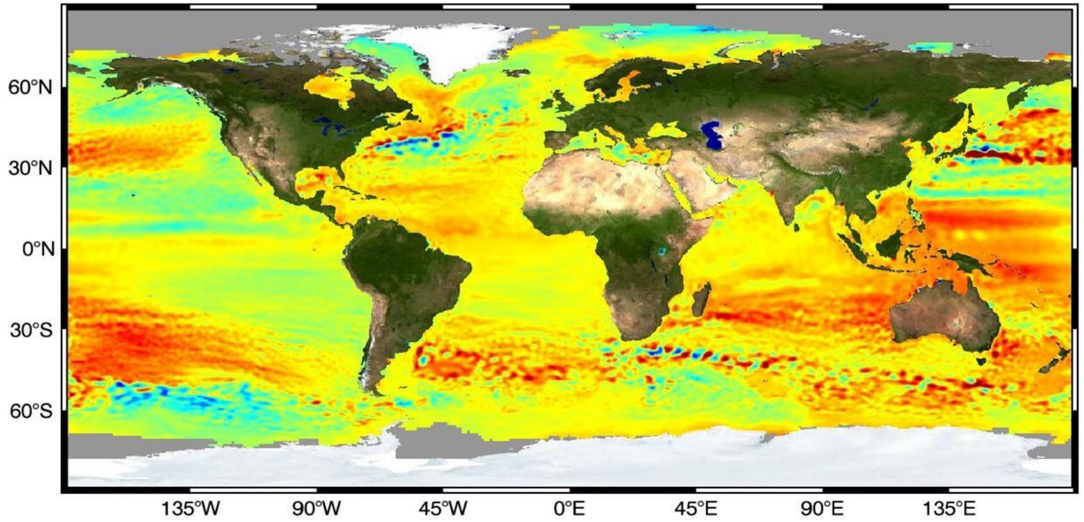


Global Mean Sea Level and Ocean Bottom Pressure Trends: ECCO V4 vs. multi-mission satellite product and GRACE

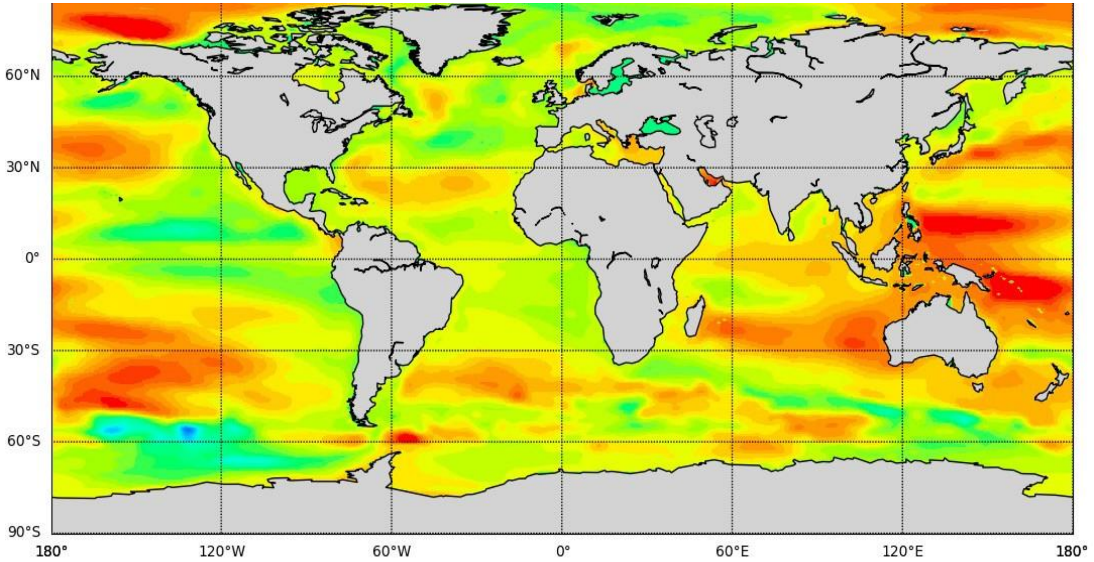


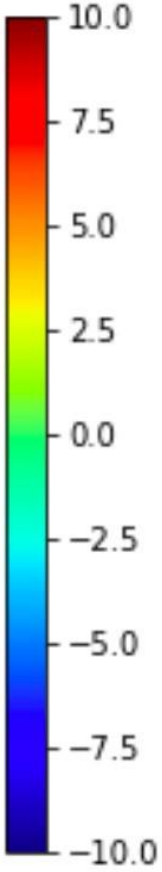
Global Mean Sea Level Trend: ECCO V4 vs. Multi-mission Satellite Product

Multi-mission satellite altimeter product



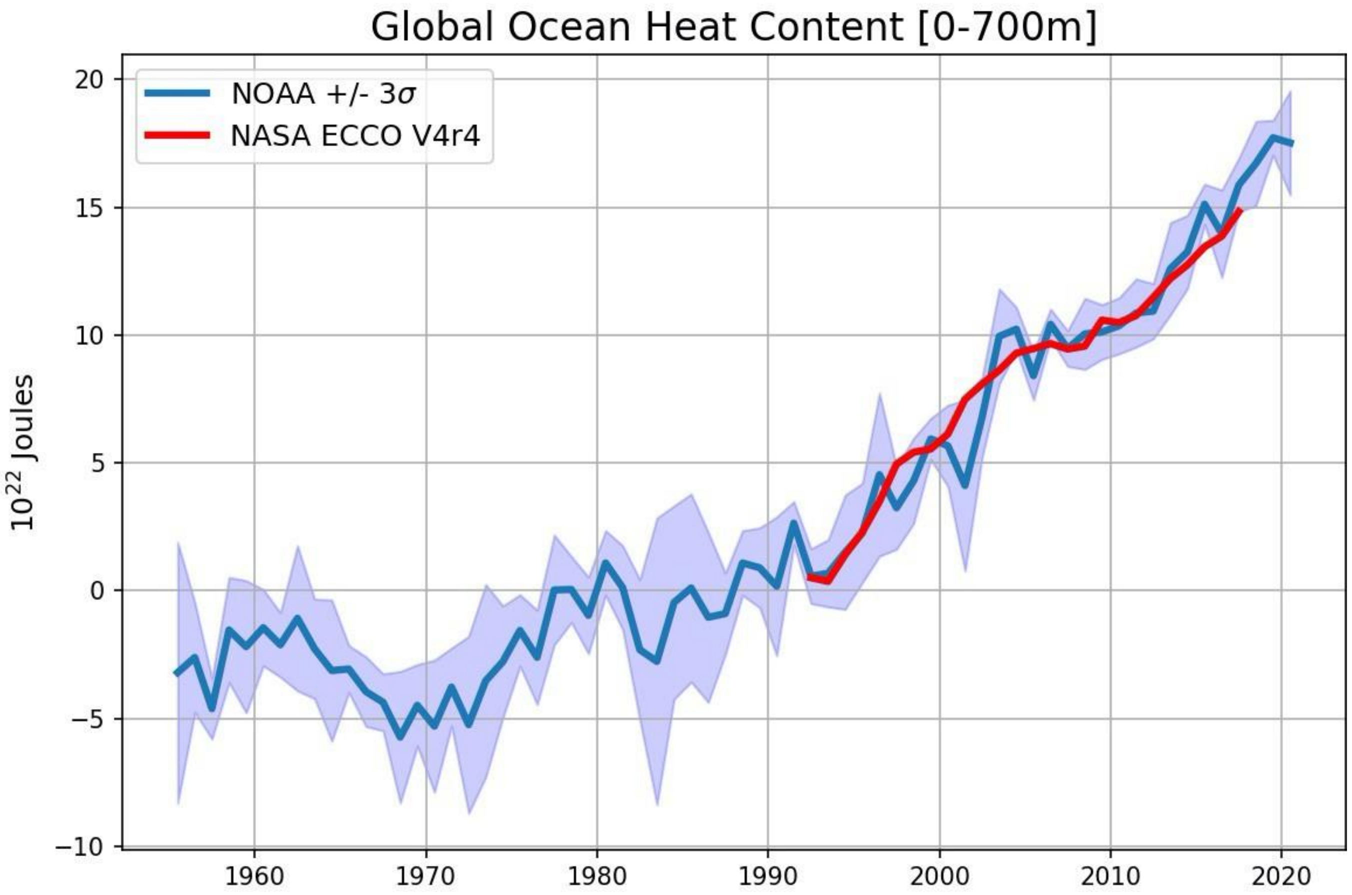
ECCO V4



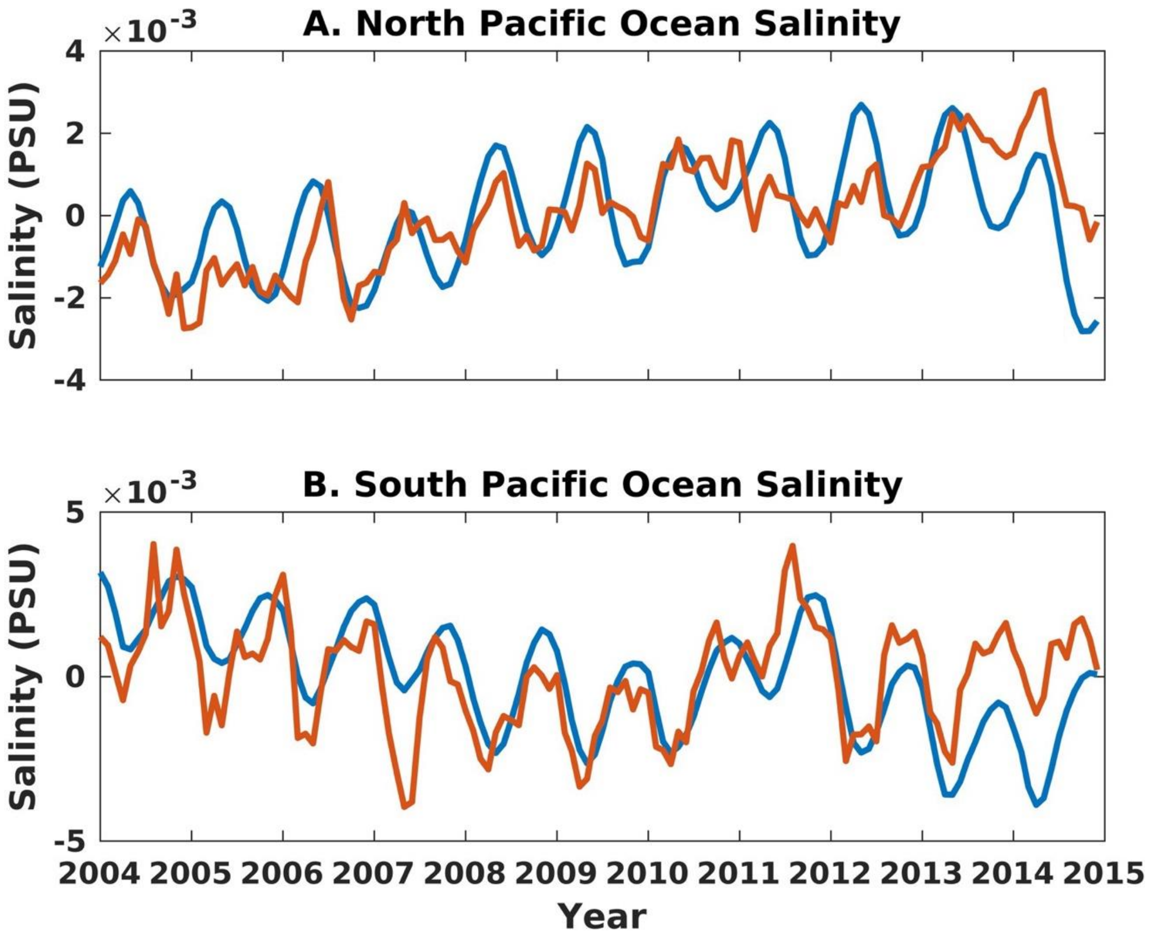


1992-2018

Upper Ocean Heat Content: ECCO V4 vs. NOAA OHC product



Basin-Scale 0-2000m Ocean Salinity: ECCO V4 vs. Argo Hydrography Product



- ECCO Version 4
- Roemmich & Gilson gridded Argo dataset

Courtesy of Chris Piecuch, WHOI

https://ecco-group.org/

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