Current Capabilities of Ocean-Sea Ice Data Assimilation

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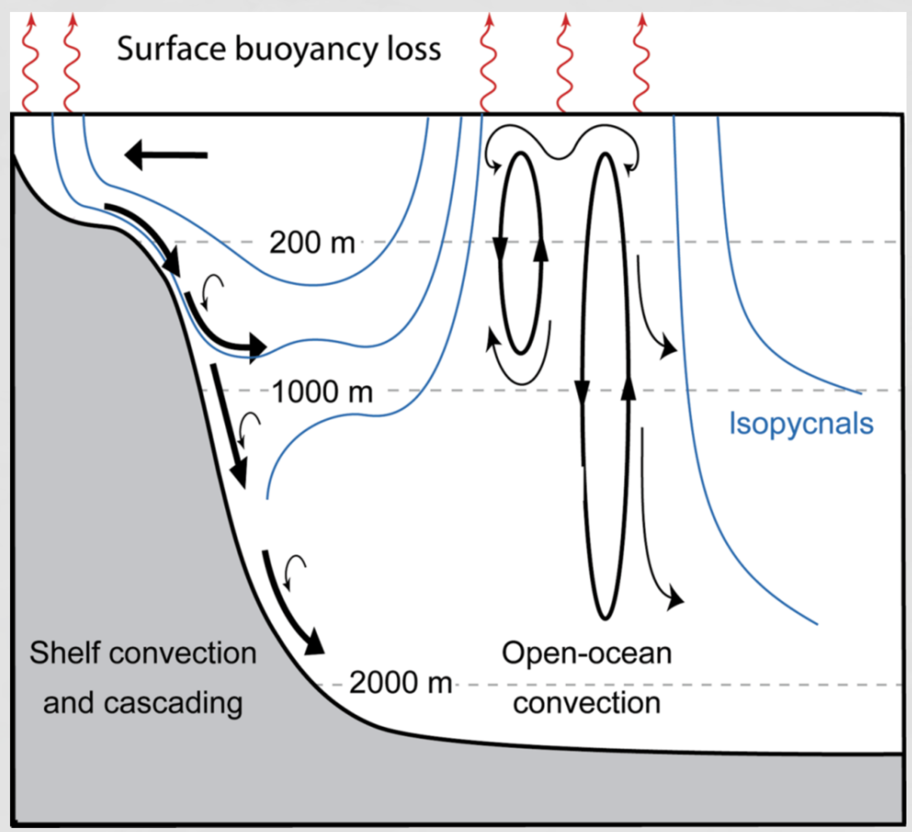
Reconstructing the Earth system for climate studies is challenging due to errors and uncertainties in initial conditions, boundary forcing, model parameterizations, and computational resource limitations.

- Imperfect boundary conditions
  - Surface atmospheric conditions (ABL in MIZ)
- Model Physics and Parameterizations
  - Coupling of sea, and ice components
  - Ice thickness distribution
- Numerical limitations
  - Spatial resolution: eddies, boundary currents, leads in sea ice
- Initial conditions
  - Ice thickness distribution
  - Ocean state

Why do we need to assimilate sea ice observations in coupled ocean-ice models?

- Coupled ocean-sea ice models drift, sometimes severely, even when hydrographic data is assimilated.
- Errors in sea ice representation can generate systematic biases in the surface boundary conditions.



Pusceddu et al. 2010

What are the common challenges associated with coupled ocean-ice data assimilation?

- Poorly known observation and model errors
  - Are observation uncertainties dominated by representation or measurement error?
  - What are their spatial and temporal dependence?
  - Sea ice observation uncertainties are non-Gaussian

- Sparse observations
  - Little in the high-latitude oceans
  - Ice data mainly limited to velocity (except summer) and concentration
  - Few thickness data

- Little-to-no reliable knowledge of covariances (ice-ice and ice-ocean)
  - Ideally, assimilating ice data (e.g., concentration) should improve:
    - ocean state beneath ice
    - other ice state variables (e.g., thickness distribution)
    - ocean and ice state in the vicinity of the observation
  - Covariances are very probably highly variable in space and time

Today’s review of ocean-ice data assimilation is limited in scope.

- Two-way coupled ocean-sea ice models
- The assimilation of **both** ice data (e.g., concentration, velocity) and hydrographic data (e.g., SST, T, S profiles, SSH)
- 5 systems described
  - Forecasting systems (days-seasons)
  - Reanalyses (decadal)
  - State estimates for climate analysis (annual-decadal)

Reviewed Projects

	Project Focus	Ice data assimilated	Assimilation Method	Time Scale
ECCO **MIT JPL**	State estimation + Climate analysis	Concentration (SSM/I)	Adjoint (Ocean + Ice)	Annual-Decadal
ECCO2 **MIT JPL**	State estimation + Climate analysis	Concentration (SSM/I) Velocity (Kwok JPL) Draft (submarine)	Green's Functions (Ocean + Ice)	Decadal
Climate Forecast System Reanalysis (CFSR) **NCEP**	Climate reanalysis Initial conditions for forecasting	Concentration	3DVar (Ocean + Atm) Direct insertion (Ice)	Decadal
FOAM **UK Met Office**	Short-term forecasting	Concentration	Variant of optimal interpolation (Ocean+Ice)	Week
TOPAZ **NERSC + Met.no**	Short-term to seasonal forecasting + Reanalysis	Concentration (AMSR-E) Velocity	EnKF (Ocean + Ice)	Week

Coupled sea ice-ocean data assimilation/state estimation

ECCO ADJOINT SYSTEM

ECCO-GODAE MIT adjoint-based estimation

- Assimilate a large suite of existing in-situ & satellite data using the adjoint method by adjusting prior surface forcing & initial conditions.
- MITOGCM, 1 x1 , 23 levels
- Current product period: 1992-2009

$$J = \sum_{t=1}^{t_f} [\mathbf{y}(t) - \mathbf{E}(t)\mathbf{x}(t)]^{\mathbf{T}} \mathbf{R}(t)^{-1} [\mathbf{y}(t) - \mathbf{E}(t)\mathbf{x}(t)]$$

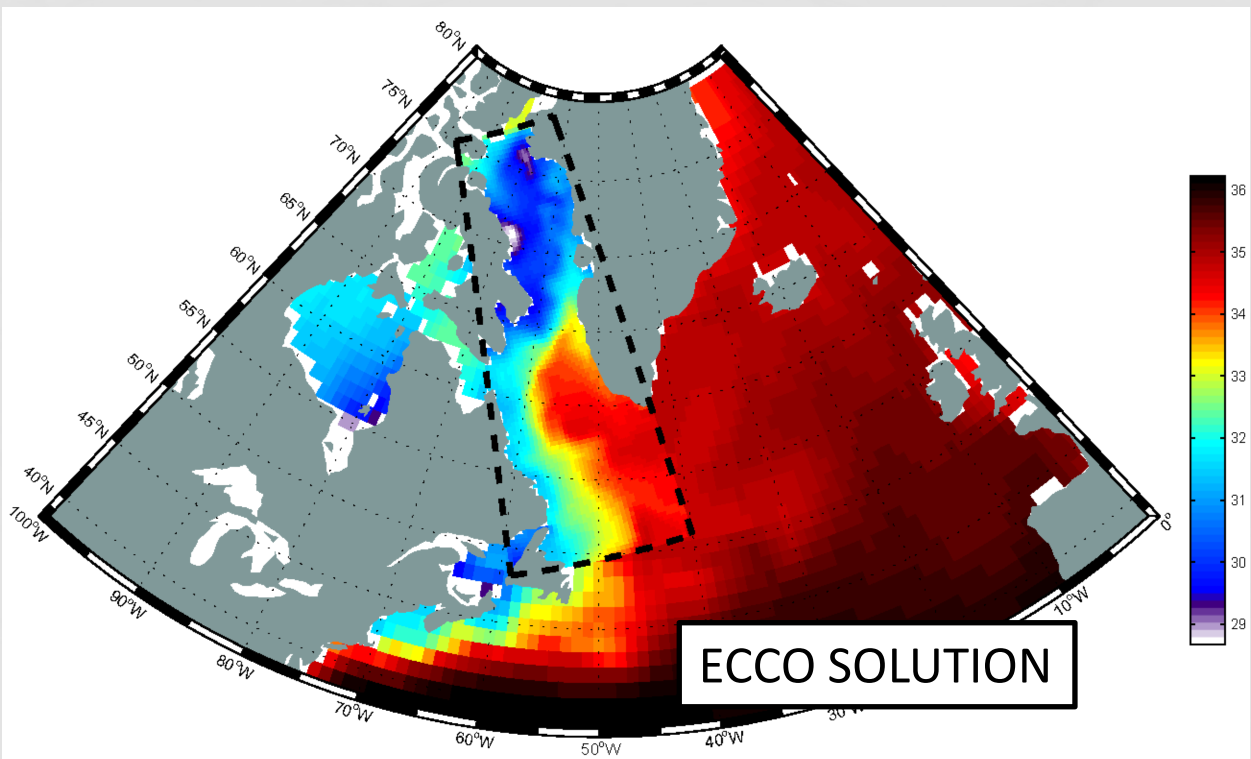
$$+ [\mathbf{x}_0 - \mathbf{x}(0)]^{\mathbf{T}} \mathbf{P}(0)^{-1} [\mathbf{x}_0 - \mathbf{x}(0)]$$

$$+ \sum_{t=0}^{t_f-1} \mathbf{u}(t)^T \mathbf{Q}(t)^{-1} \mathbf{u}(t)$$

DATA CONSTRAINTS
Sea level: Altimetry (TOPEX/Poseidon, JASON-1, GFO, ERS-1/2, ENVISAT)
Sea level: tide gauges
Wind stress: scatterometry (NSCAT, ERS-1/2, QuikSCAT)
SST: AVHRR, TMI on TRMM; AMSR-E on Aqua
T & S climatology (time -mean & seasonal cycle)
T & S: CTD synoptic sections
T profiles: XBTs
T & S profiles: ARGO Floats
Sea surface salinity: in-situ survey
Temperature and velocity: TOGA-TAO mooring array
Temperature & salinity: Elephant seal profiles (experimental)
Geoid: GRACE

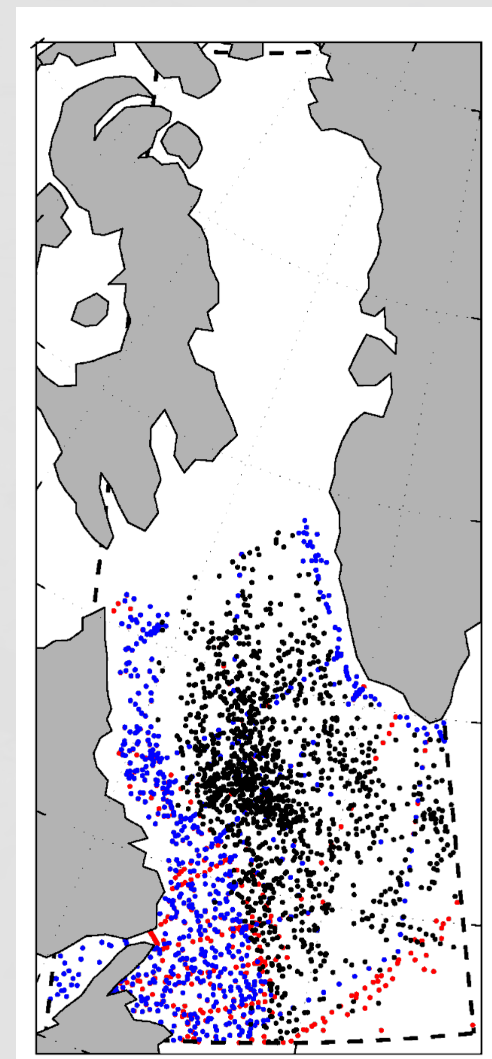
Model Controls: Initial conditions, atmospheric state

The 1/3 degree (32 km) regional model is one-way nested inside the 1-degree ECCO solution.



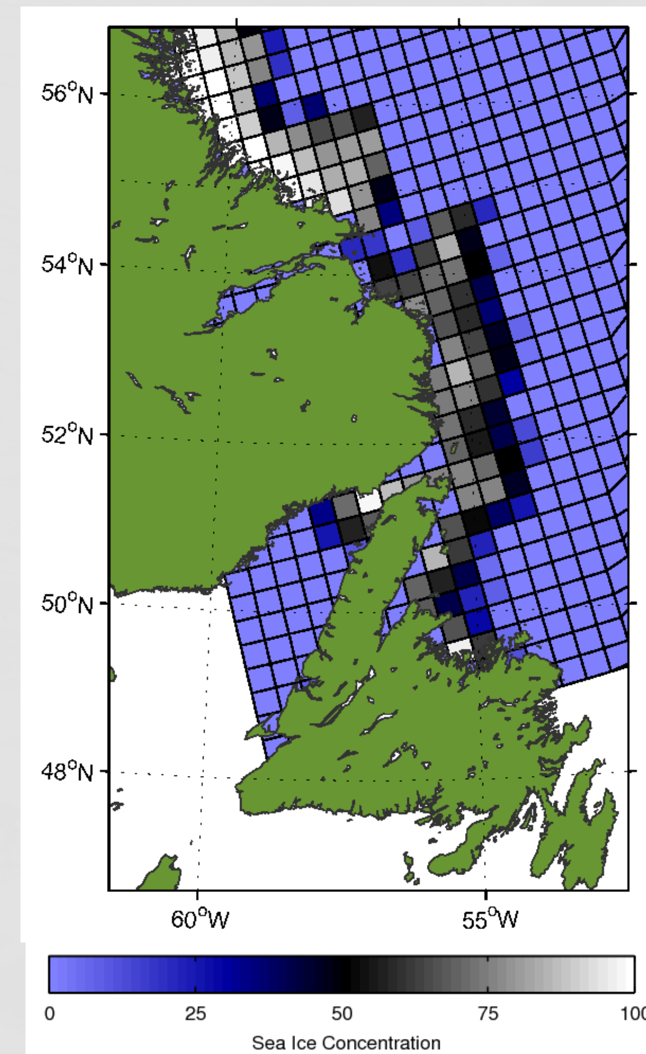
Salinity at 20 m. State Estimate and ECCO solution 3/10/1997

Location of in situ ocean obs, 1996-1997



Blue = Ship-based CTD
Red = XBT
Black = Profiling Floats

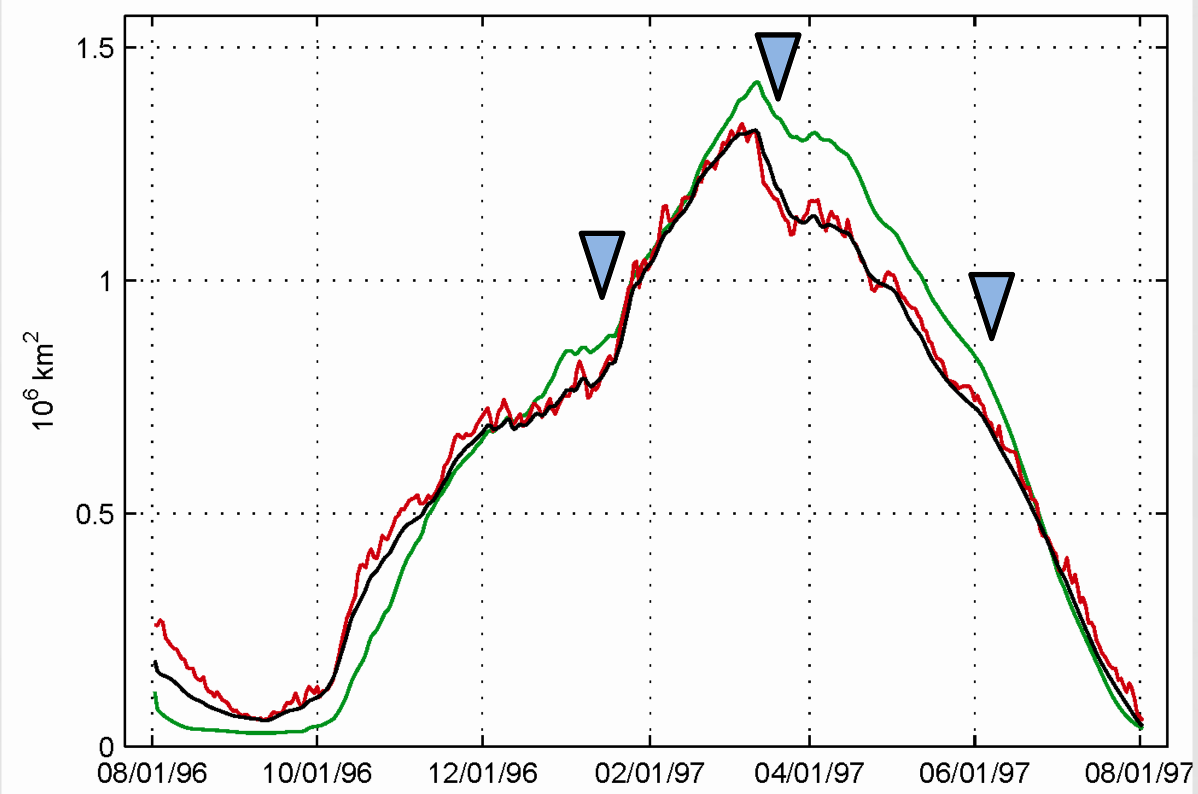
Sea Ice Concentration Data 25 km SSM/I product



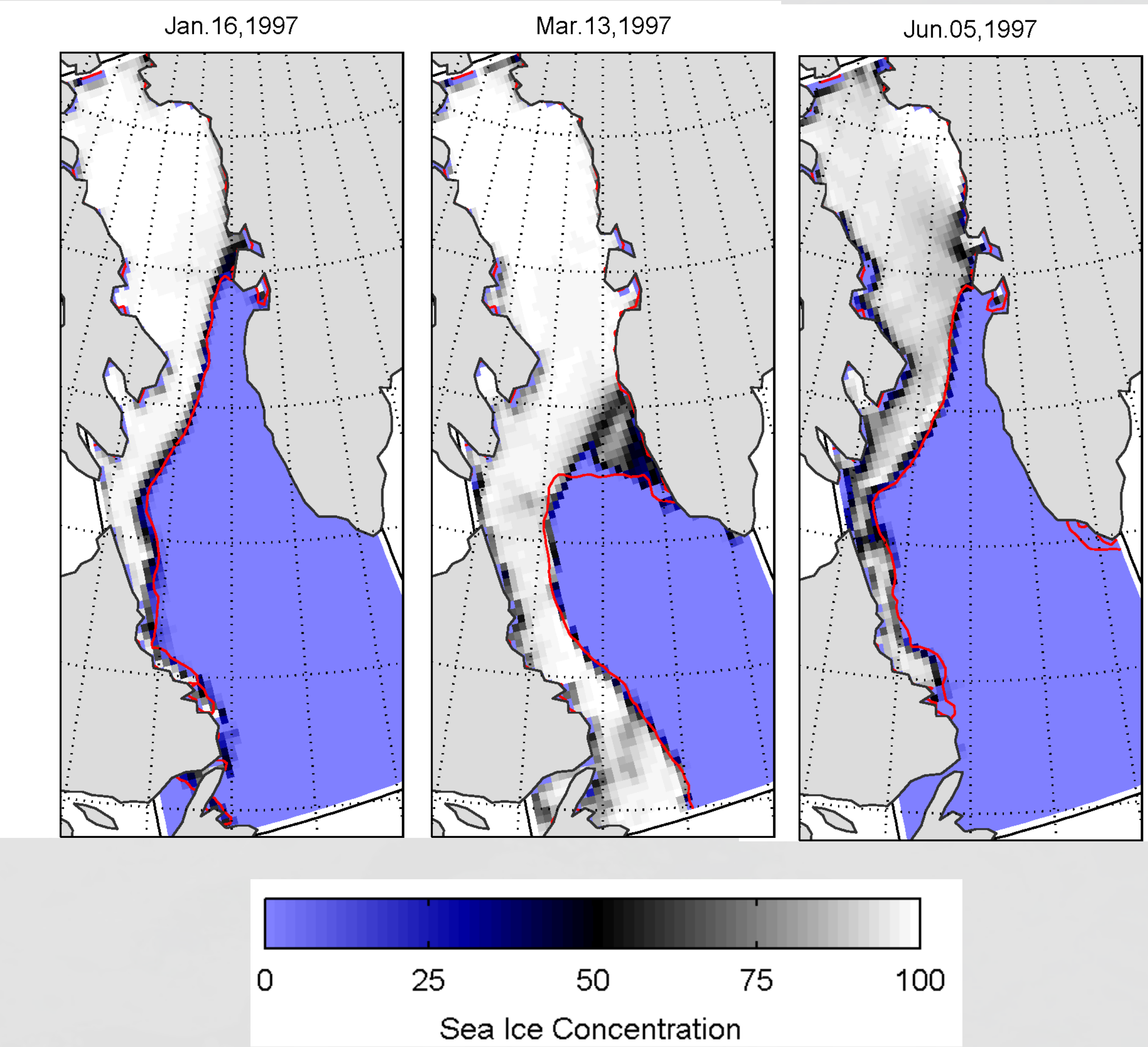
Ice conc. obs uncertainties spatially and temporally variant

The reconstruction of the ice and ocean states were made consistent with observations and their uncertainties.

Total sea ice area



Black: State estimate
Red: SSM/I Observations
Green: First-guess



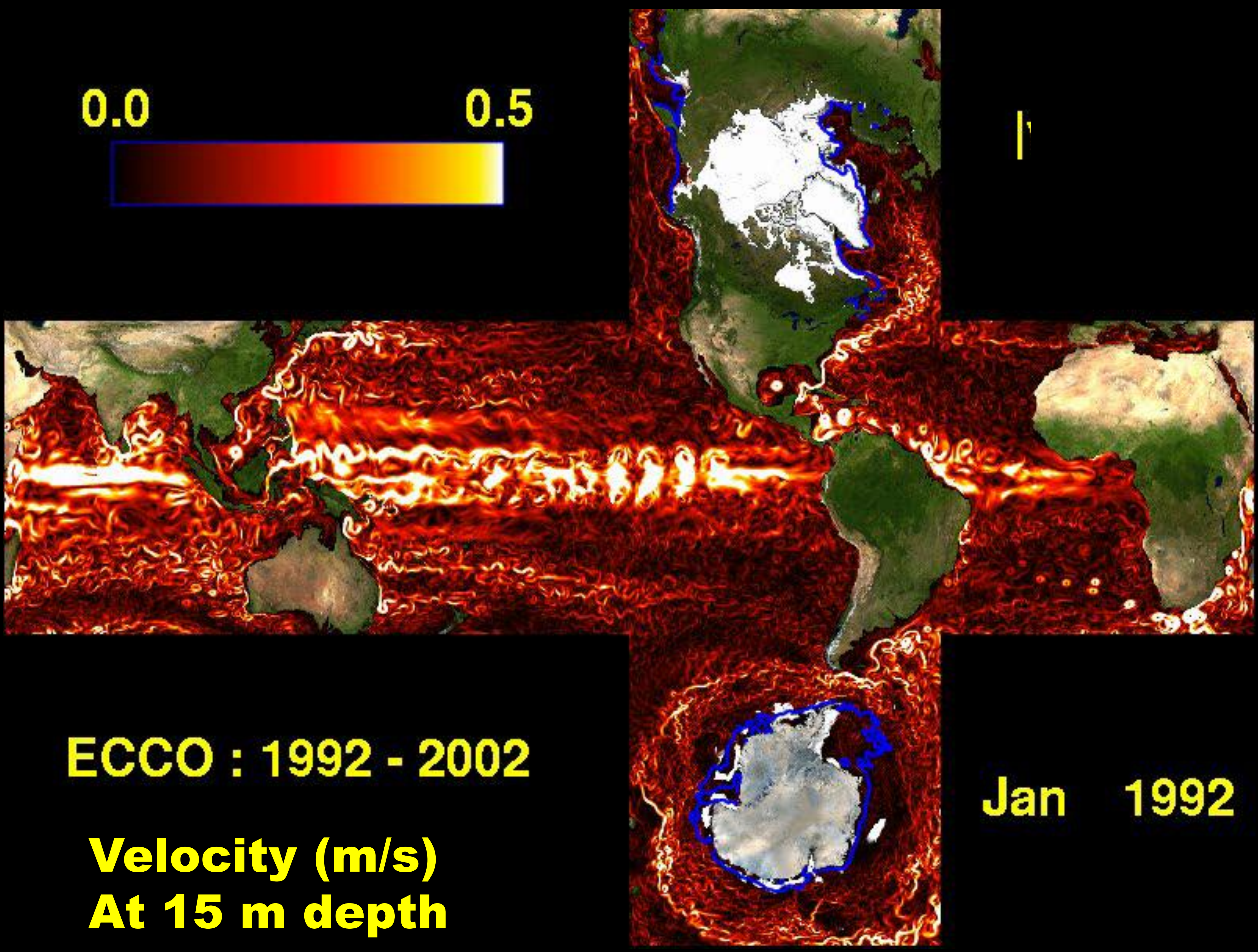
Coupled sea ice-ocean data assimilation/state estimation

ECCO2 GREEN’S FUNCTIONS SYSTEM

ECCO2: High-Resolution Global-Ocean and Sea-Ice Data Synthesis

Objective: synthesis of global-ocean and sea-ice data that covers the full ocean depth and that permits eddies.

Motivation: improved estimates and models of ocean carbon cycle, understand recent evolution of polar oceans, monitor time-evolving term balances within and between different components of Earth system, etc.

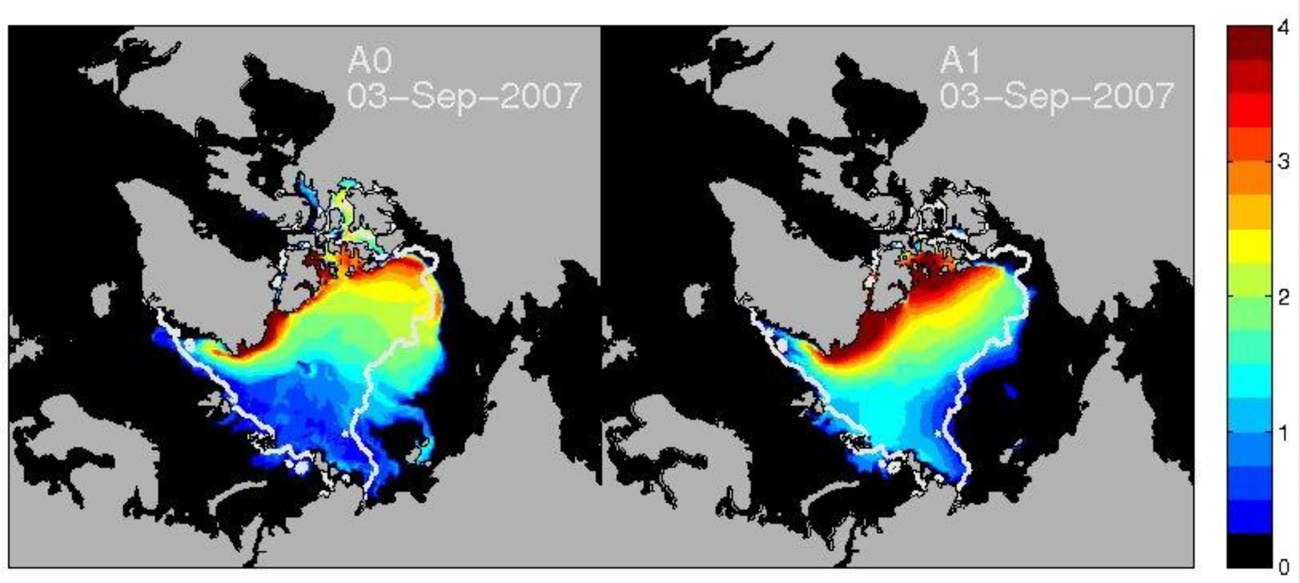


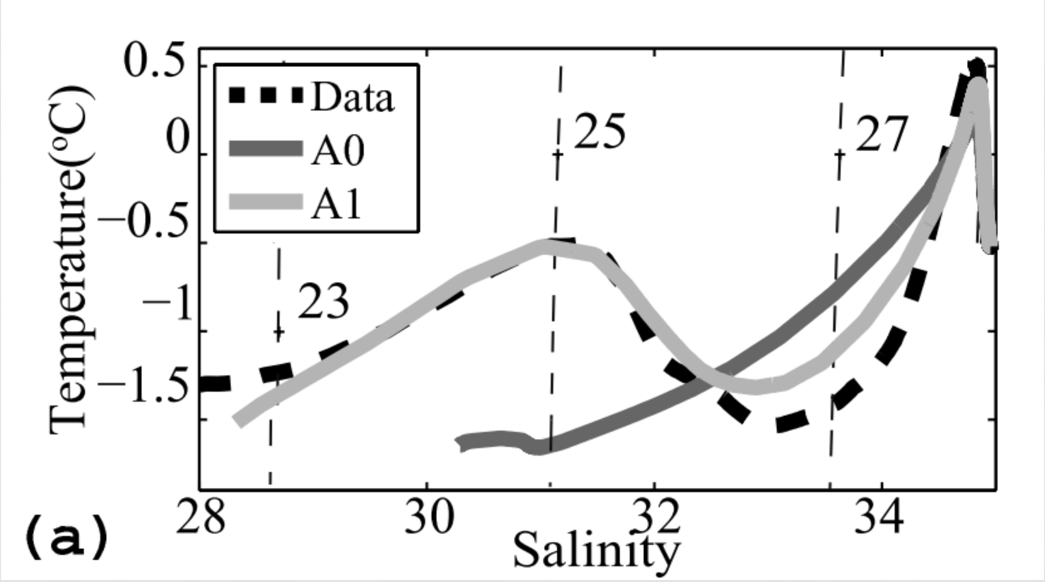
Forward model:

- MITgcm
- cubed-sphere configuration
- 18-km horizontal grid
- 50 vertical levels
- KPP vertical mixing
- dynamic-thermodynamic sea ice

First-guess (A0) model parameters were adjusted to ultimately reduce the model-data misfit cost function in the state estimate (A1).

Parameter	A0	A1
Initial conditions	ECCO2	WOA05
Atmospheric forcing	ECCO2*	JRA25
Ocean albedo	0.1507	0.1556
Sea ice dry albedo	0.8783	0.7
Sea ice wet albedo	0.7869	0.7060
Snow dry albedo	0.9686	0.8652
Snow wet albedo	0.8270	0.8085
Ocean/air drag	1.0185	0.9997
Air/sea ice drag	0.002	0.00114
Ocean/sea ice drag	0.0052	0.0054
Ice strength P^*	2.6780	2.2640
Lead closing H_o	0.5	0.6074
Vertical diffusivity	10^{-5}	5.44×10^{-7}
Salt plume	off	on
River runoff factor	1	1.2472



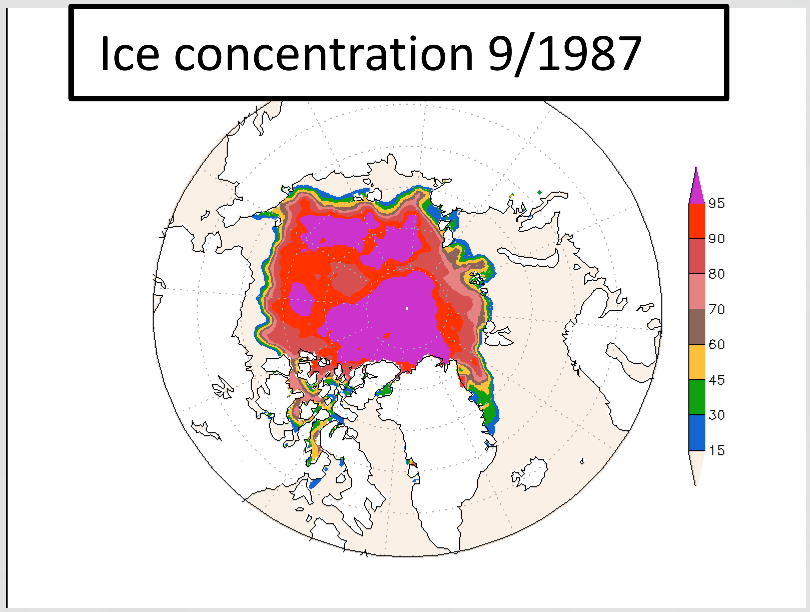


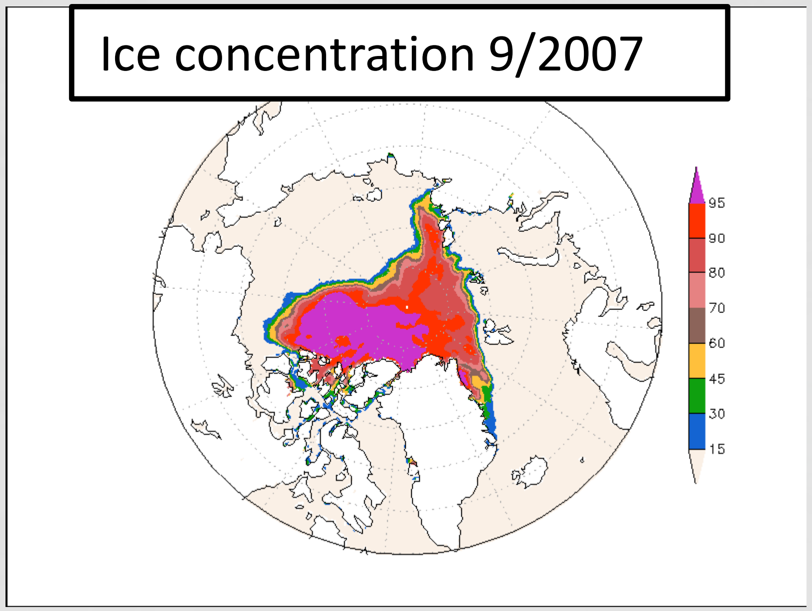
Coupled sea ice-ocean data assimilation

CFSR HYBRID ASSIMILATION SYSTEM

CFSR assimilates ice and ocean obs. in an atmosphere-ocean-land surface-sea ice system.

- 1/4-1/2 degree horizontal res.
- Interactive sea ice model component
  - Ice state freely evolves over forecast step
  - Atmosphere is likely improved in the vicinity of the marginal ice zone
- Direct replacement of ice concentration in analysis step
  - Assumes ice forecast has no skill
  - unless SST analysis is > 273.3 K or observed concentration < 15%
- No explicit ice observation error or background error covariances
  - ice innovation conserves salt when new ice is formed or all ice is removed





Saha et al., 2010

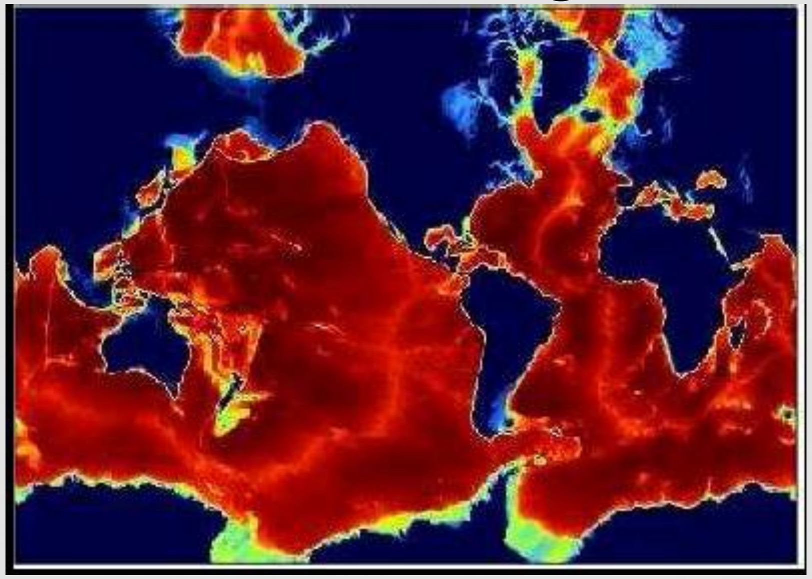
Coupled sea ice-ocean data assimilation for short-term forecasting

FOAM OI DATA ASSIMILATION SYSTEM

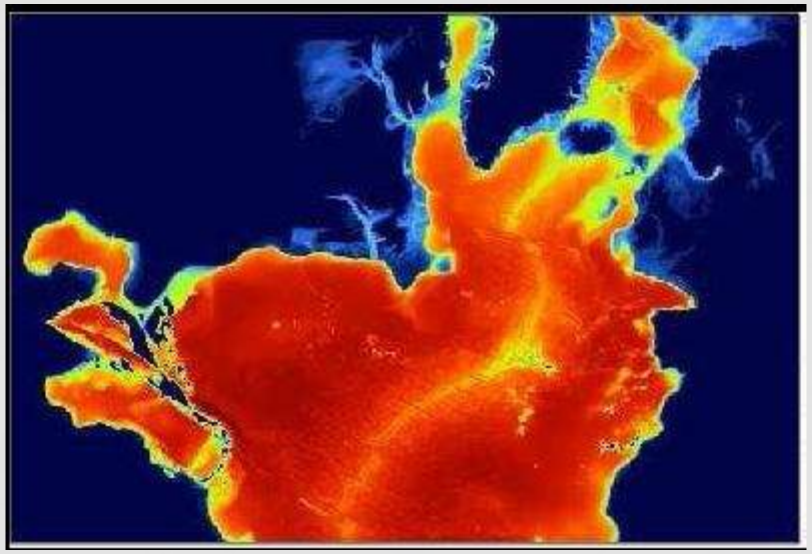
The FOAM system assimilates ocean and ice observations to initialize forecasts.

- 1/12-1/4 degree horizontal res.
- Interactive sea ice model component
  - Ice state freely evolves during forecast
  - Met Office NWP forecast used as atmospheric forcing
- Spatially and temporally-varying ice observation errors derived from hindcast experiments
- No formal background error covariances
  - *Ad hoc ice concentration-ice thickness covariance*: new concentration adds ice in thinnest category
  - *Ad hoc ice volume-ocean salinity covariance*: ocean salinity is conserved after ice volume increments in analysis step

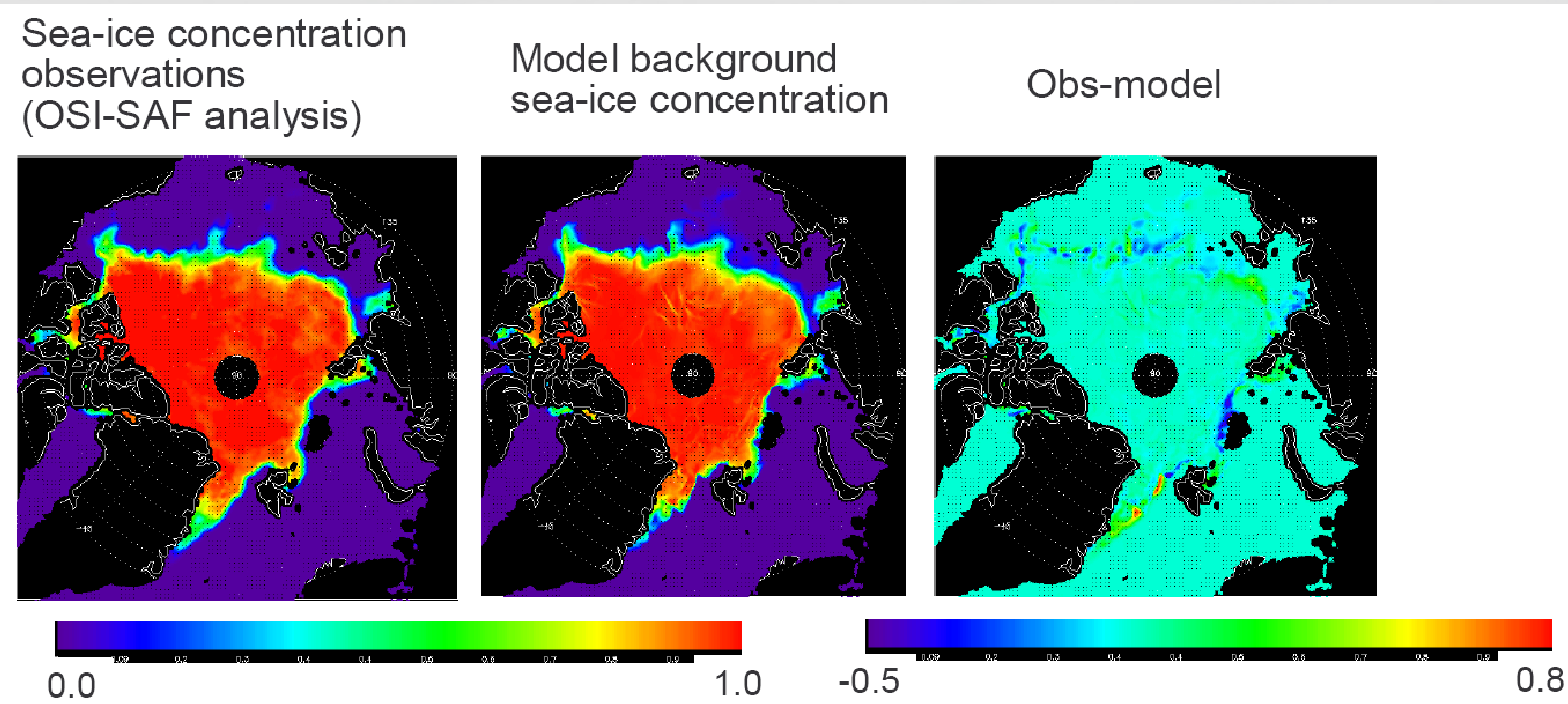
¼-deg Global



1/12-deg N. Atlantic



The FOAM system generally can reduce ice concentration RMS error in the analysis to below 10%.



From Poster: **The global FOAM system**, Martin 2008

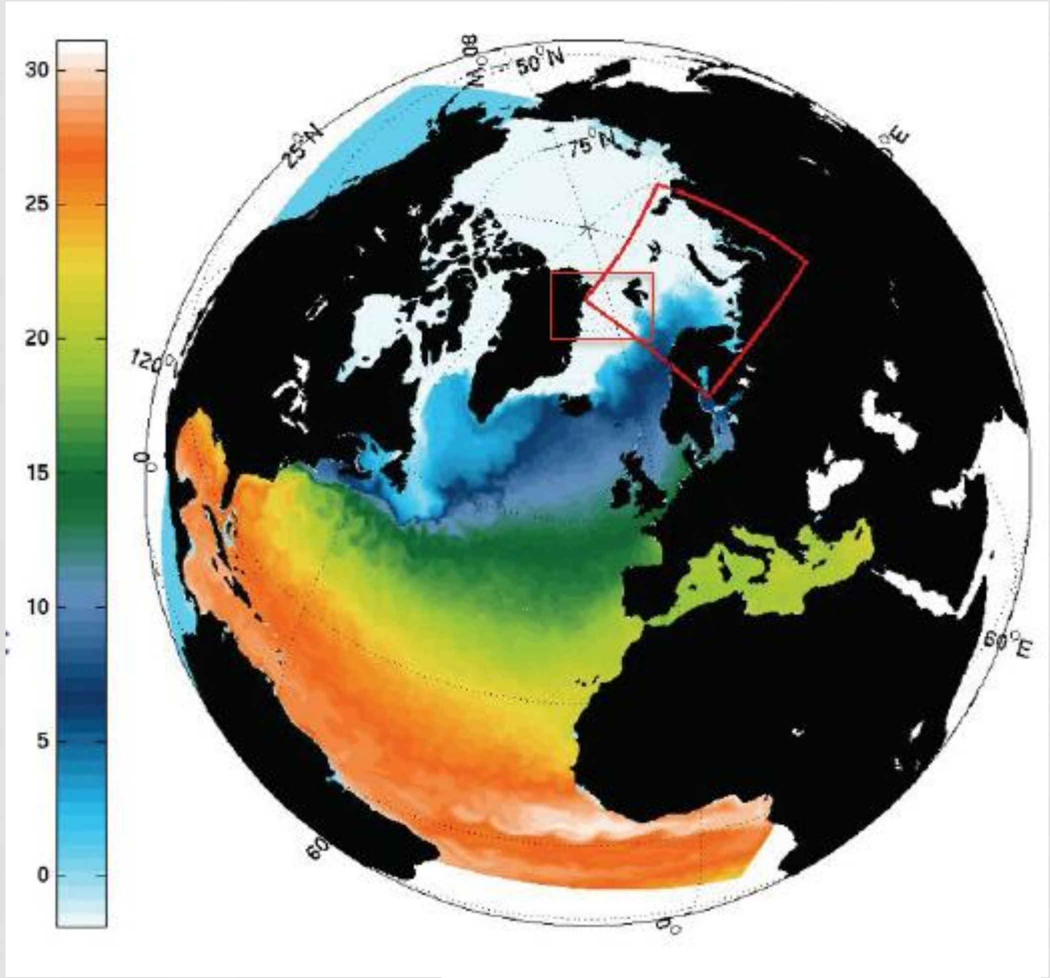
Coupled sea ice-ocean data assimilation for short-term forecasting and reanalysis

TOPAZ ENKF SYSTEM

The TOPAZ system assimilates ocean and ice observations to initialize 10 day forecasts using the EnKF.

- 11-16 km horizontal res.
- Interactive sea ice model component
  - Ice state freely evolves over forecast step
  - ECMWF NWP forecast used as upper boundary forcing (constant ice boundary conditions)
- Ice concentrations obs. errors are a function of ice concentration
  - 10% baseline
  - up to 70% when ice concentration <= 50%)
- Background error covariances calculated from 100 member ensemble
  - "smooth localization" ~ 300 km
  - After analysis step, ocean and ice states may not be consistent (but are physically bound)

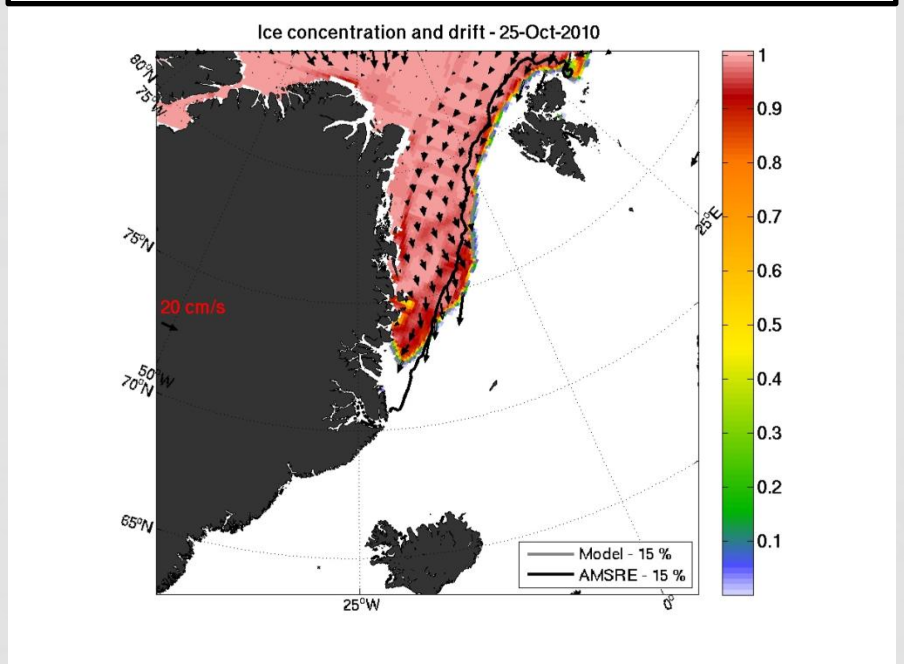
TOPAZ3 Domains: Arctic/N. Atlantic
Fram Strait, Barents Sea



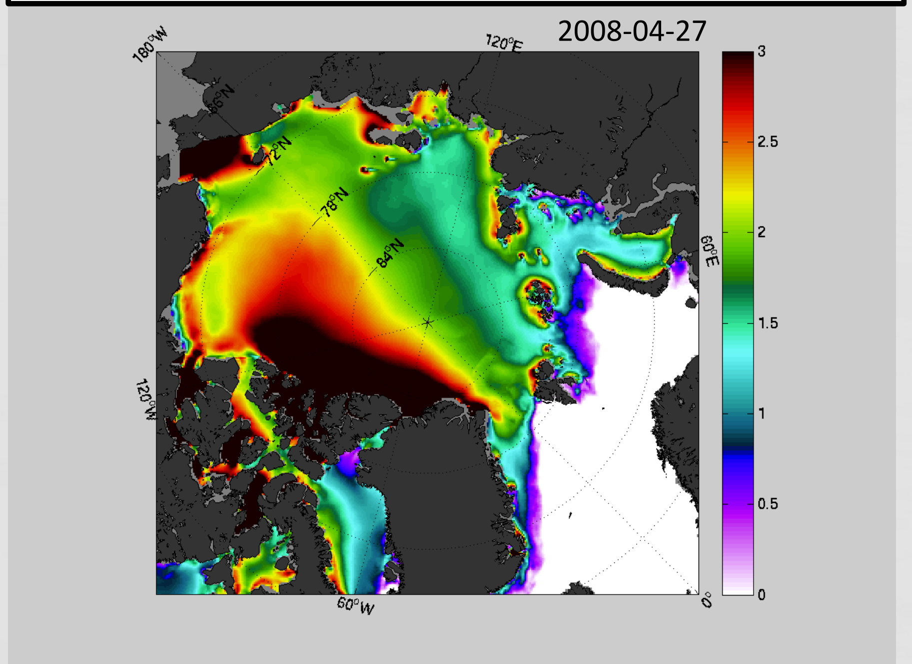
TOPAZ3 SST May 1990 week 2

TOPAZ system reproduces ice edge position, concentration, and drift well and provides estimates of unobserved variables such as ice thickness.

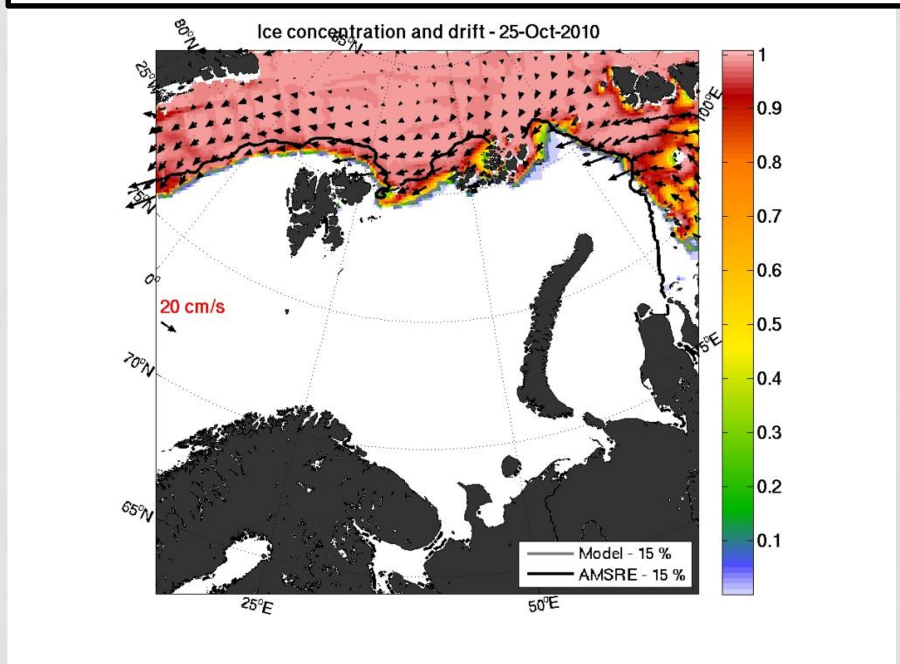
Greenland Sea: Ice Concentration Analysis



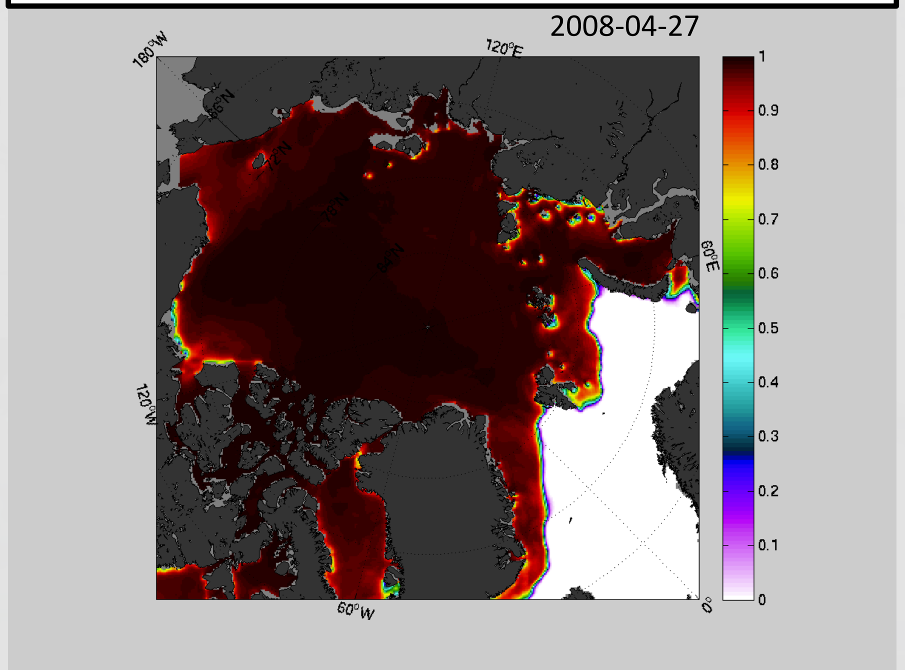
Arctic Ocean : Ice Thickness Analysis



Barents Sea: Ice Concentration Analysis



Arctic Ocean: Ice Concentration Analysis



Summary

	Ice data assimilated	Ice obs. uncertainties	Ocean-ice coupling in assimilation (covariance info)
ECCO **MIT JPL**	Concentration (SSM/I)	Spatially and temporally-varying measurement and representation errors	Ocean and Ice states are always consistent because model state freely evolves from the model physics
ECCO2 **MIT JPL**	Concentration (SSM/I) Velocity (Kwok JPL) Draft (submarine)	Constant representation error	Ocean and Ice states are always consistent because model state freely evolves from the model physics
CFSR **NCEP**	Concentration	Model is assumed to have no skill.	Ocean and atmosphere are not updated after ice innovation
FOAM **UK Met Office.**	Concentration	Spatially-varying representation error	Salt - but not energy - is conserved after ice innovation
TOPAZ **NERSC+ Met.no**	Concentration (AMSR-E) Velocity	Constant	Covariance structure estimated from ensemble

Future Plans for U.S. centers

	New Sea Ice Data	Assimilation Method	Model configuration
ECCO **MIT JPL**	Higher resolution ice concentration, velocity, and freeboard and draft.	Adjoint method	1-degree global and 1/10-degree Arctic+North Atlantic Sea Ice-Ocean model
ECCO2 **MIT JPL**	Ice thickness from new remote sensing platforms	Green's Functions + Adjoint method	1/8-degree global and regional (e.g., Arctic, Southern Ocean, West Antarctica) Sea Ice-Ocean model
CFSR **NCEP**	Ice velocity and thickness	3DVar and Direct Insertion	?
GFDL	Concentration, thickness, velocity	EnKF	High res global Atmosphere-Sea Ice-Ocean model (S. Zhang's talk)
U.S. Navy	Concentration	3DVar (NCODA)	1/12-degree global Sea Ice-Ocean

Open questions

- What are the right model controls for state estimation methods used for climate analysis?
  - Are adjusting initial and boundary conditions sufficient or should we also try to focus on model parameters?
  - Could the answer depend on the approach (adjoint vs. Green's Function)?
- For coupled reanalysis efforts (e.g., CFRS), is anything more than direct insertion of ice data required for the solution to be useful for initializing prediction systems?
- Will the assimilation of near real-time estimates of ice motion improve short-term forecasts?
- Can we quantify how the assimilation of ice data improves the forecasts, reanalyses, and climate state reconstructions of the ocean?
- Do the background error covariances derived from the EnKF ensembles really represent the relationship between the ocean and ice states given their highly nonlinear interaction?
- What is the impact of assimilating sea ice data into coupled atmosphere-ocean-sea ice models for the initialization of long-term (decadal) on climate predictability?

Bottlenecks to Coupled Ocean-Ice Data Assimilation in the U.S.

- **Lack of ice and high-latitude ocean observations :** lack of ice thickness data remains a major problem
- **The sea ice models**: ODA groups do not necessarily have access to expert sea ice modelers – ice models are often outdated and may not be appropriate for data assimilation.
- **Sea ice data expertise:** ODA groups and ice observation specialists with knowledge on the data and its errors tend to be separate communities.
- **The ice-ocean coupling:** Tends to be done in an *ad hoc* way in global models and is therefore likely a major source of systematic model bias.
- **Covariances :** There is virtually no knowledge of the appropriate ice-ice and ocean-ice covariances.

Recommendations

- Observation side:
  - More *in* situ ocean observations at high latitudes
  - **Climate analysis**: consistency of data across observing platforms
  - **Forecasting:** ice motion in near-real time
  - Provide uncertainties with product(e.g., DMI OSI-SAF, GHRSST)
  - Atmospheric reanalyses should come with 1) uncertainties and/or 2) easy access to database of observations/uncertainties assimilated so we can make our own guess as to its skill

- Statistics side:
  - Research into understanding ice-ice, ice-ocean covariance structure

- Modelling side:
  - More research on how to properly couple ice and ocean components of global-scale models
  - More support for interaction between ice modelers and existing ocean forecasting/state estimation groups.
  - More support to port "modern" sea ice models into existing ocean models.

End