The Arctic Ocean and Sea Ice State Estimate:
A synthesis of observations and model

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Estimating the Circulation and Climate of the Ocean
http://ecco-group.org

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Outline

Q. How have existing obs helped improve modeling effort?

Q. How opportunity for collaboration has the network enabled?

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1. Background + Motivation
2. Data+Model synthesis

   An estimate consistent with observations and model physics

   2A. Observational network

   2B. Optimization

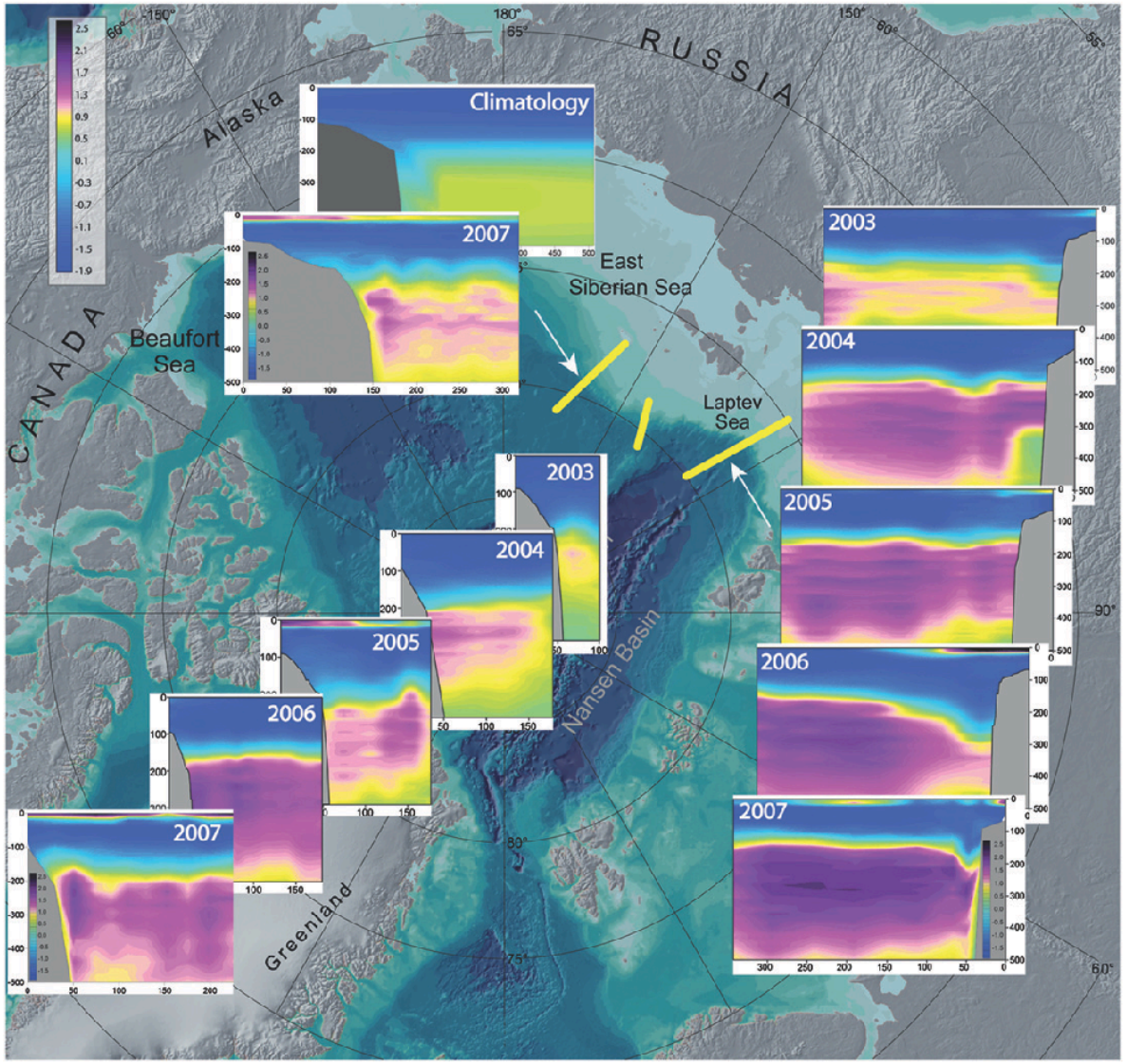
   2C. Collaboration opportunities (1 example: Pacific inflow)
3. Summary

1. Recent observed changes

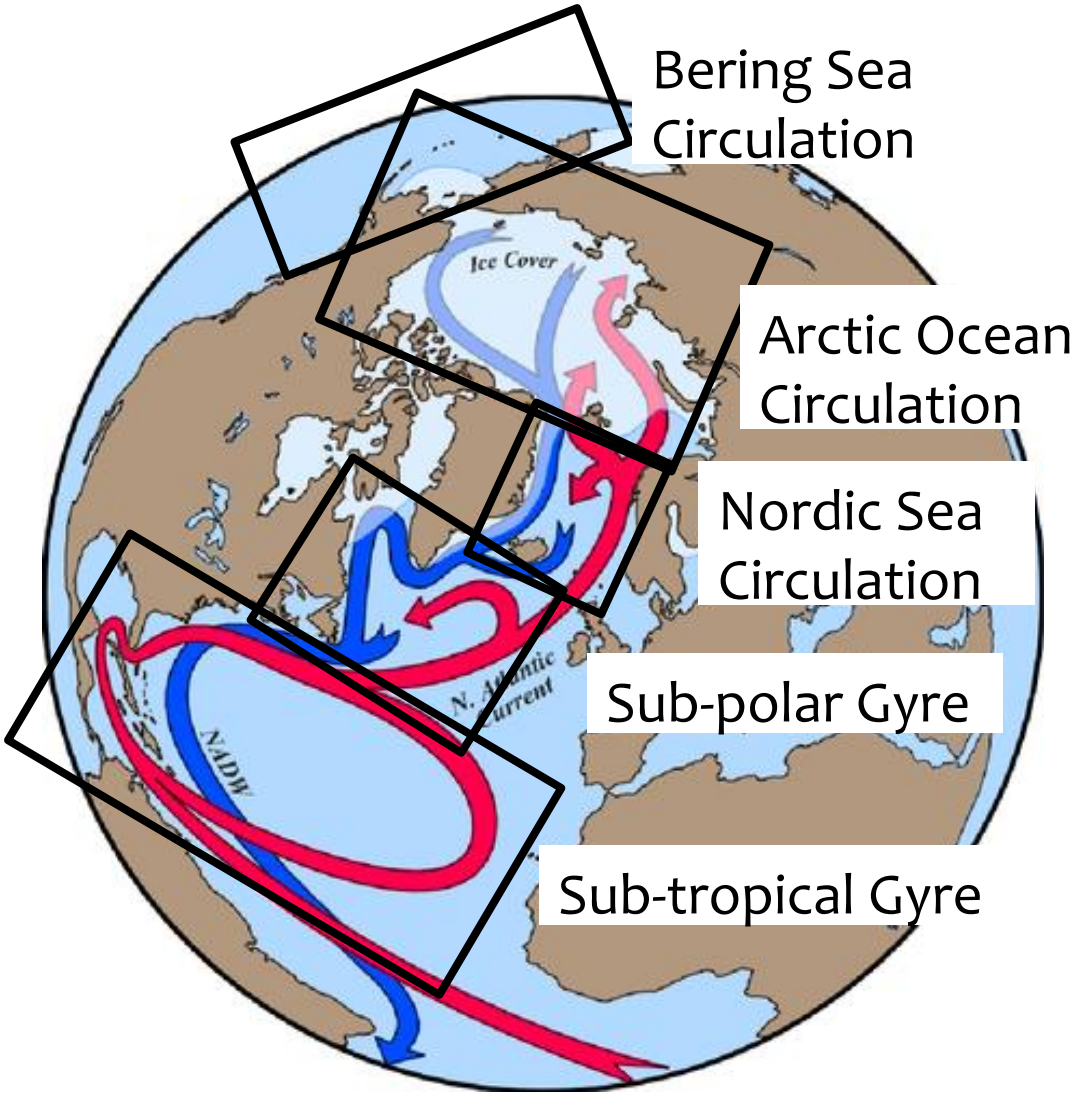
2000's: warm pulses of Atlantic Water into Arctic interior

Polyakov et al. [2012]
Dmitrenko et al. [2008]
Beszczynska-Möller et al. [2012]

Controlling mechanisms?



1. Large-scale Circulation



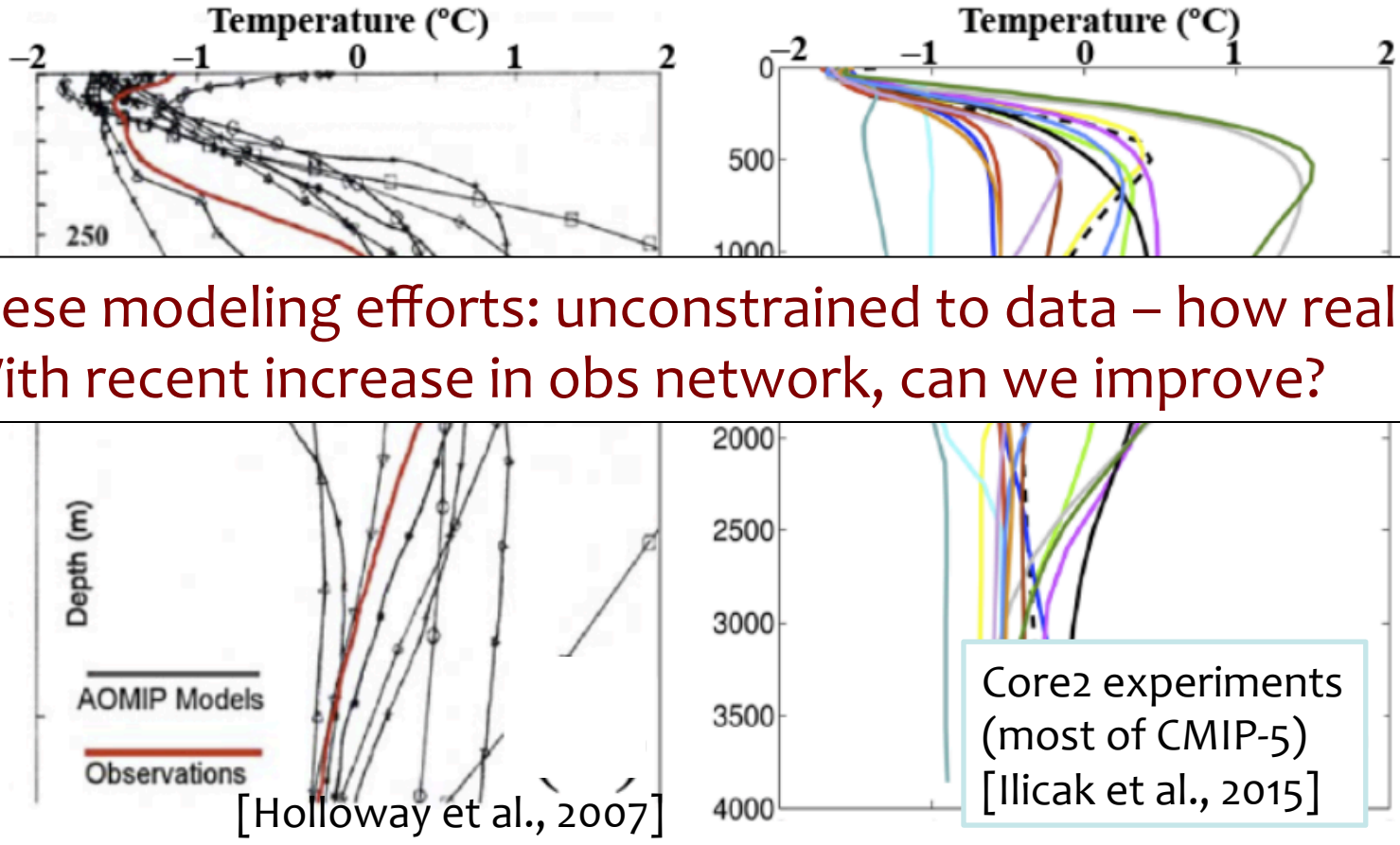
- Upstream
- Downstream

Dynamical models:

- conservation laws
- consistent with obs
- reconstruct time-mean, time-variable properties
- budgets
- controling mechanism

1. Current Modeling efforts

Canada Basin



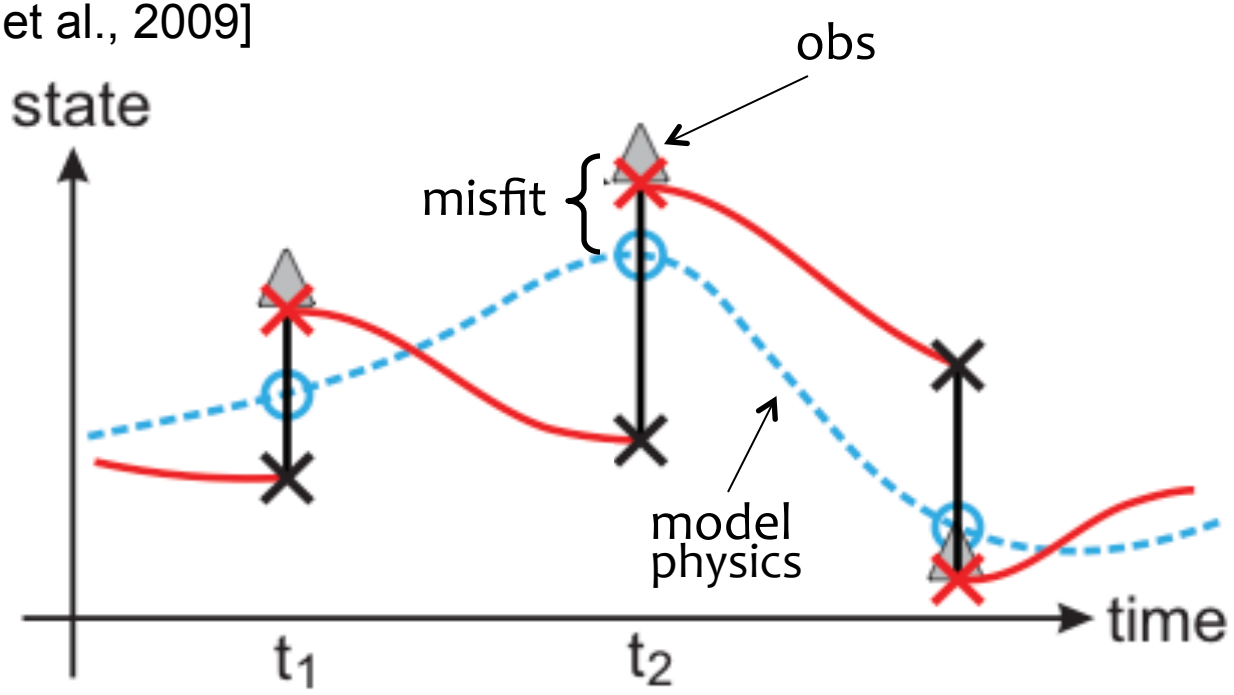
[Holloway et al., 2007]

Core2 experiments
(most of CMIP-5)
[Ilicak et al., 2015]

These modeling efforts: unconstrained to data – how realistic?
With recent increase in obs network, can we improve?

2. Inversion: combining observations and model

[Wunsch et al., 2009]



Control variables {u}:

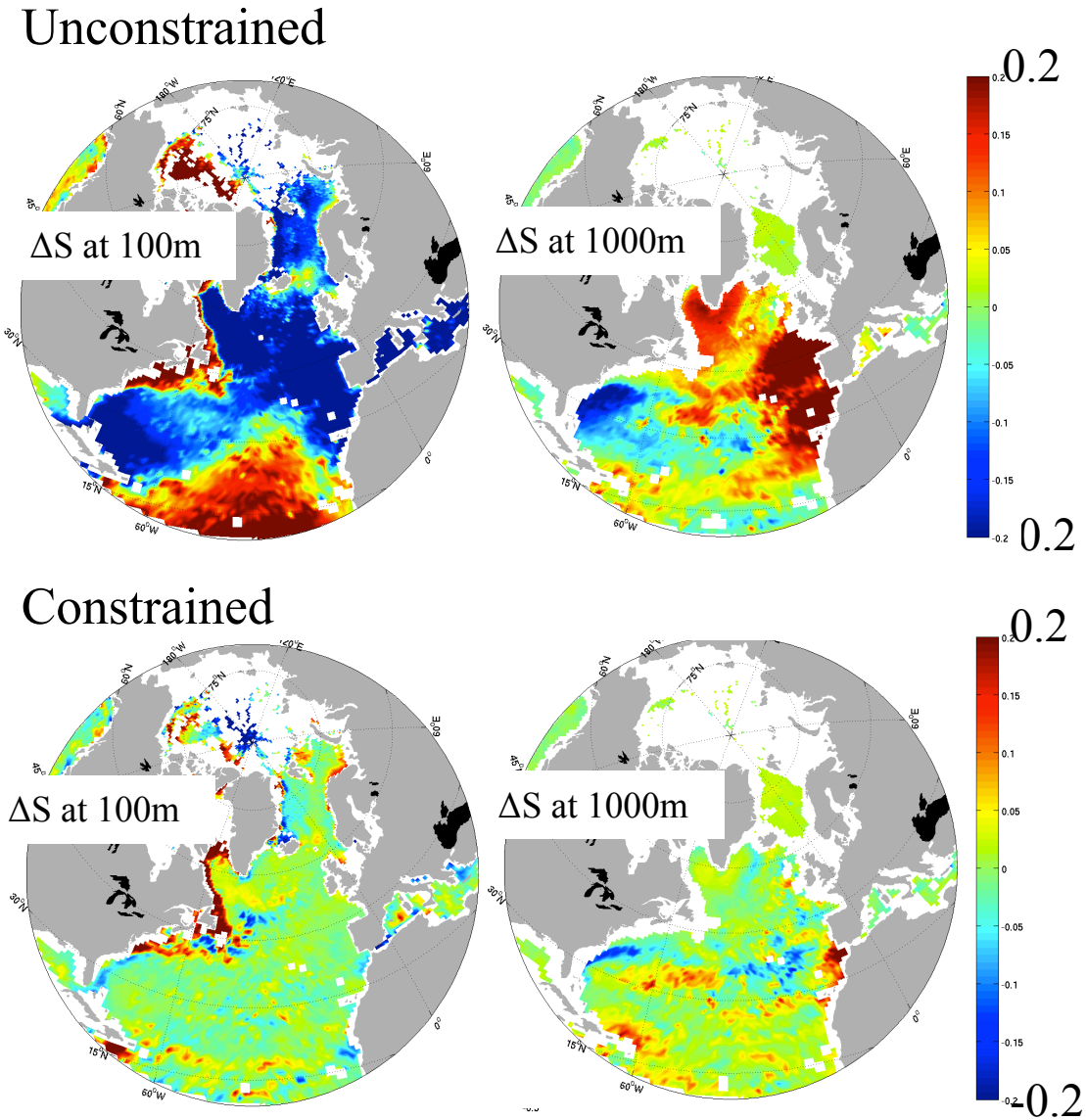
- Parameters which we invert for to minimize model-data misfits
- 1D, 2D, 3D

Least-square minimization:

- Define objective $J = (\text{misfit})^2$
- Solve $\partial J/\partial\{u\} = 0$ (subject to constraints)

2. ECCO-v4: Global bi-decadal state estimate [Forget et al., 2015]

- Global focus
- Coarse resolution (1°)
- Misfits to observed salinity 1992-2011



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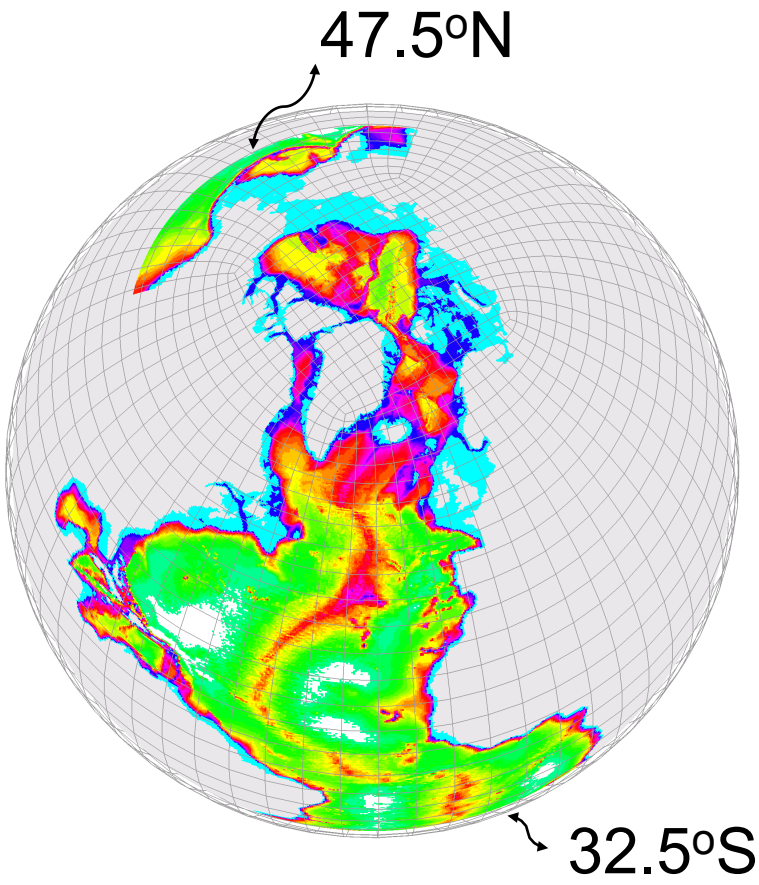
2. the Arctic Sub-polar gyre sTate Estimate (ASTE)

- Nested within the global ecco-v4
- **14 km in the Arctic**
- Optimization period: **2002-2013** (GRACE, ICESat, ITP)

- Initial conditions:
  - WOA14 modified (ocean),
  - PSC (ice)

- **Control variables:**
  - initial conditions
  - time-varying atmospheric state,
  - **3-D ocean mixing parameters**



2A. data constraints

- Satellite and insitu
  (ARGO, ITP, NABOS, BGEP)
- Diverse platforms
  e.g., floats, submarine,
  ship tracks, mooring
- Sea ice + ocean T/S/U/V
- Cover Arctic main gateways
  e.g., Fram, Davis, Bering

- Diverse obs streams
- Online misfit calculations & optimization

Data Type	Spatial coverage	Temporal coverage	Description	Source
Sea ice				
Velocity	Arctic	2002–2012	passive microwave & AVHRR, IABP	*rkwok.jpl.nasa.gov/radarsat/3dayGr_table.html* *nsidc.org/data/docs/daac/nsidc0116_icemotion.gd.html* Kwok and Cunningham [2008], Fowler et al. [2013]
		2012–2015	ASCAT & SSMI	*ftp.ifremer.fr/ifremer/cersat/products/gridded/psi-drift*
		1997–2015	IMB buoys	*imb.erdc.dren.mil/buoysum.htm*, Perovich et al. [2013]
		2009–2015	ITP-V	Cole et al. [2014, 2015]
Thickness	Arctic	2011–2015	CryoSat-2	*www.meereisportal.de/datenportal.html*, Laxon et al. [2013a]
	Arctic	2010–2015	SMOS	*icdc.zmaw.de/l3c_smos_sit.html*, Tian-Kunze et al. [2014]
	Arctic	2003–2008	ICESat	*rkwok.jpl.nasa.gov/icesat/index.html* Kwok and Cunningham [2008], Kwok et al. [2009]
	Arctic	1997–2015	IMB buoys	*imb.erdc.mil/buoysum.htm*, Perovich et al. [2013]
	West Arctic	2003–2015	BGOS ULS	*www.whoi.edu/beaufortgyre*,Krishfield et al. [2014]
	Arctic	2002	Submarine ULS	*www.nsidc.org*
	GINs	2002	AWI ULS mooring	Witte and Fahrbach [2005]
Concentration	Arctic	2002–2015	SSMI / OSISAF	*osisaf.met.no/p/ice/index.html*
FW transport	Fram Strait	2002	passive	Kwok and Rothrock [1999], Kwok et al. [2004]
	CAA	1997–2002	microwave	Kwok [2006]
Ocean				
ITP (T,S)	Arctic	2004–2015	Ice-Tethered Profilers	*www.whoi.edu/itp/data/* Krishfield et al. [2008b], Toole et al. [2011b]
Hydrographic Survey (T,S)	GINs, Fram Str.	1996–2006	ASOF	*www.pangaea.de/*
	Beaufort Sea	2003–2013	BGEP	*www.whoi.edu/beaufortgyre/home/*
	Laptev Sea	1993–2003		*doi.pangaea.de/10.1594/PANGAEA.761766*, Bauch et al. [2009]
	East Arctic	2007		*doi.pangaea.de/10.1594/PANGAEA.763451*, Bauch et al. [2011]
	Chukchi Sea	2002–2004		*psc.apl.washington.edu/HLD/Bstrait/Data/*
	GINs	1980–2013	historical T/S	Våge et al. [2015]
Mooring (T,S,currents)	Fram Strait	1997–2010	ASOF	Fahrbach et al. [2001], Beszczynska-Möller et al. [2012]
	East Arctic	2002–2013	NABOS	*nabos.iarc.uaf.edu/*,Pnyushkov et al. [2013] and
	West Arctic	2002–2013	CABOS	Polyakov et al. [2012]
	Beaufort Gyre	2004–2015		*www.whoi.edu/page.do?pid=66566*
	Bering Strait	2002–2015		*psc.apl.washington.edu/HLD/Bstrait/Data/*
	Davis Strait	2004–2015		*iop.apl.washington.edu/data.html*
	North Pole	2000–2015	NPEO	*psc.apl.washington.edu/northpole/index.html*
Transports				
– Heat	Fram Strait	1997–2010	ASOF	Schauer and Fahrbach [2004] &
– Freshwater	Fram Strait	1997–2010	ASOF	Beszczynska-Möller et al. [2012]
– Heat	Bering Strait	1990–2015	mooring	Woodgate et al. [2005] &
– Volume	Bering Strait	1990–2015	mooring	Woodgate et al. [2006] &
– Freshwater	Bering Strait	1990–2015	mooring	Woodgate et al. [2012]
Data portal			IARC	*oregon.iarc.uaf.edu/dbaccess.html*
	High Latitude	2002–2015	IARC	*climate.iarc.uaf.edu/geonetwork/srv/en/main.home*
			ICES	*ocean.ices.dk/HydChem/HydChem.aspx?plot=yes*
			SBI	*www.eol.ucar.edu/projects/sbi/*
	CAA	2002–2015	BIO	*www.bio.gc.ca/science/data-donnees/base/run-courir-en.php*
	Arctic	2002–2015	ACADIS	*www.aoncadis.org/home.htm*
MDT	High Lat.	2002–2009	ICESat,Envisat& GRACE&GOCE	Farrell et al. [2012], Andersen and Knudsen [2009] & Johannessen et al. [2014],*grace.jpl.nasa.gov*
OBP	High Lat.	2004–2014	GRACE mascon	Watkins et al. [2015],*grace.jpl.nasa.gov*

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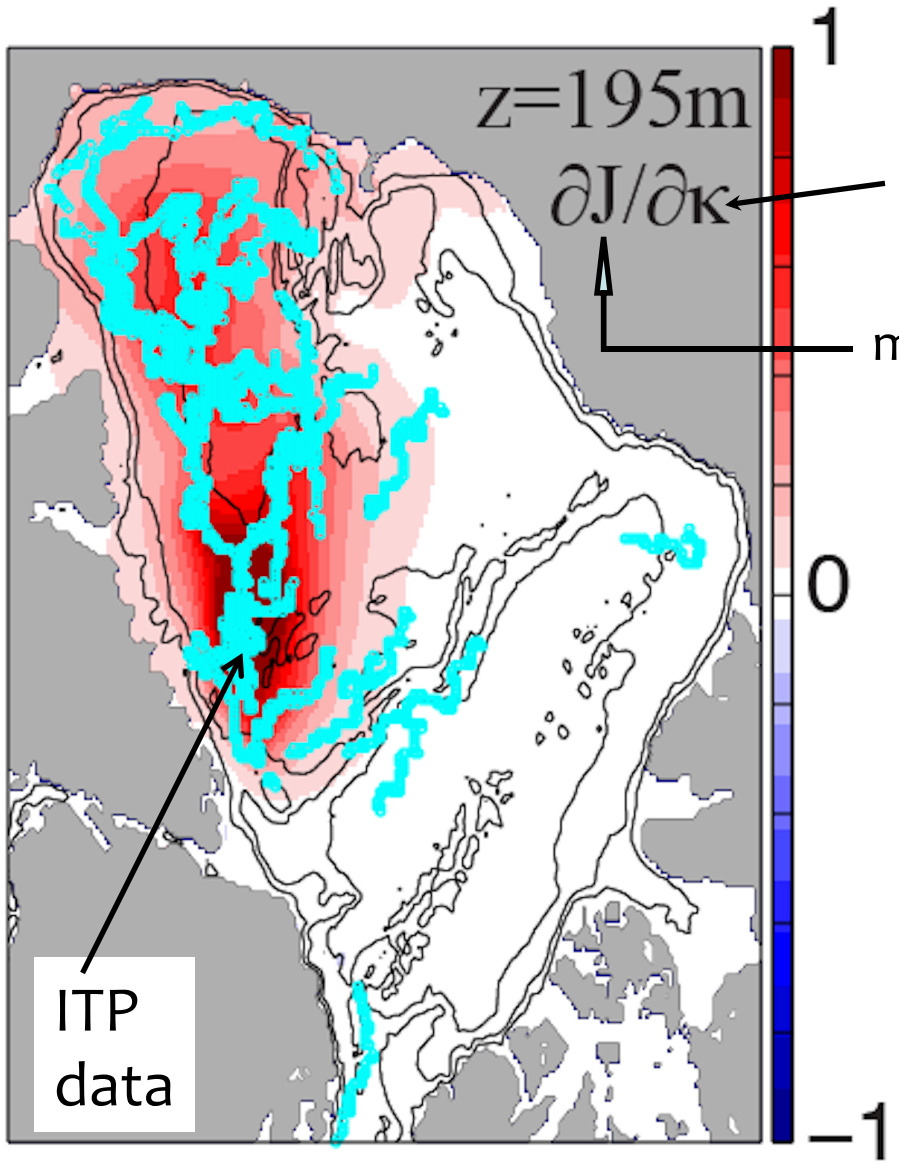
2B. Optimization: Importance of data



Model gains information (sensitivity ∂J/∂κ) where there are obs.

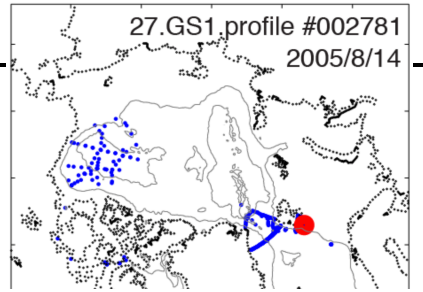
2B. Optimization: Misfit reduction

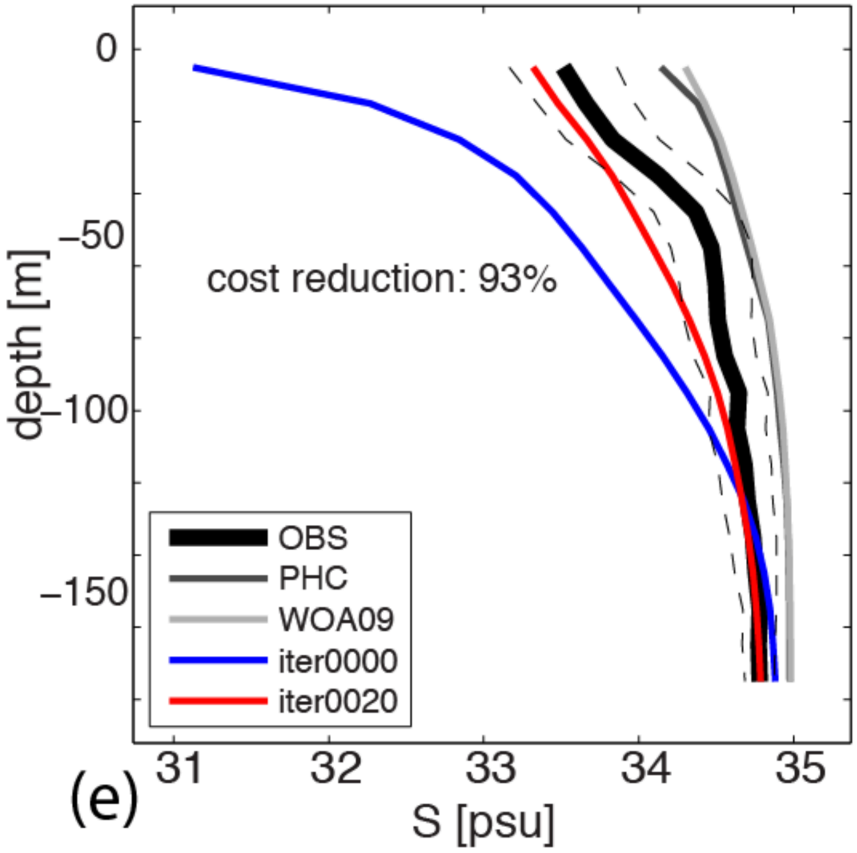
Adjustments to:

- atmospheric forcing
- mixing parameters
- initial hydrography

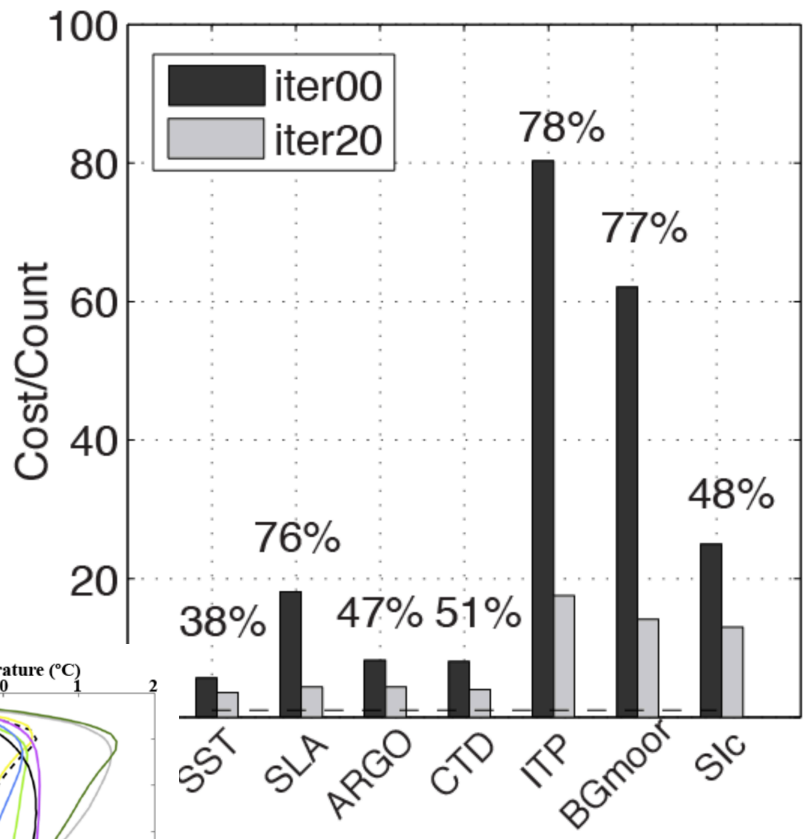
[Nguyen et al, in prep]

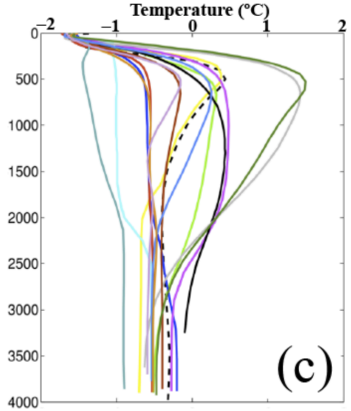
Collaborative efforts to interpret κ (e.g., with I.Fer, L.Rainville, J.Toole, S.Cole, L.Padman)





2B. Optimization: Misfit reduction





State estimate:

- Start from some trajectory
- **Systematic way** to minimize misfits
- Consistent with model physics *and* with obs.

Applications:

- Budget analyses
- Circulation patterns
- Source and pathways
- Controling mechanisms
  - FW content,
  - Greenland FW flux
  - mass/heat/FW transports

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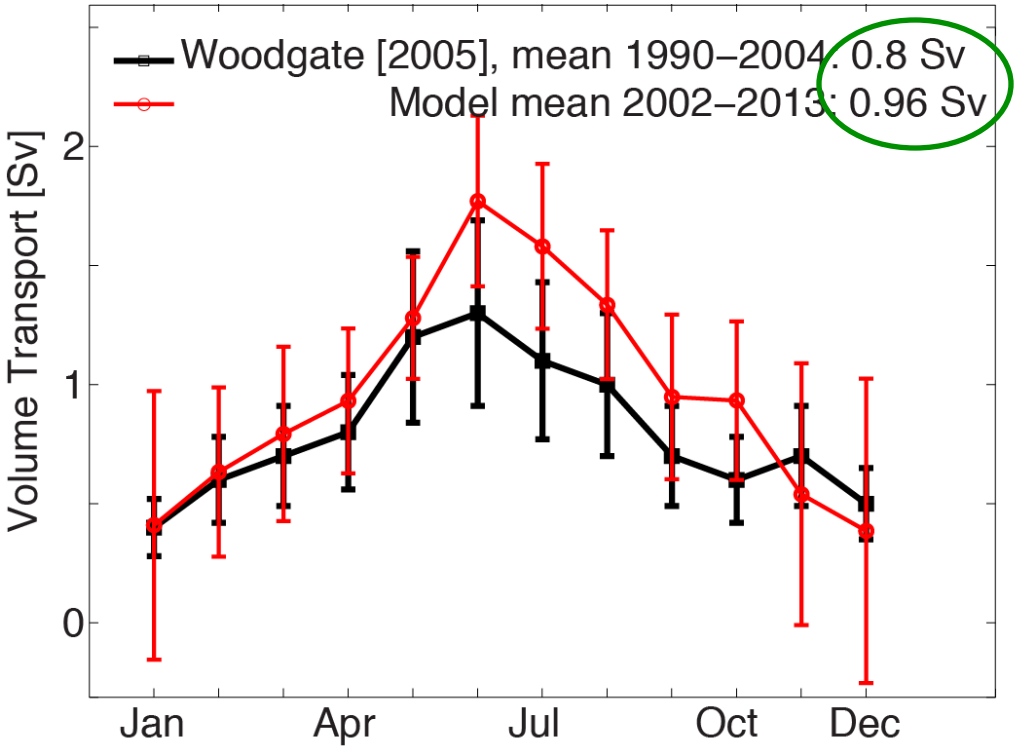
2C. Collaborative Research: Bering Strait transport

- 40% of FW into the Arctic (large in mean *and* in variability)
- An important part of the global FW cycle
  [Woodgate et al., 2015]



Recent increase in Volume and Heat inflows

- Local atmospheric effect?
- Local versus large-scale sensitivities in the Pacific and Atlantic ocean?

Steps: (a)

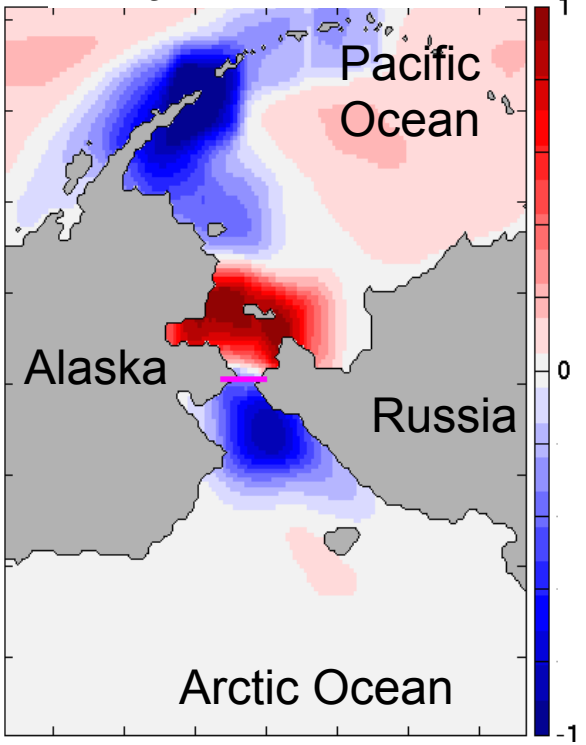
$$J = \sum_{x,z} \left\{ \frac{1}{365} \sum_{day=1}^{365} V_{north} dx dz \right\}$$

2C. Collaborative research: Bering Strait transport

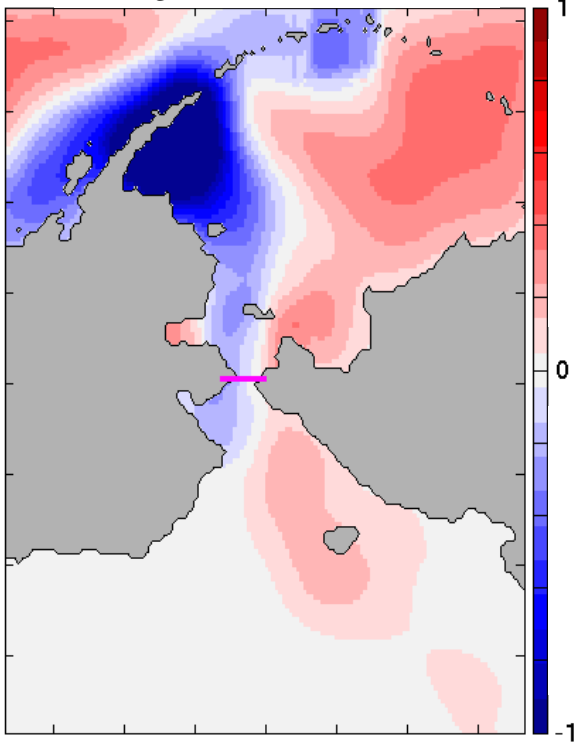
Steps: (b) $\frac{\partial J}{\partial S}$ ⟵ (and other control variables)

Heimbach et al., 2010
Fenty & Heimbach, 2013ab,
Fukumori et al., 2014,

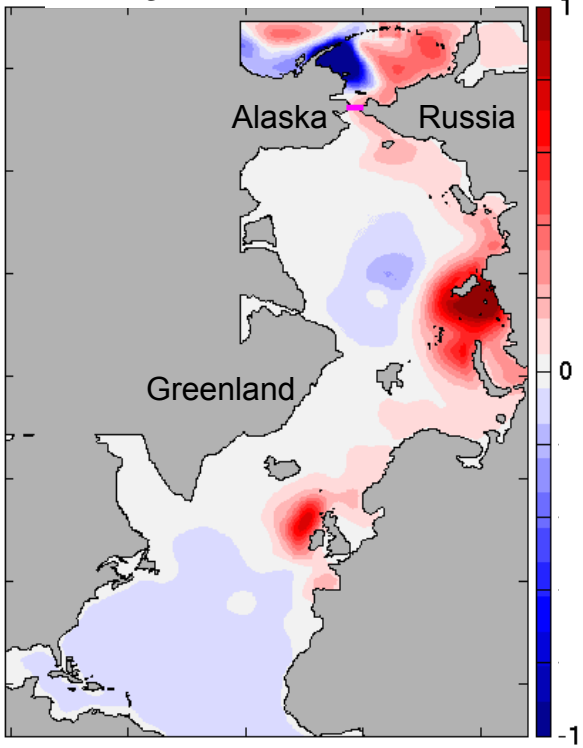
T_{final} – 1/2month



T_{final} – 3months



T_{final} – 9months



3. Going forward

State Estimate:

- systematic reduction of model-observation misfits
- (capable of) synthesizing all available data from AON
- Allows for climate studies, e.g., circulation, budget, feedbacks

Collaboration:

- Mixing (J. Toole, WHOI, L. Padman, ESR)
- Time mean Arctic ocean T/S and circulation – (J. Toole, WHOI)
- Sea-ice climatology – (I. Fenty, JPL)
- Pacific inflow dynamics – (R. Woodgate, UW)
- Observing Network (L.Rainville and C.Lee, UW)

Thank you. Questions?