Sensitivities of sea-ice export through the Canadian Arctic Archipelago using MITgcm ocean/sea-ice adjoint model

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

Long-term goal: truly global, high-resolution, coupled ocean/sea-ice state estimation

ECCO2: High-Resolution Global-Ocean and Sea-Ice Data Synthesis @ NASA/Ames

MIT
Marshall, Campin, Heimbach, Hill, Mazloff, Wunsch

JPL
Fu, Kwok, Lee, Menemenlis, Zlotnicki

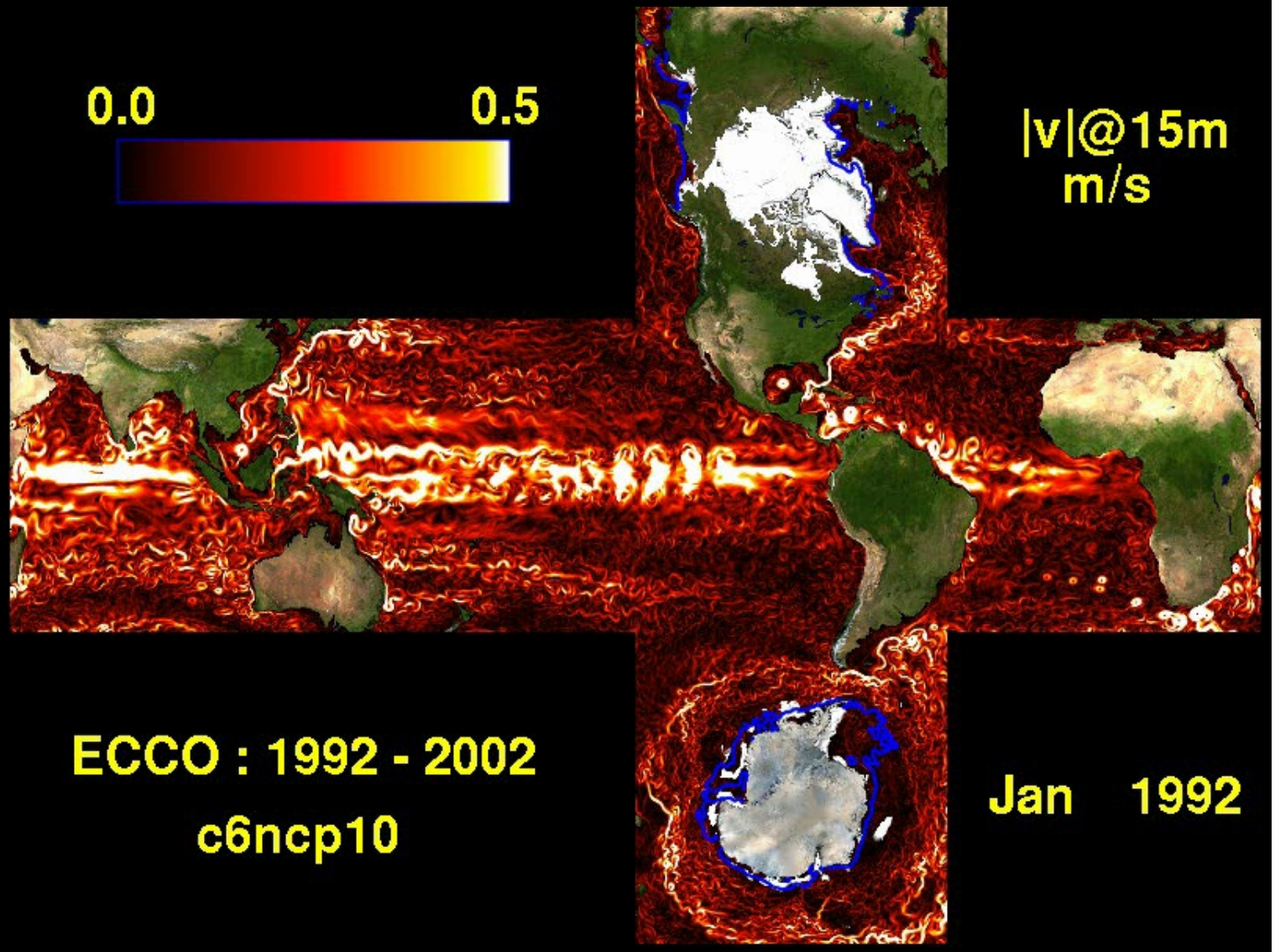
GSFC
Rienecker, Suarez

ARC
Henze, Taft

HARVARD
Tziperman, Zanna

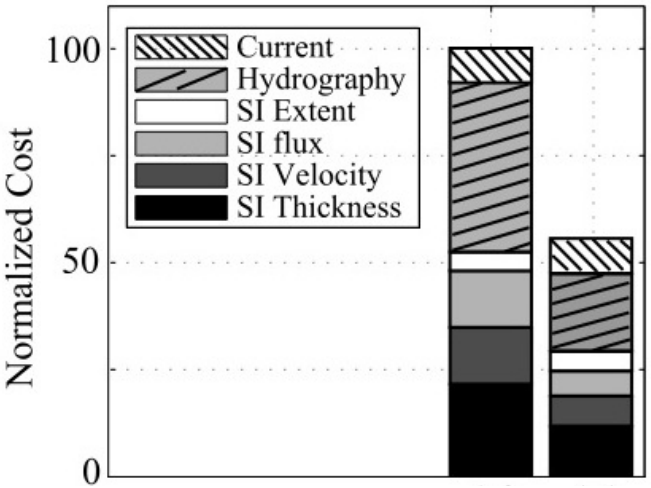
GFDL
Adcroft

ARGONNE
Hovland, Utke

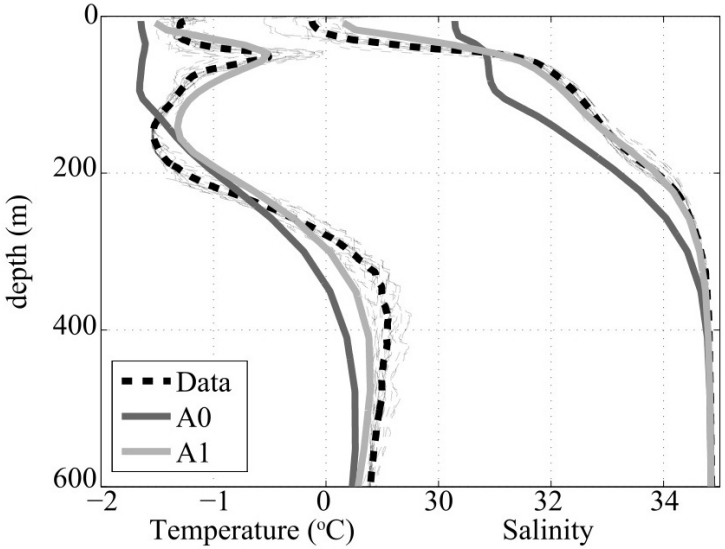


ECCO2 Arctic Ocean studies

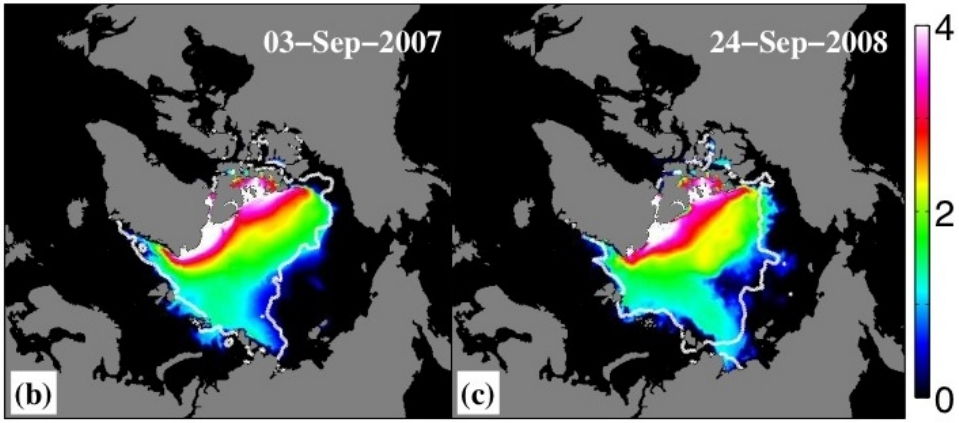
Arctic cost function reduction



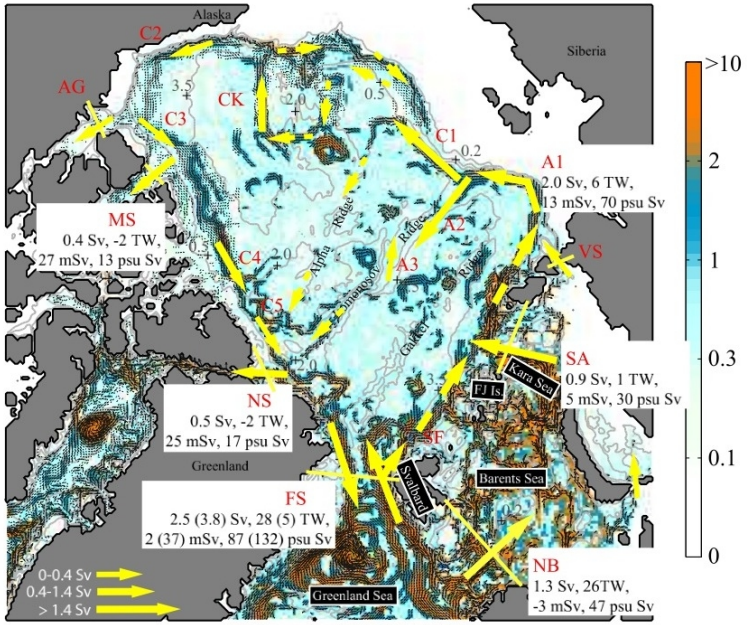
Canada Basin Hydrography



2007-2008 summer sea ice minima



Atlantic water pathways



Nguyen et al., 2009 & Nguyen et al., in preparation

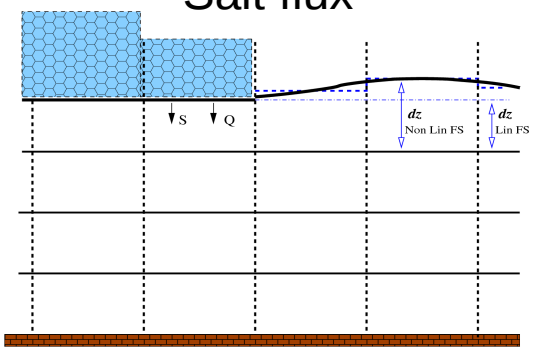
The MITgcm sea-ice model

- Thermodynamics
  - Based on *Zhang & Hibler ,1997*
  - Two-category, zero-layer, snow melting and flooding *(Semtner, 1976; Washington & Parkinson, 1979)*
  - Sea ice loading and dynamic ocean topography *(Campin et al., Ocean Modelling, 2008)*
- Dynamics
  - Both ported on C-grid for use in generalized curvilinear grids
  - Two solvers available for viscous-plastic (VP) rheology:
    - Line Successive Relaxation (LSR) implicit *(Zhang & Hibler, 1997)*
    - Elastic Viscous-Plastic (EVP) explicit *(Hunke & Dukowicz, 1997)*
  - Various advection schemes available
- An ***exact*** (with respect to ***tangent linearity***) adjoint,
  - generated via automatic differentiation tool TAF

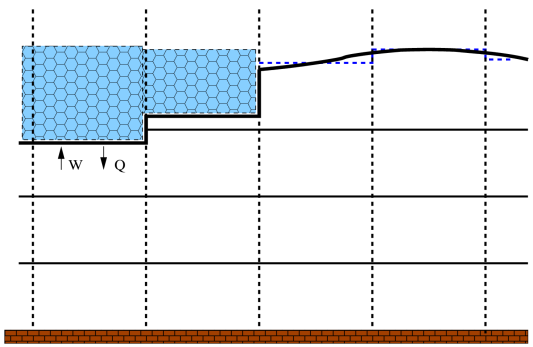
- ***Losch et al. (submitted to Ocean Modelling, 2009a)***
- ***Heimbach et al. (submitted to Ocean Modelling, 2009b)***

Sea Ice - Ocean coupling with z* coordinate

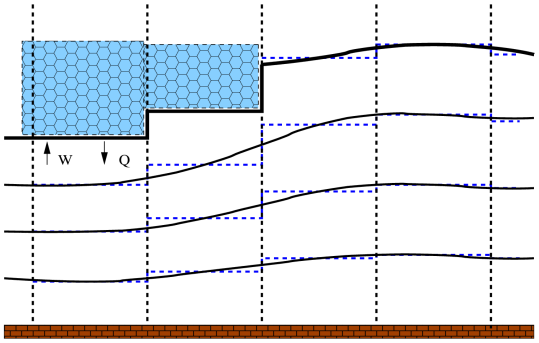
"Salt flux"



z



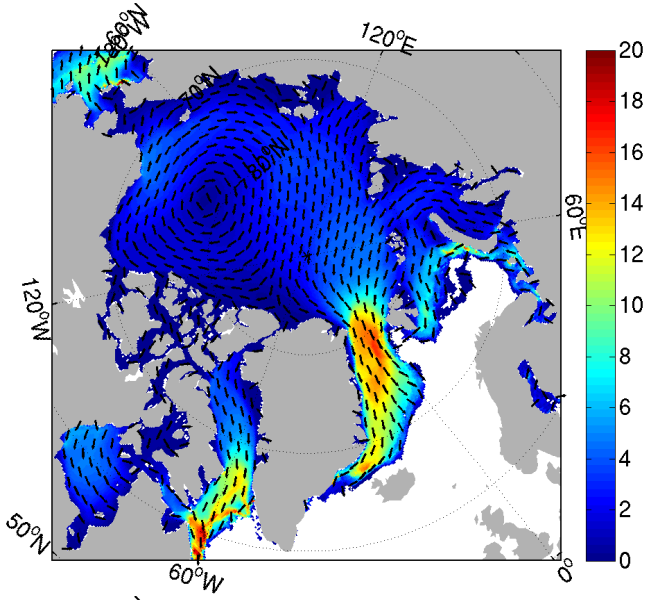
z*



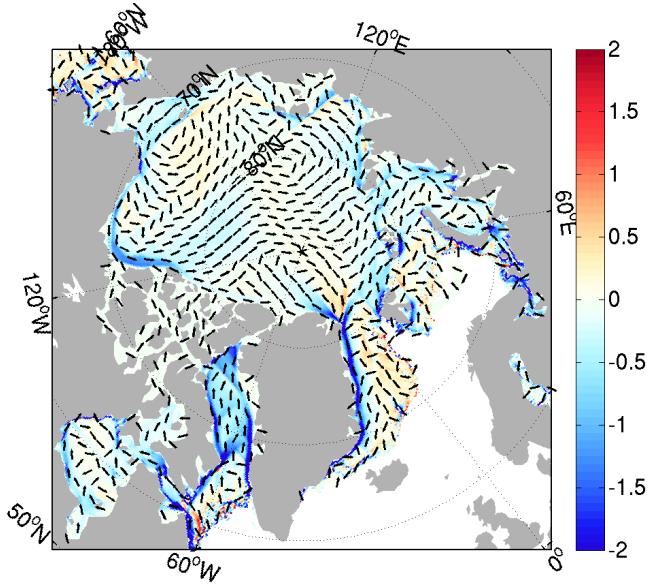
Campin, Marshall and Ferreira

Ocean Modelling, 2008

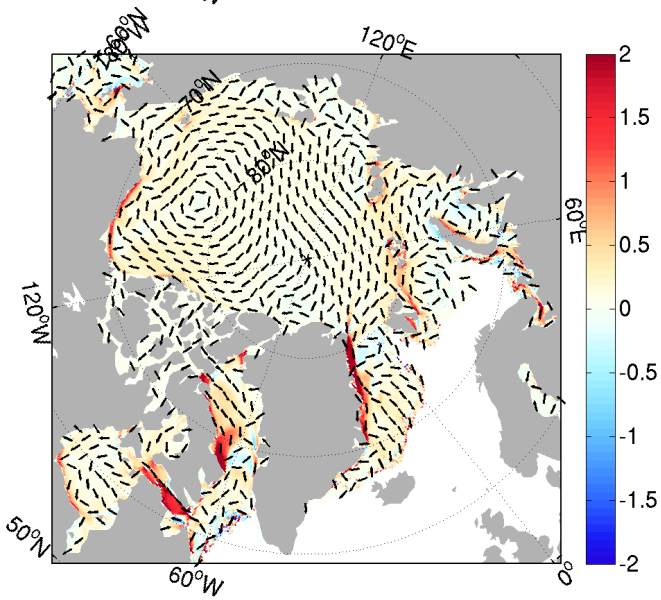
The forward model - configuration sensitivities
Ice drift velocities



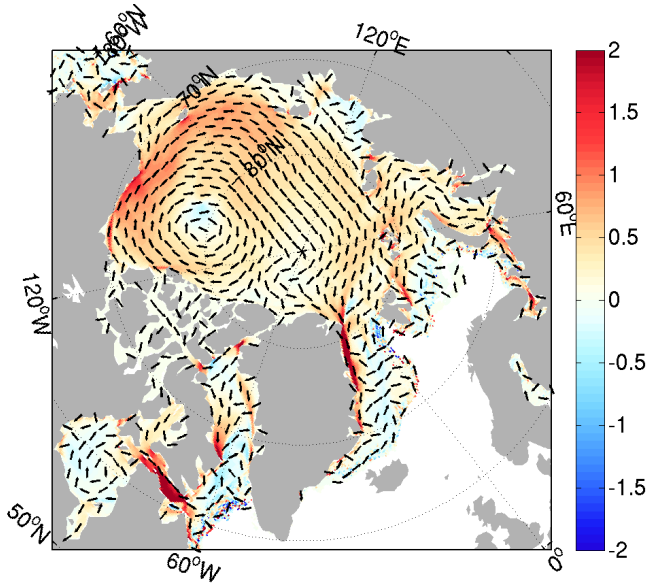
C-grid LSR no-slip (C-LSR-ns)



B-LSR-ns minus C-LSR-ns



C-LSR-fs minus C-LSR-ns



C-EVP-ns minus C-LSR-ns

The MITgcm/sim adjoint models generated via Automatic Differentiation (AD)

- Model code

$$\vec{v} = \mathcal{M}_\Lambda\left(\mathcal{M}_{\Lambda-1}\left(\ldots\ldots\left(\mathcal{M}_0\left(\vec{u}\right)\right)\right)\right)$$

- Adjoint code

$$\delta^*\vec{u} = M_0^T \cdot M_1^T \cdot \ldots\ldots \cdot M_\Lambda^T \cdot \delta^*\vec{v}$$

- Automatic differentiation:

each line of code is elementary operator $\mathcal{M}_\lambda$

$\longrightarrow$ rules for differentiating elementary operations

$\longrightarrow$ yield elementary Jacobians M_λ

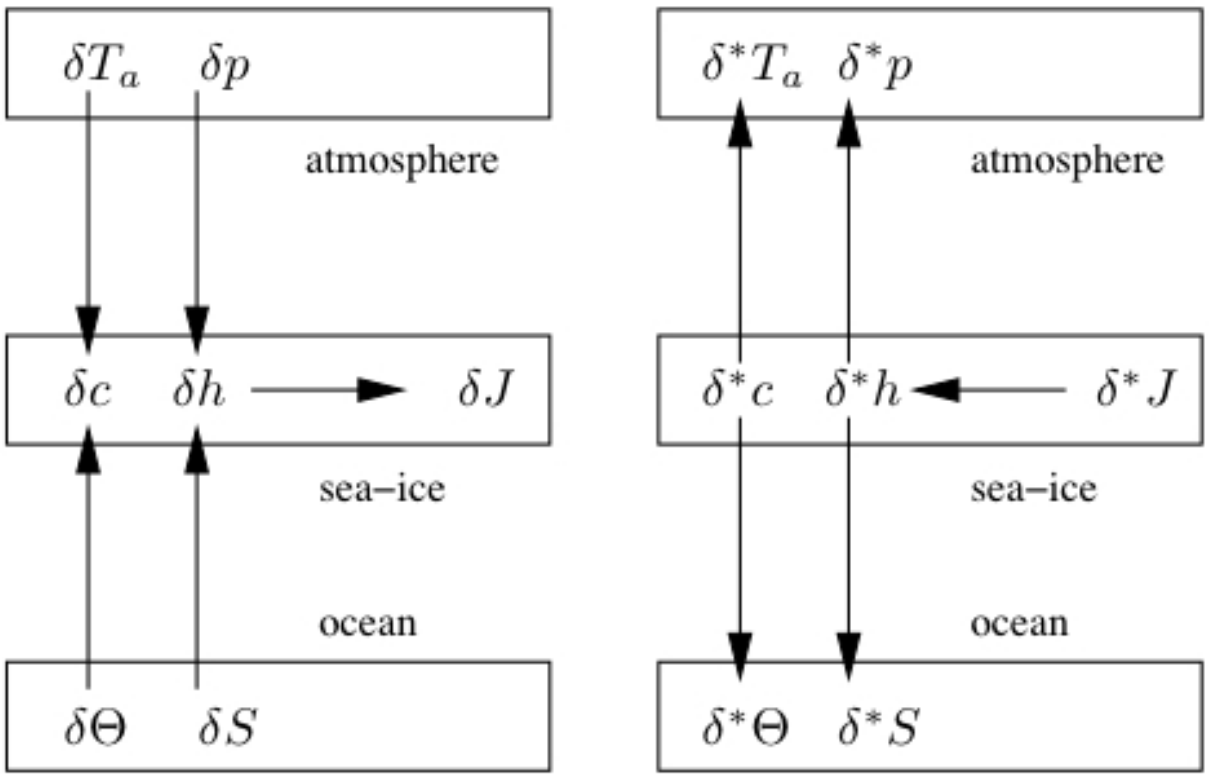
$\longrightarrow$ composition of M_λ's according to chain rule

yield full tangent linear / adjoint model

- TAMC / TAF source-to-source tool (Giering & Kaminski, 1998)

$$\left.\begin{array}{l}\bullet\ \text{model } \mathcal{M}\\ \bullet\ \text{independent } \vec{u}\\ \bullet\ \text{dependent } \mathcal{J}\end{array}\right\} \xrightarrow{\text{TAMC / TAF}} \left\{\begin{array}{l}\text{TLM } M, \text{ or}\\ \text{ADM } M^T, \text{ or}\\ \text{gradient } \delta^*\vec{u} = \vec{\nabla}_u\mathcal{J}\end{array}\right.$$

The coupled ocean/sea-ice adjoint

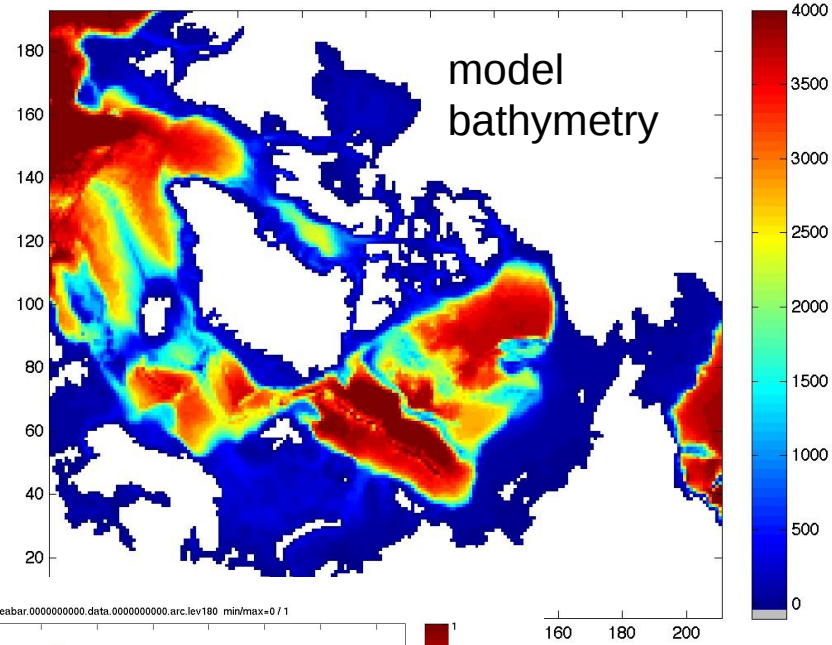


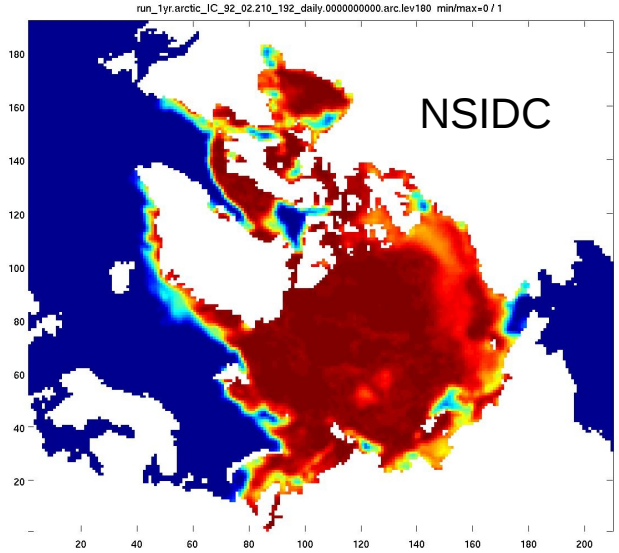
Sensitivity of ice export to all elements in the coupled state:

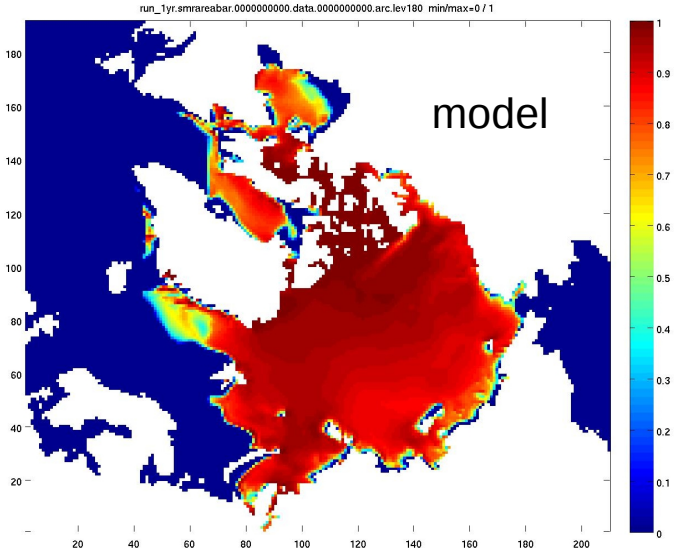
- **sea-ice** (e.g. thickness, concentration, snow cover)
- **ocean** (temperature, salinity, velocities)
- **atmospheric boundary condition** (SAT, specific humidity, precipitation, shortwave radiation, wind velocity)

Arctic configuration

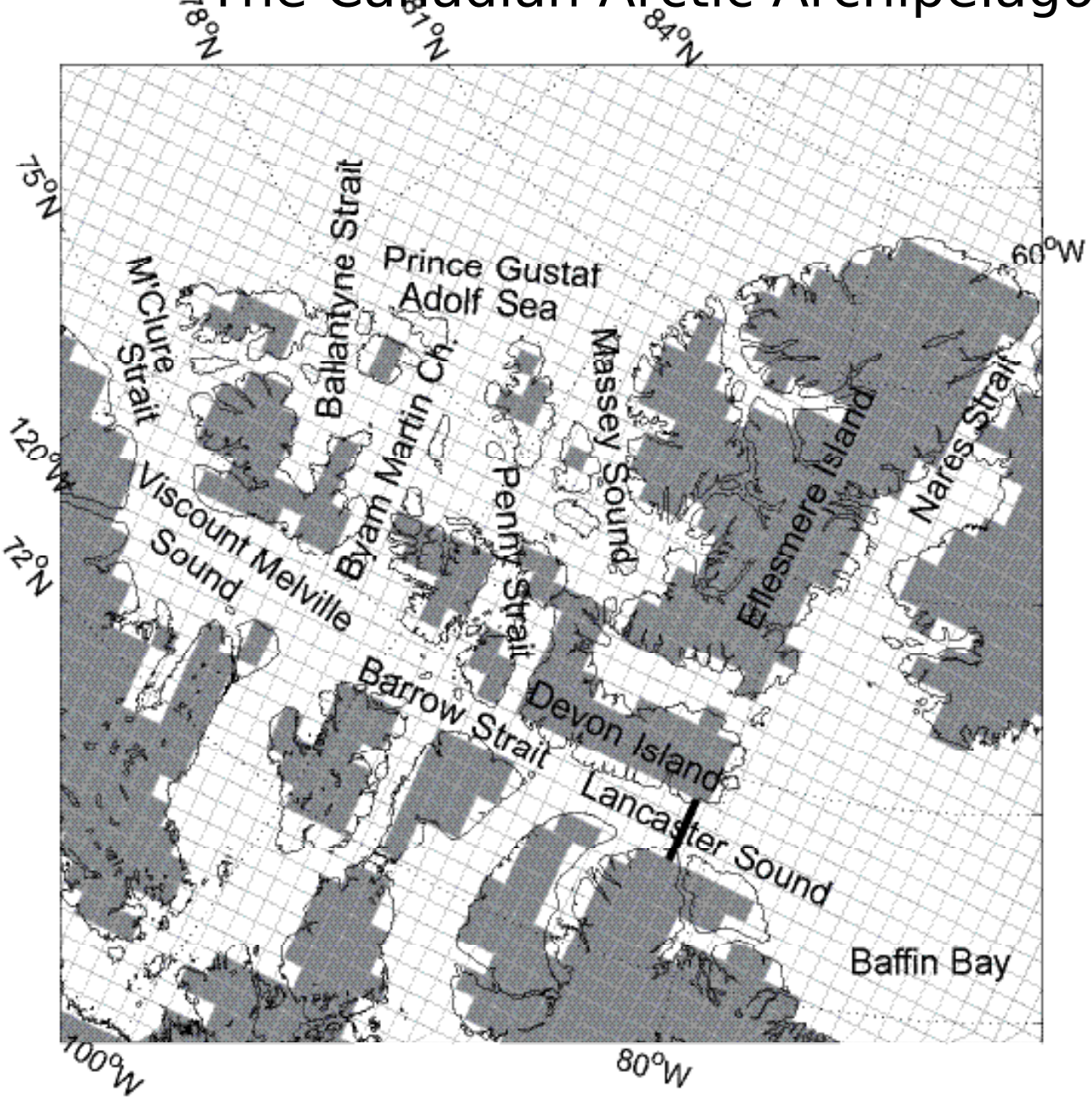
- Coarsened Arctic face of the ECCO2 global cubed sphere (from ~18 km to ~36 km horizontal resolution)
- Underlying ocean model uses various parameterization schemes (KPP, GM/Redi)
- 6-hourly forcing via NCEP/NCAR atmospheric state, converted to open-ocean air-sea fluxes via Large & Yeager (2004)
- Sea-ice dynamics via LSR on C-grid
- Adjoint runs on 80 processors (e.g. IBM SP, SGI Altix)



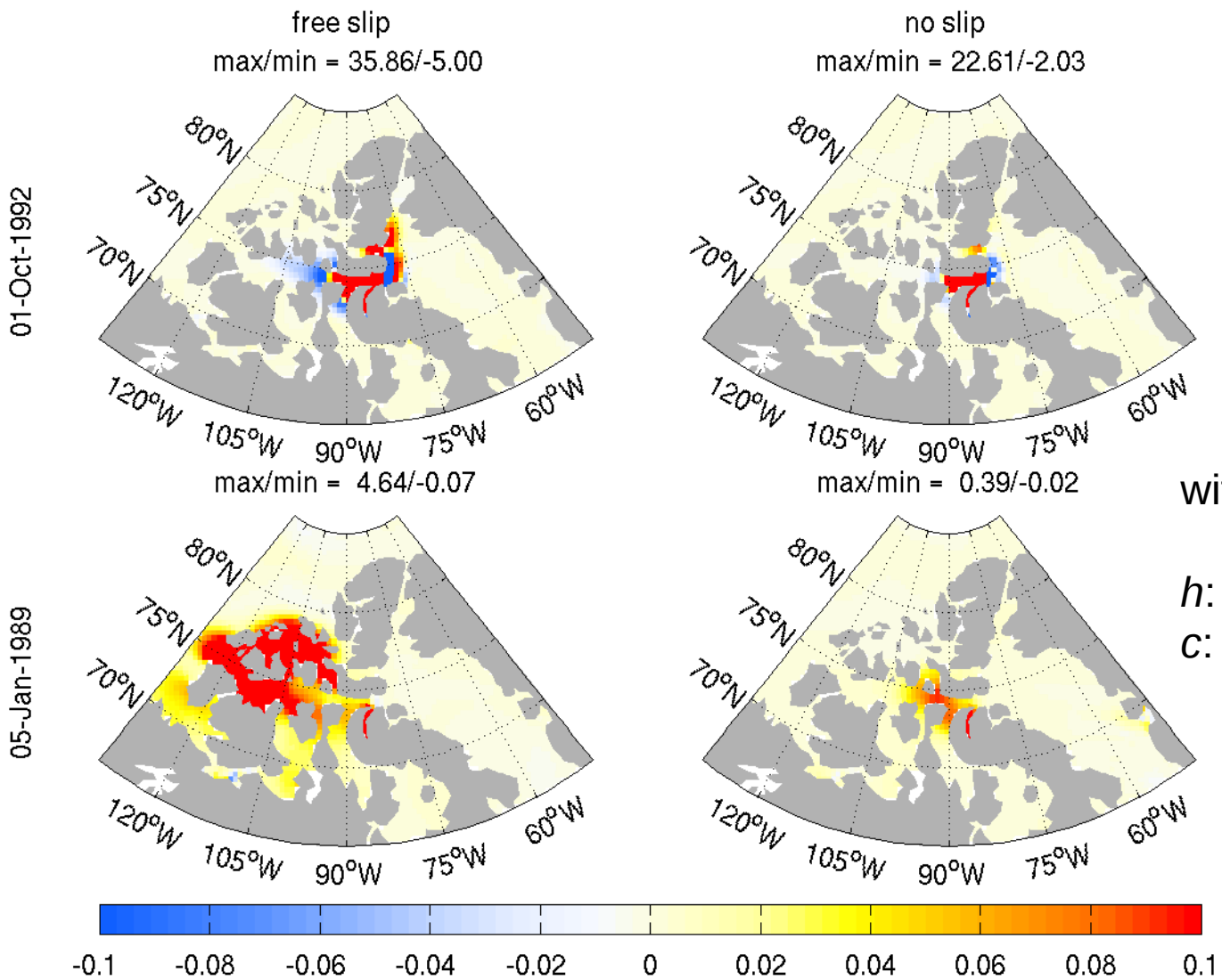




The Canadian Arctic Archipelago



Adjoint sensitivity of solid (snow & ice) freshwater transport through Lancaster Sound



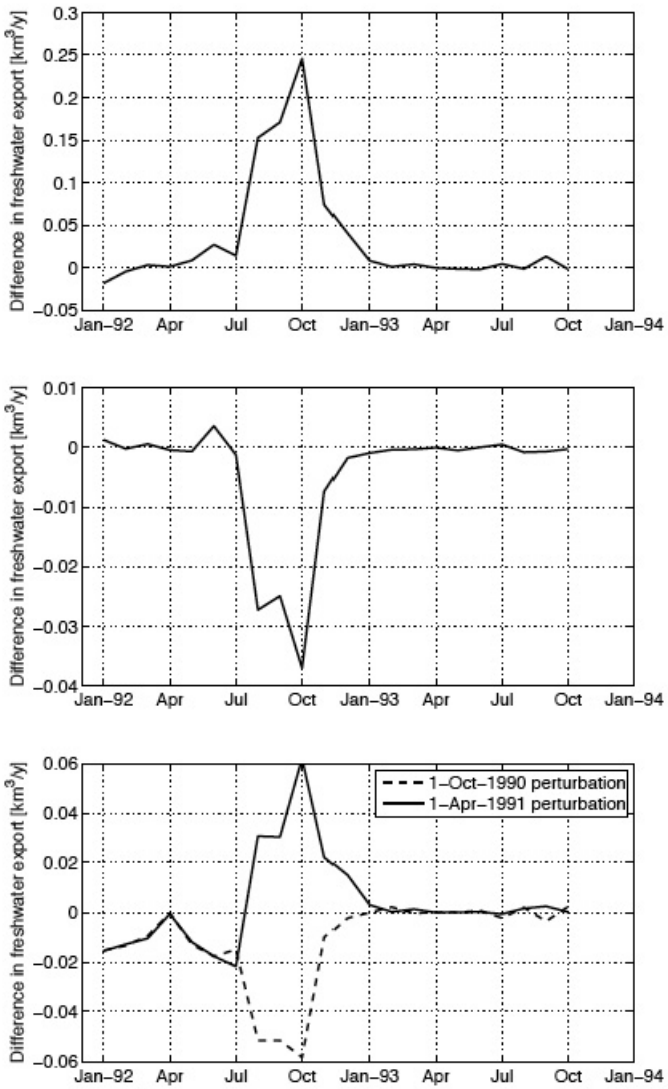
dJ / d(hc)

[m^2s^{-1}/m]

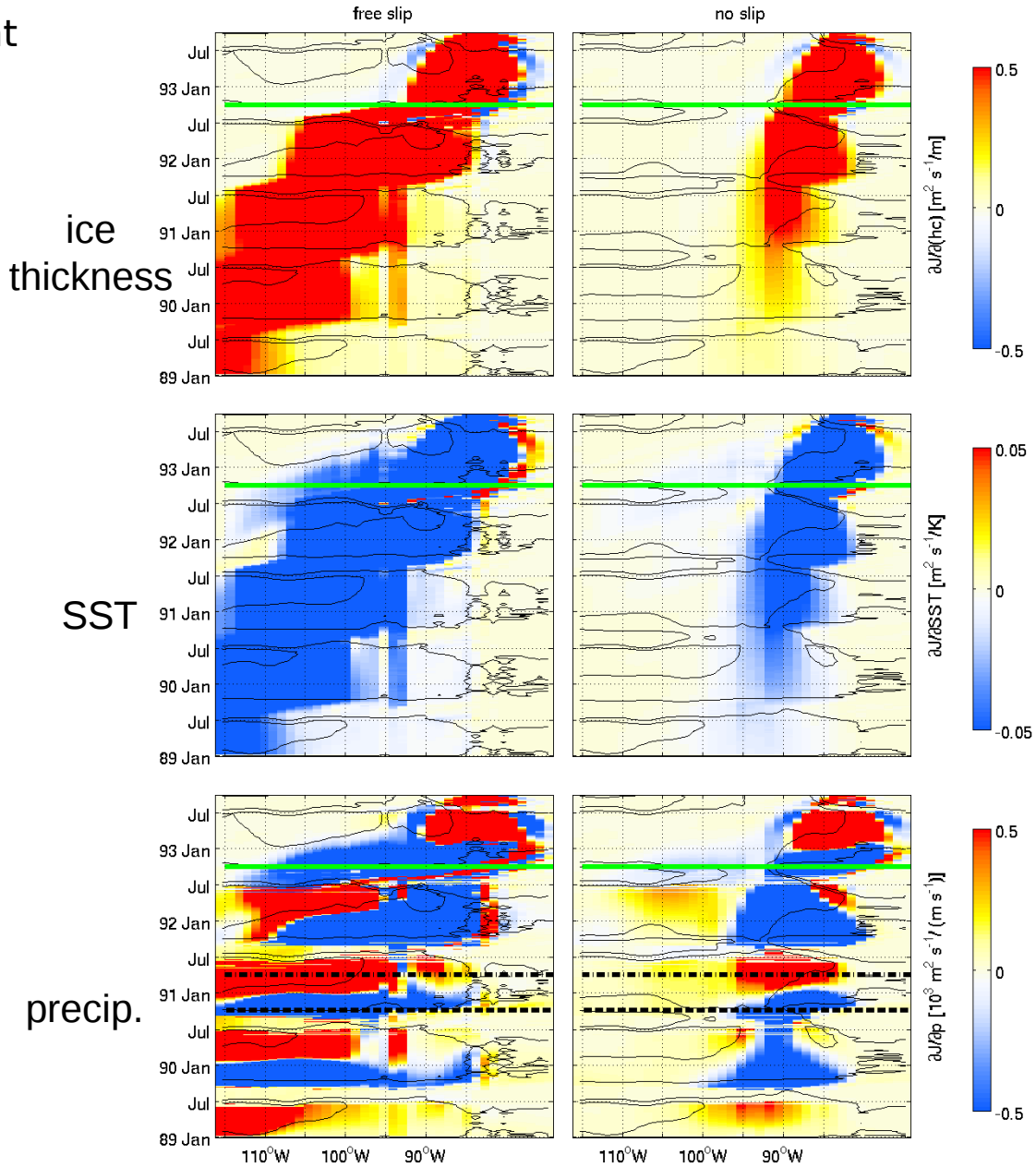
with

h: effective thickness
c: ice concentration

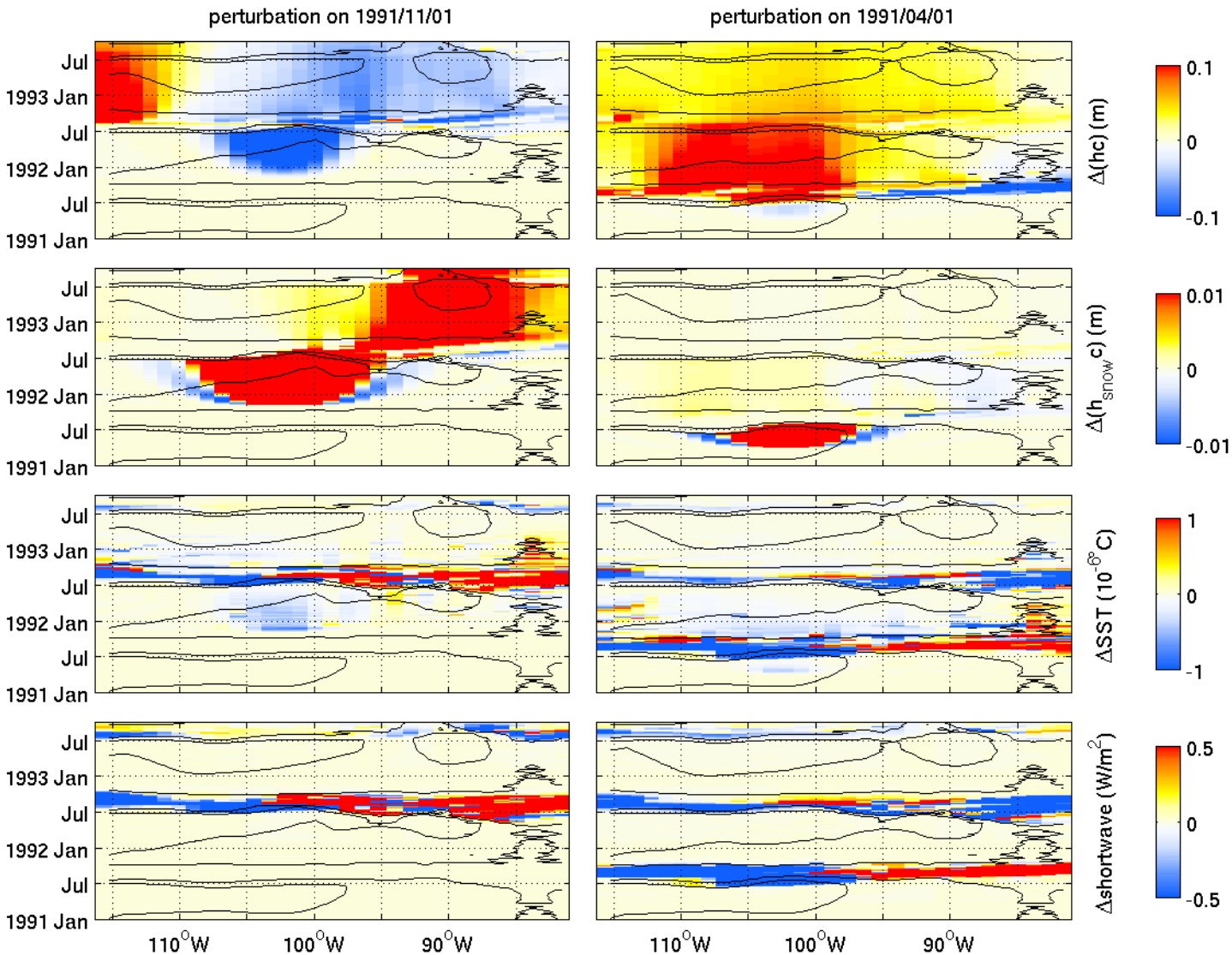
Perturbed - unperturbed ice export, testing the adjoint



Longitude-time diagrams of sensitivities (slice through Lancaster Sound)



Origin of sign change in precipitation sensitivities



Some Results & Outlook

- Complement configuration sensitivities (e.g. free-slip vs. no-slip boundary conditions) through aspects related to state space

- Adjoint model generated via automatic differentiation

- Adjoint sensitivities reveal pathways of ice export influences as function of underlying ocean/atmosphere state

- May reveal unexpected sensitivity behavior (e.g. here, sign of precipitation sensitivities)

- A crucial step to ascertain useful gradients for state estimation, which is the ultimate goal

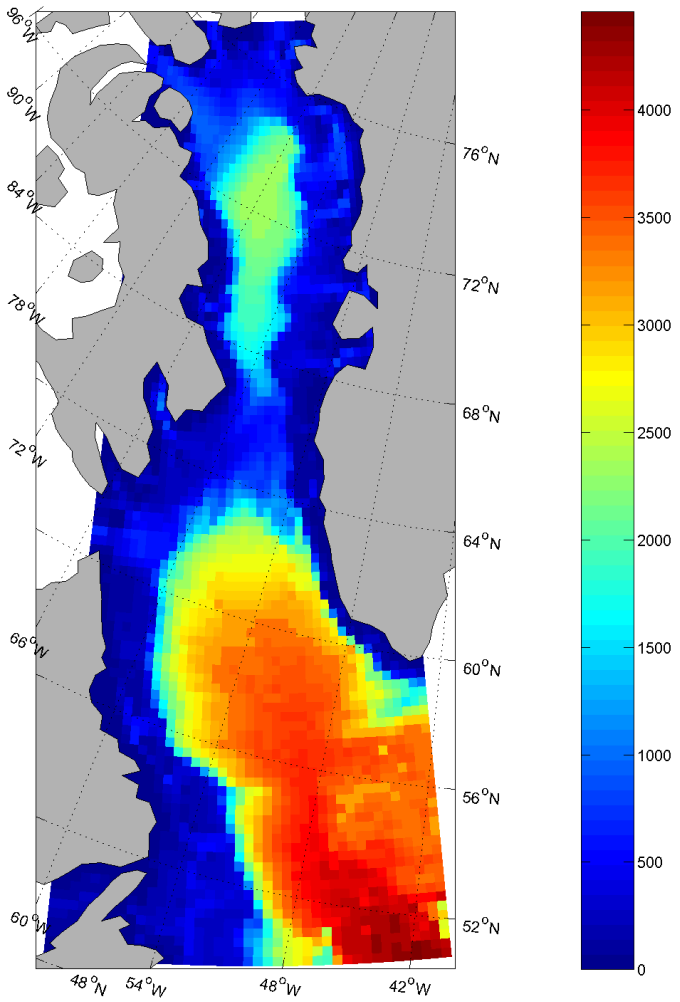
- Coupled problem ought to propagate sensitivities across the model components;

  ➔ could be explored in state estimation

  ➔ obs of one component constrain the other component

Outlook: Sea-ice state estimation in a limited-area setup of the Labrador Sea

- MITgcm with Curvilinear Grid
  - 30 km x 30 km → 30 km x 16 km
  - 23 vertical levels
- 1.5 layer dynamic-thermodynamic sea ice model with snow
  - Stress-Strain rate based on Hibler (1980) ellipse
- Open boundaries
  - Weak sponge layers at Southern and Eastern edges
- Resolved Labrador and Greenland Shelves
  - Critical for sea ice production and advection
  - Important for boundary currents
- Computational efficient
  - Parallel: 1 real hr/ simulated year on 6 nodes

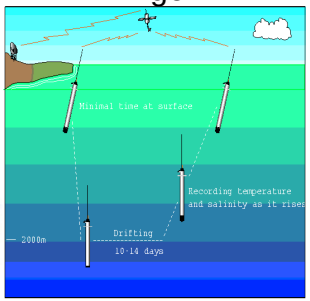


Bathymetry of model domain. Each distinct pixel is on cell

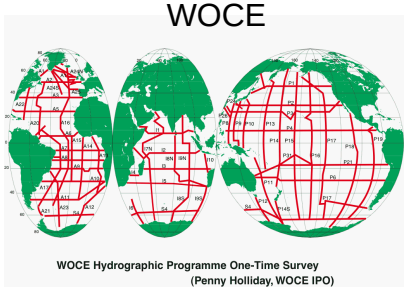
Ian Fenty (Ph.D. thesis, 2009)

Ocean State Estimation (data assimilation)

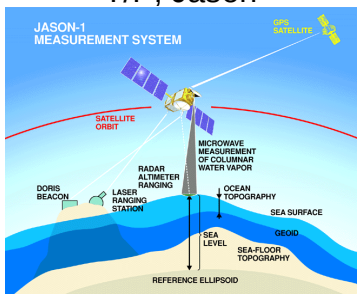
Argo



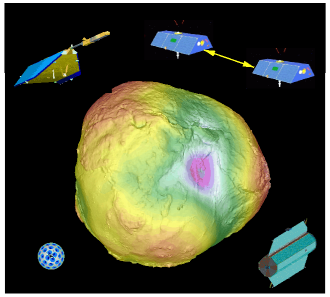
WOCE



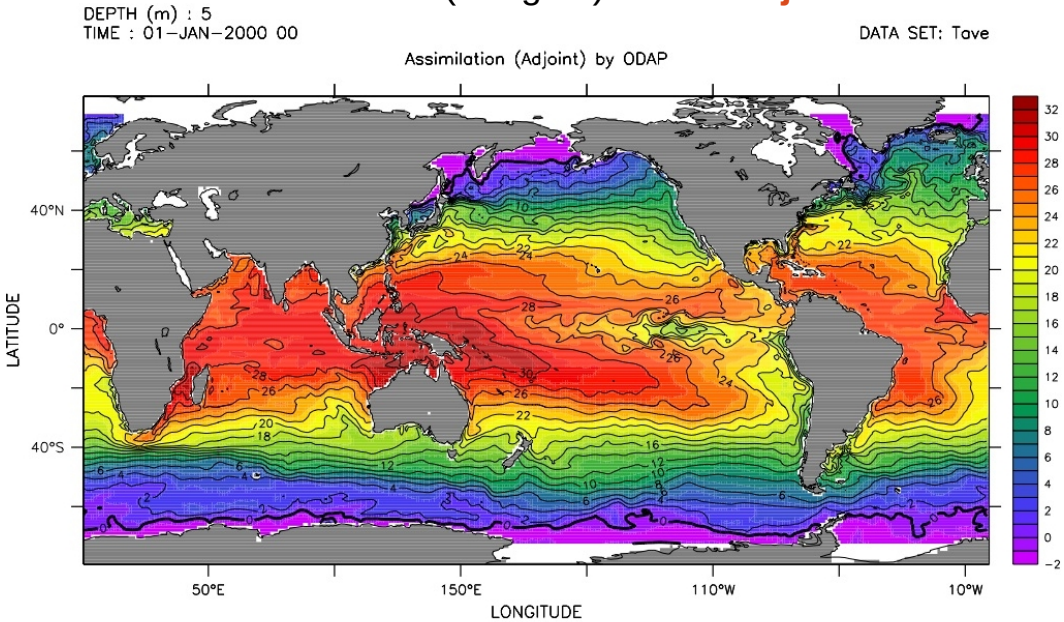
T/P, Jason



GRACE



How to synthesize? Estimation/optimal control problem:
Use a **model** (MITgcm) and its **adjoint**:

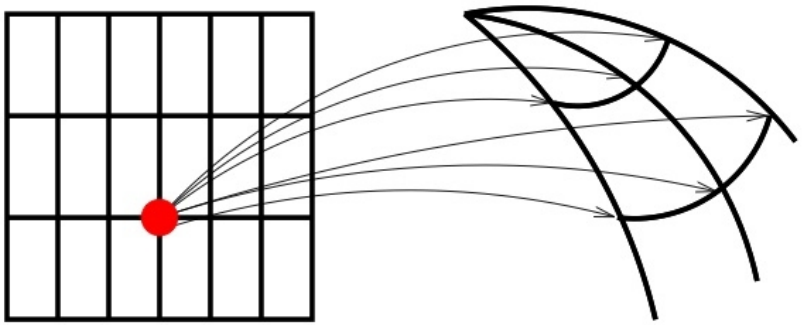


Temperature (Deg C)

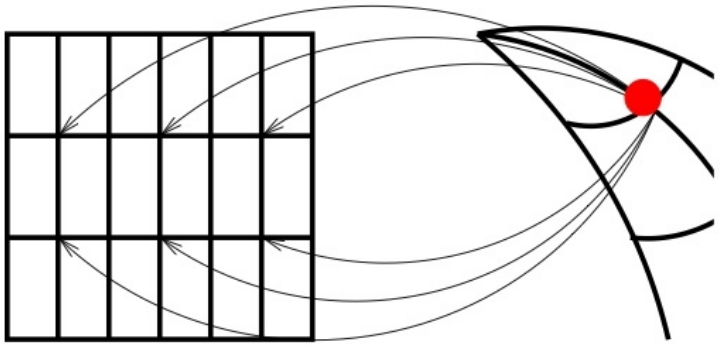
Sensitivity calculations in forward or reverse

- **Finite difference approach:**
  - Take a "guessed" anomaly (SST) and determine its impact on model output (MOC)
  - Perturb each input element ($\mathrm{SST(i,j)}$) to determine its impact on output (MOC).

- **Reverse/adjoint approach:**
  - Calculates "full" sensitivity fi eld
    $$\frac{\partial\,\mathrm{MOC}}{\partial\,\mathrm{SST}(x,y,t)}$$
  - Approach:
    Let $\mathcal{J} = \mathrm{MOC}$, $\vec{u} = \mathrm{SST(i,j)}$
    $$\longrightarrow \boxed{\vec{\nabla}_u \mathcal{J}(\vec{u})} = \frac{\partial\,\mathrm{MOC}}{\partial\,\mathrm{SST}(x,y,t)}$$



Impact of ***one input*** on ***all outputs***



Sensitivity of ***one output*** to ***all inputs***