Sensitivities of sea-ice export through the Canadian Arctic Archipelago in a coupled ocean/sea-ice adjoint modeling framework

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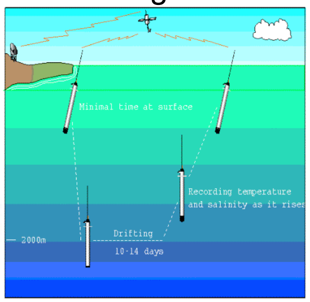
http://www.ecco-group.org
http://mitgcm.org

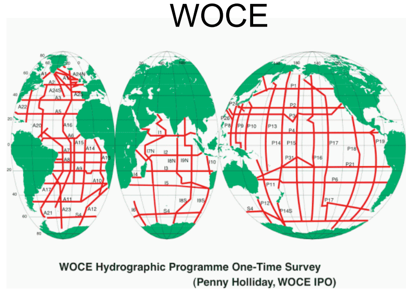
Ocean State Estimation
(data assimilation)

SEaOS

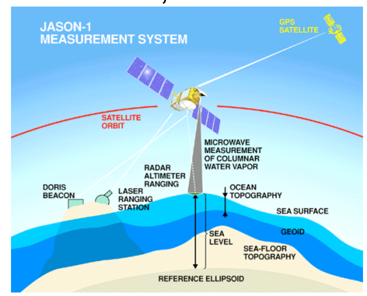
Argo



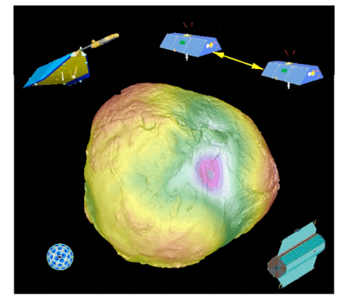
WOCE



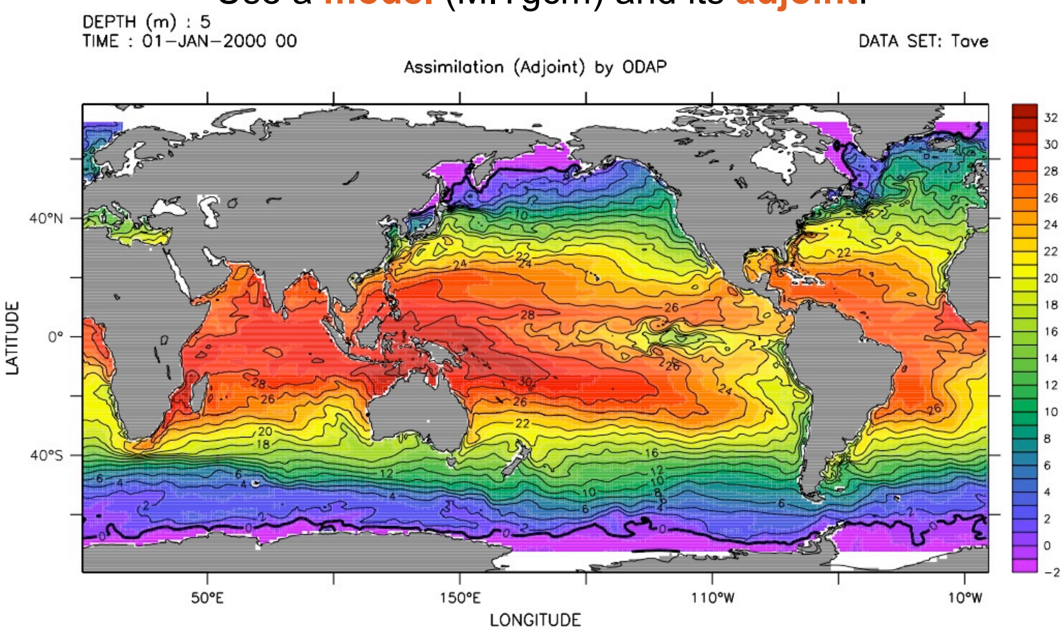
T/P, Jason



GRACE

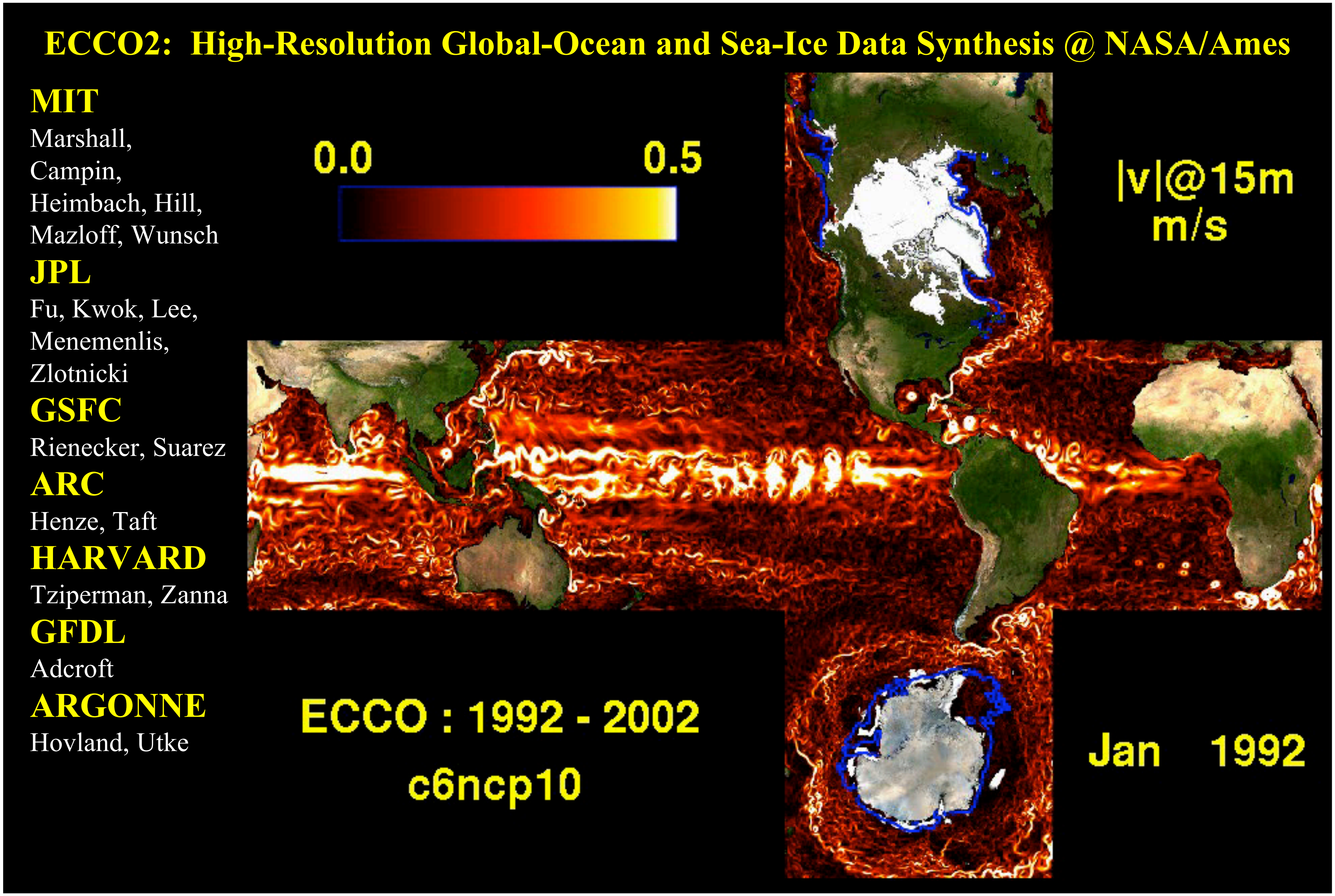


How to synthesize? Estimation/optimal control problem:
Use a **model** (MITgcm) and its **adjoint**:



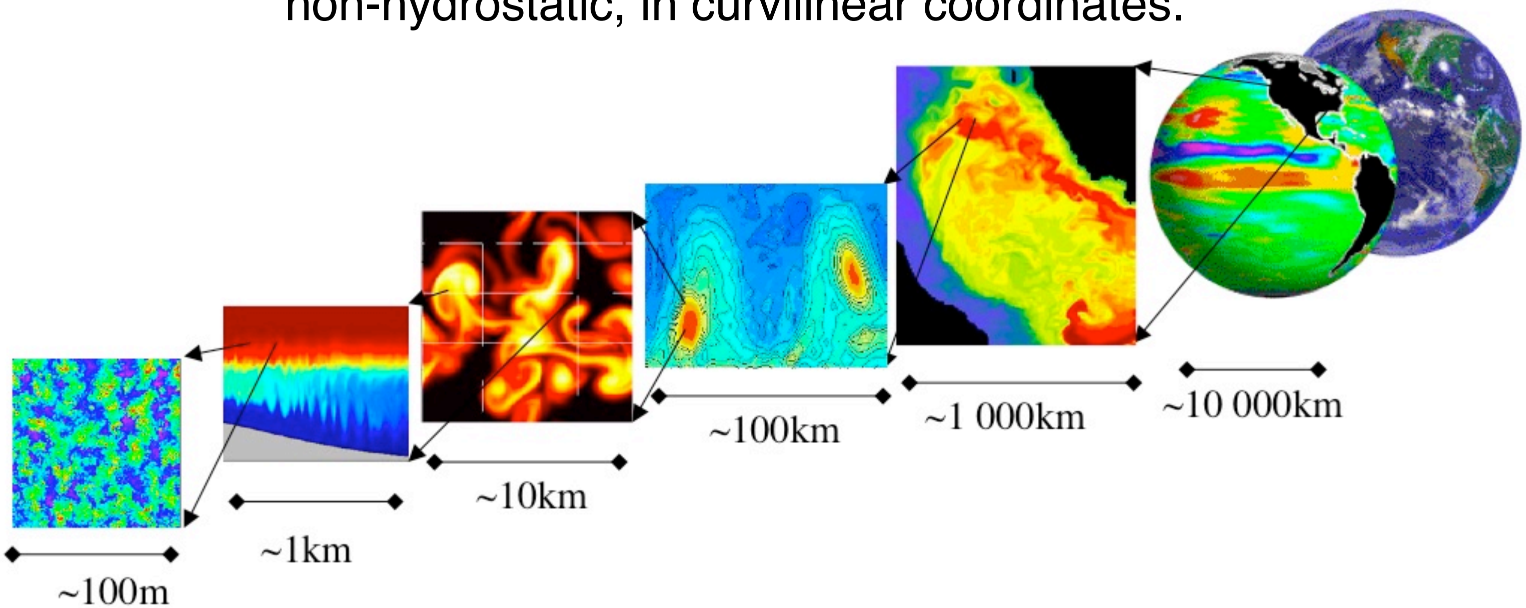
Temperature (Deg C)

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



The MIT general circulation model (MITgcm)

Parallel implementation of a general-purpose grid-point algorithm for a Boussinesq or non-Boussinesq fluid, hydrostatic or non-hydrostatic, in curvilinear coordinates.



- z-level or pressure vertical coordinates (ocean - atmosphere isomorphism)
- nonlinear free surface and z^* vertical coordinates
- finite-volume formulation with partial cells
- various parameterization schemes (GM/Redi, KPP, Leith, Smagorinsky)
- thermodynamic/dynamic sea-ice model (Hibler-type)
- ocean biogeochemical model
- cubed-sphere global grid topology

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., in press 2008)*
- Dynamics
  - Two solvers available for viscous-plastic (VP) rheology:
    - Line Successive Relaxation (LSR) implicit *(Zhang & Hibler, 1997)*
    - Elastic Viscous-Plastic (EVP) explicit *(Hunke & Dukowicz, 1997)*
  - Both ported on C-grid for use in generalized curvilinear grids
  - 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)***

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

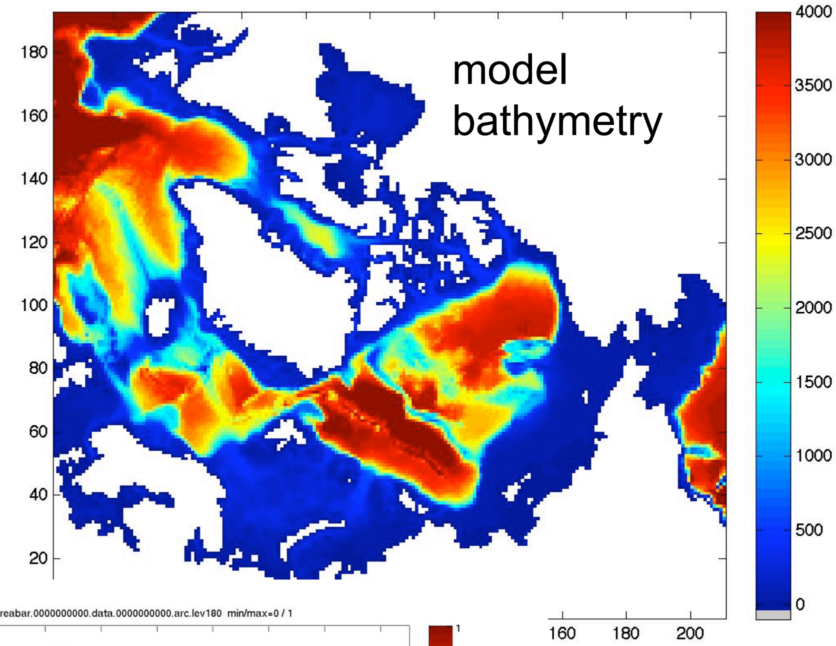
yield full tangent linear / adjoint model

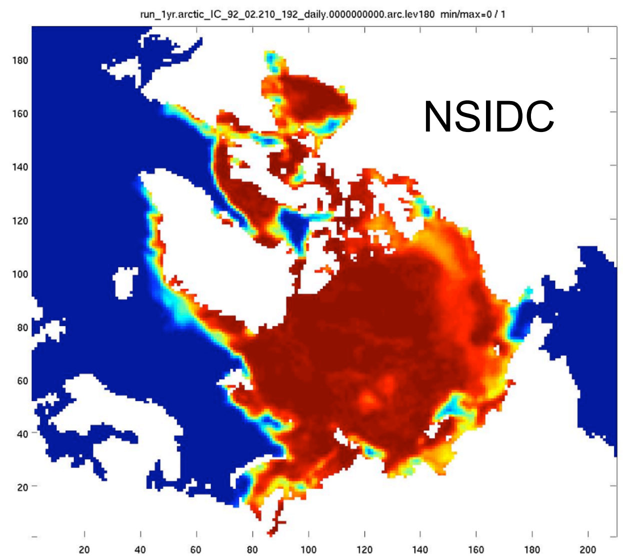
- TAMC / TAF source-to-source tool (Giering & Kaminski, 1998)

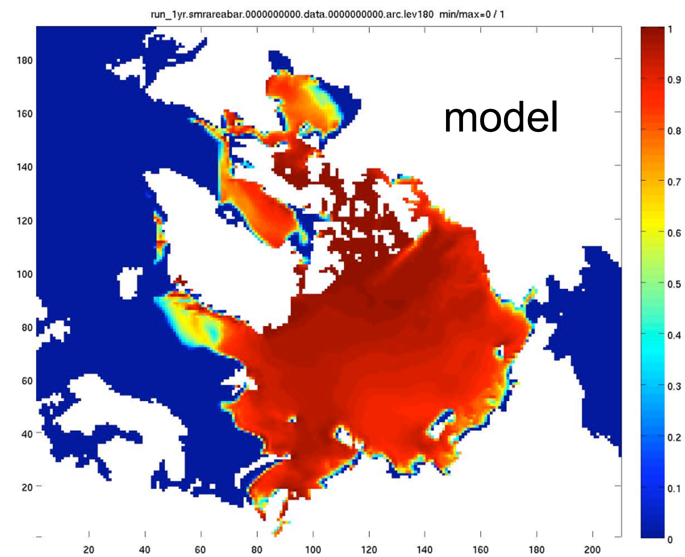
$$\left.\begin{array}{l} \bullet \text{ model } \mathcal{M} \\ \bullet \text{ independent } \vec{u} \\ \bullet \text{ dependent } \mathcal{J} \end{array}\right\} \xrightarrow{\text{TAMC / TAF}} \left\{\begin{array}{l} \text{TLM } M, \text{ or} \\ \text{ADM } M^T, \text{ or} \\ \text{gradient } \delta^*\vec{u}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

Arctic configuration

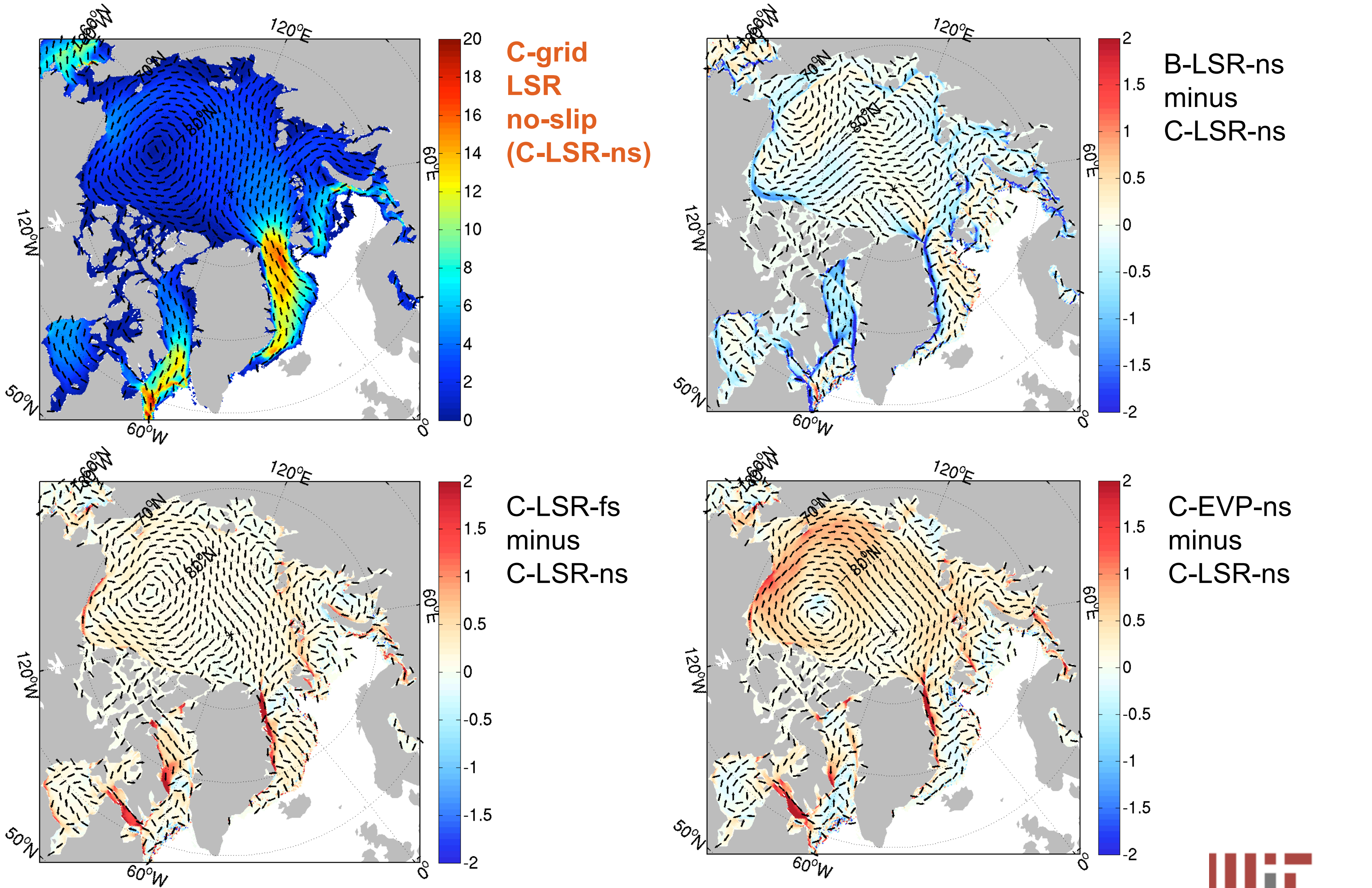
- Coarsened Arctic face of the ECCO2 global cubed sphere (from ~18 km to ~36 km horizontal resolution)
- Underlying ocean model uses various parameterization schemes (KPP, GM/Redi)
- 6-hourly forcing via NCEP/NCAR atmospheric state, converted to open-ocean air-sea fluxes via Large & Yeager (2004)
- Sea-ice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



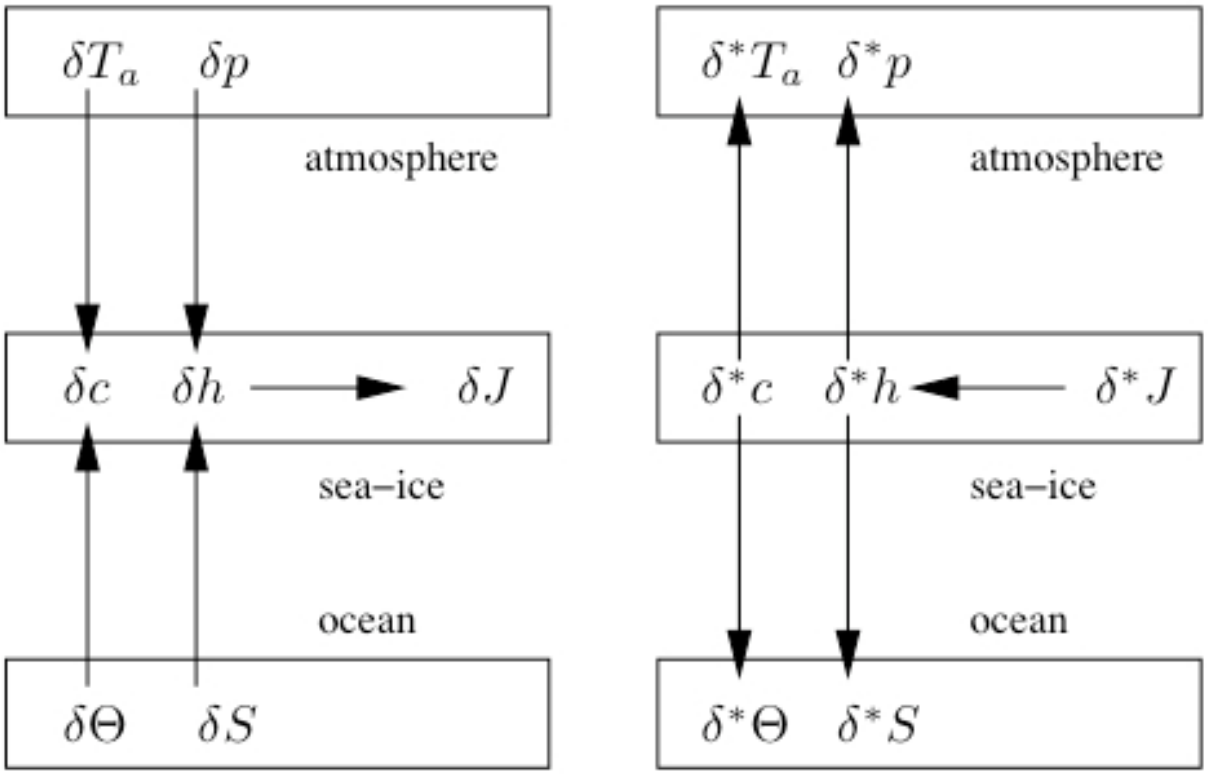




The forward model - configuration sensitivities
Ice drift velocities



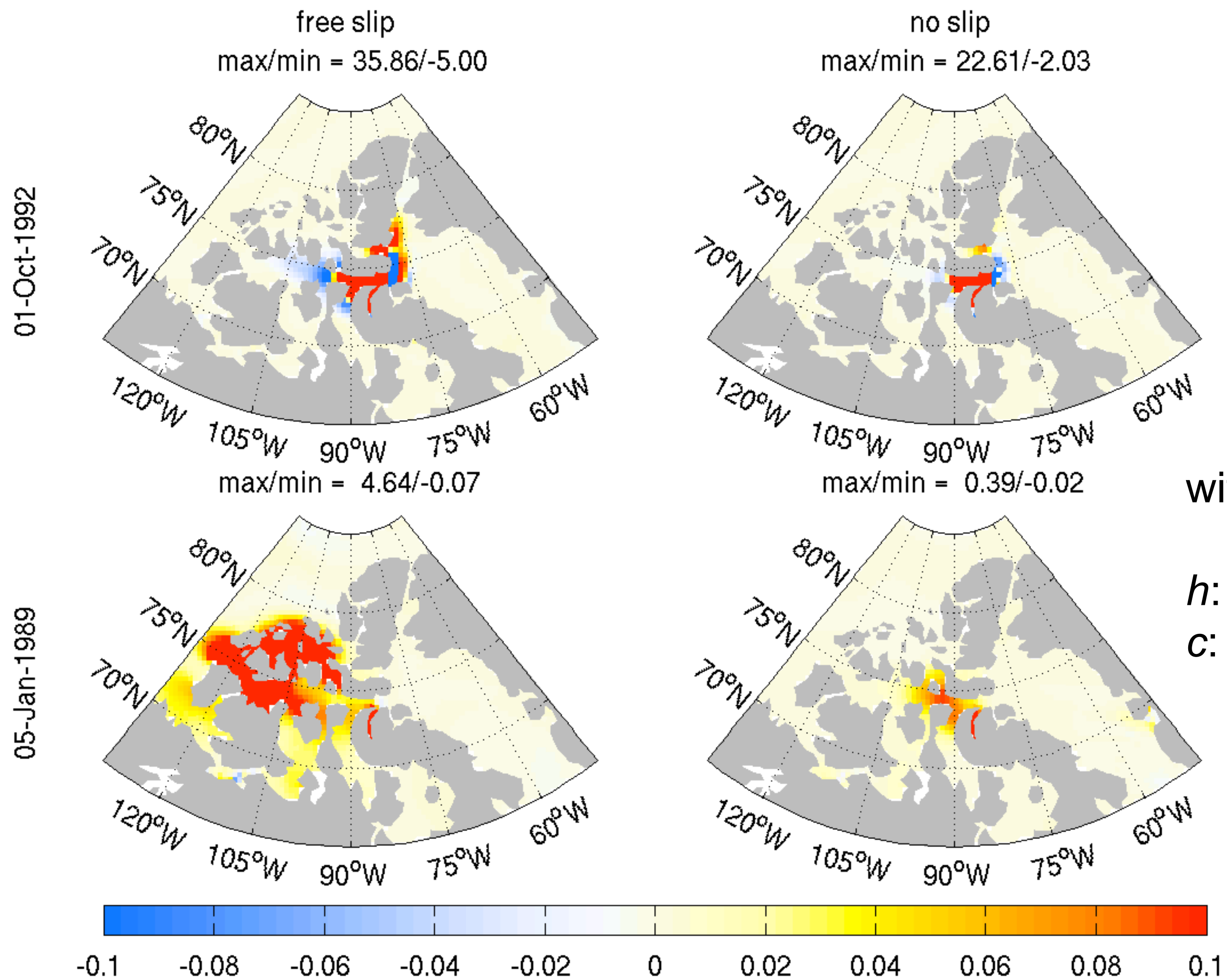
The coupled ocean/sea-ice adjoint



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)

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



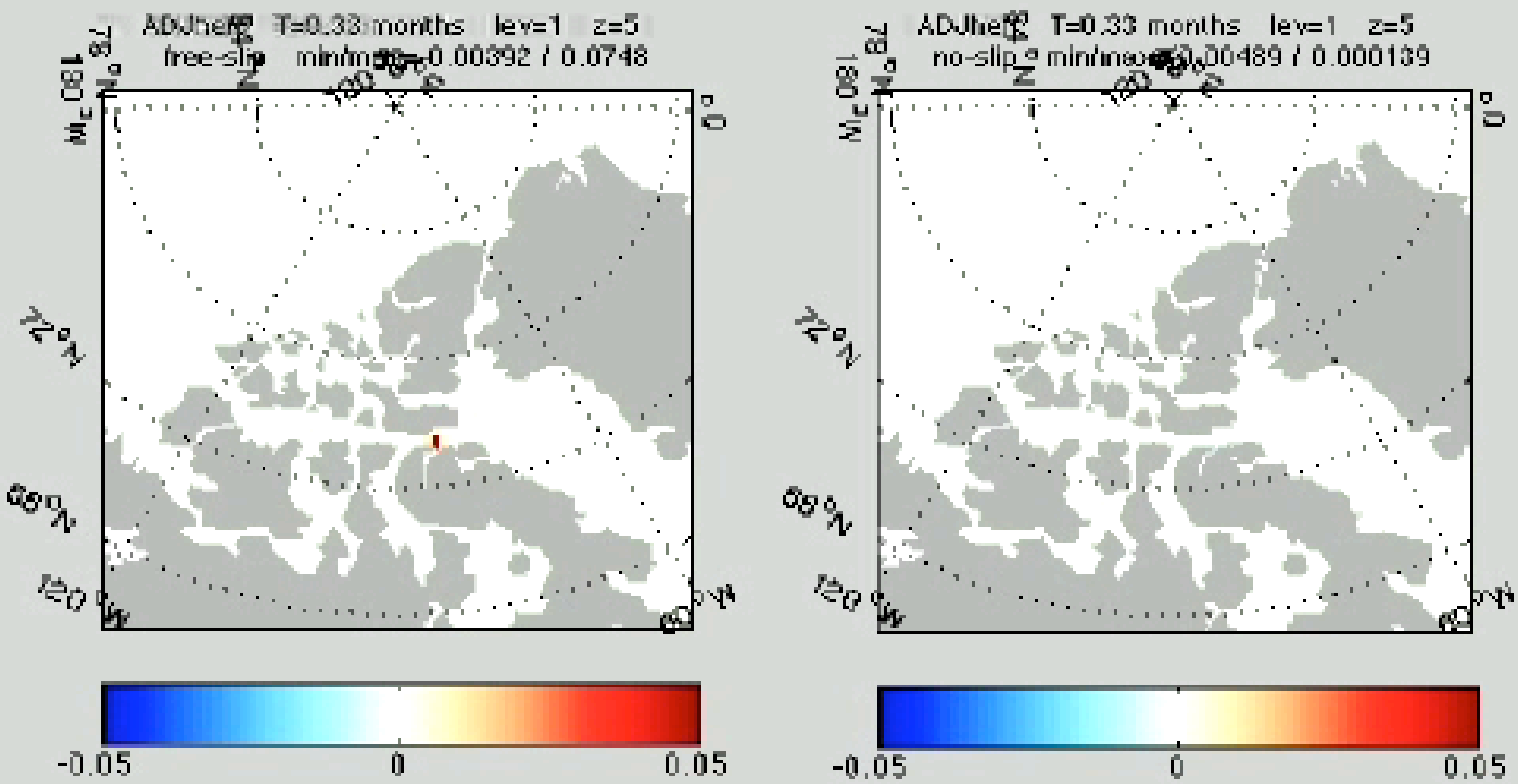
dJ / d(hc)

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

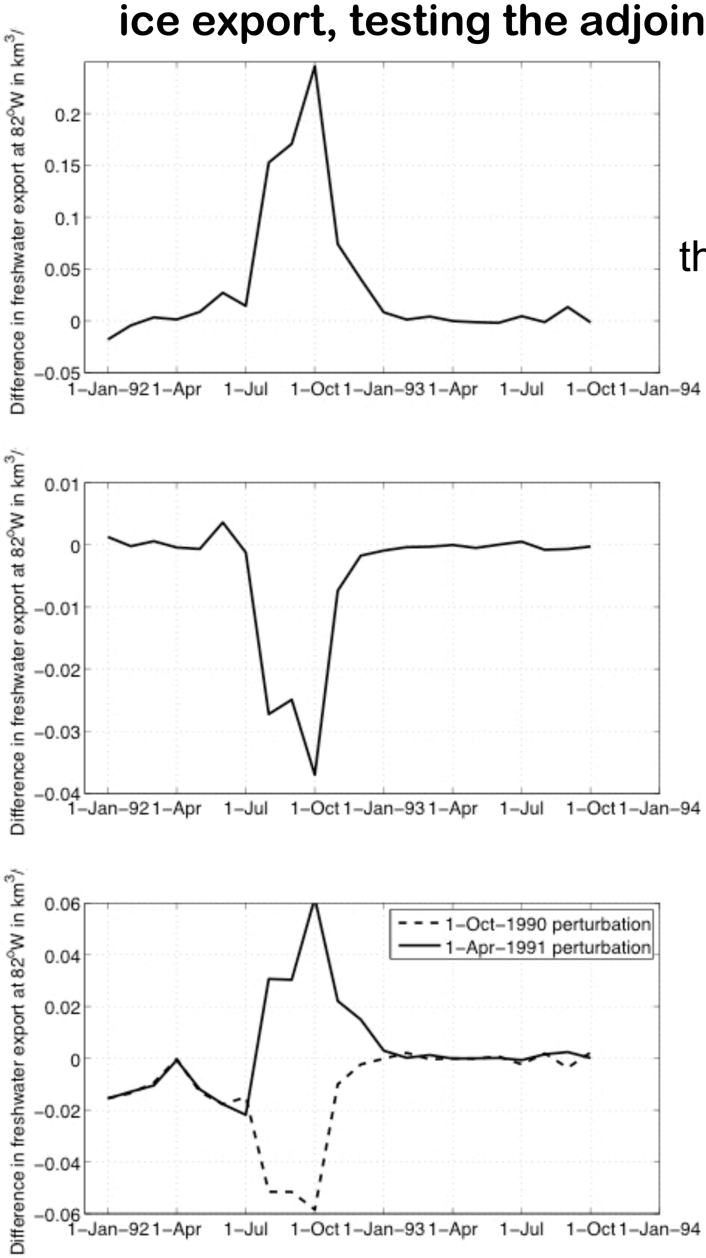
with

h: effective thickness
c: ice concentration

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



Perturbed - unperturbed ice export, testing the adjoint

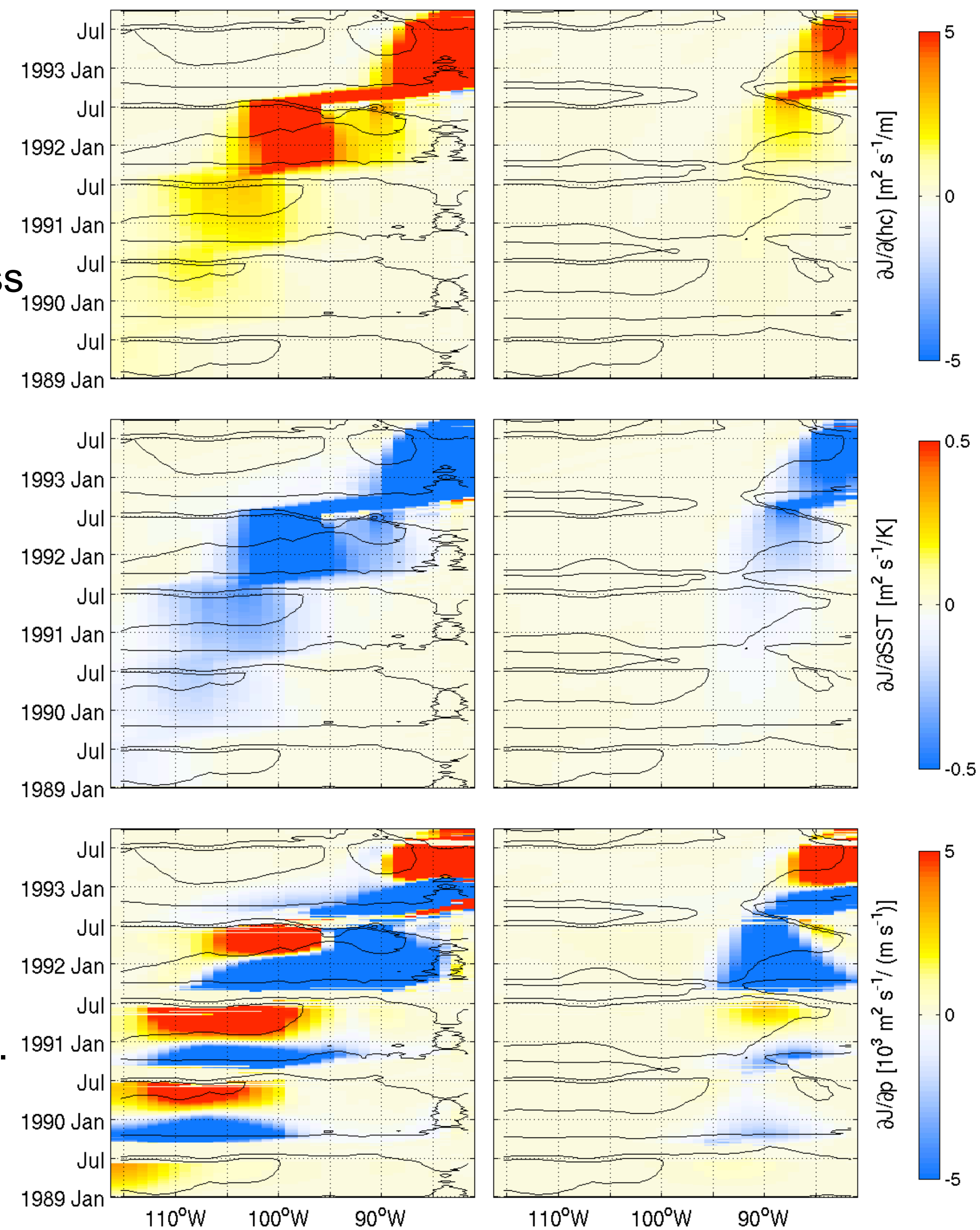


Longitude-time diagrams of sensitivities (slice through Lancaster Sound)

ice thickness

SST

precip.



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, oscillatory 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;

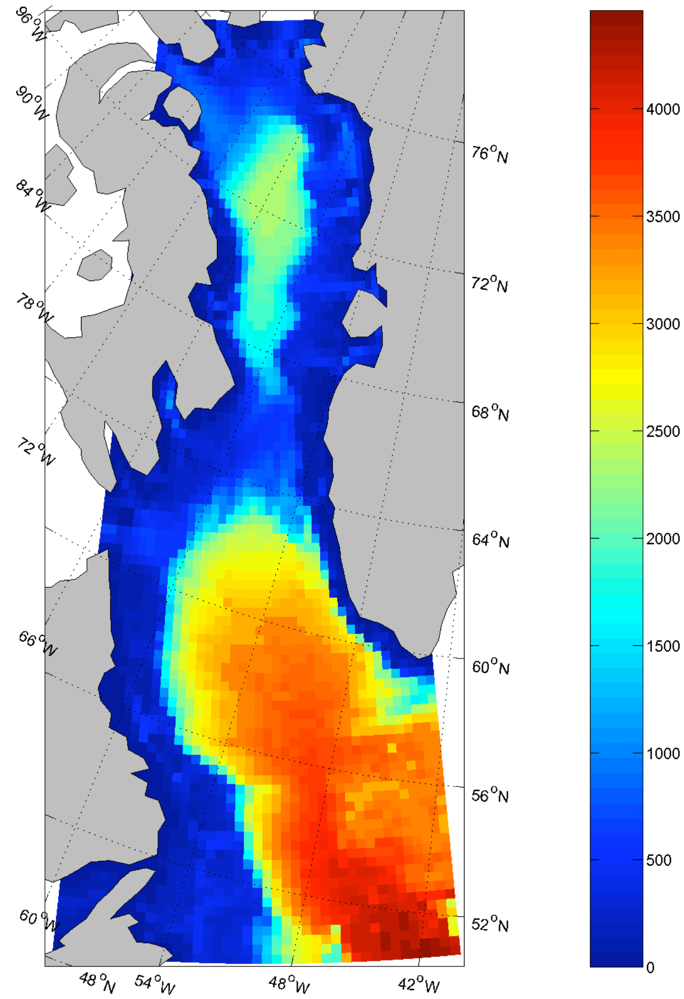
  ➔ could be explored in state estimation

  ➔ 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

Ian Fenty (Ph.D. thesis)
See also:
MOCA-09, Montreal, July, 2009

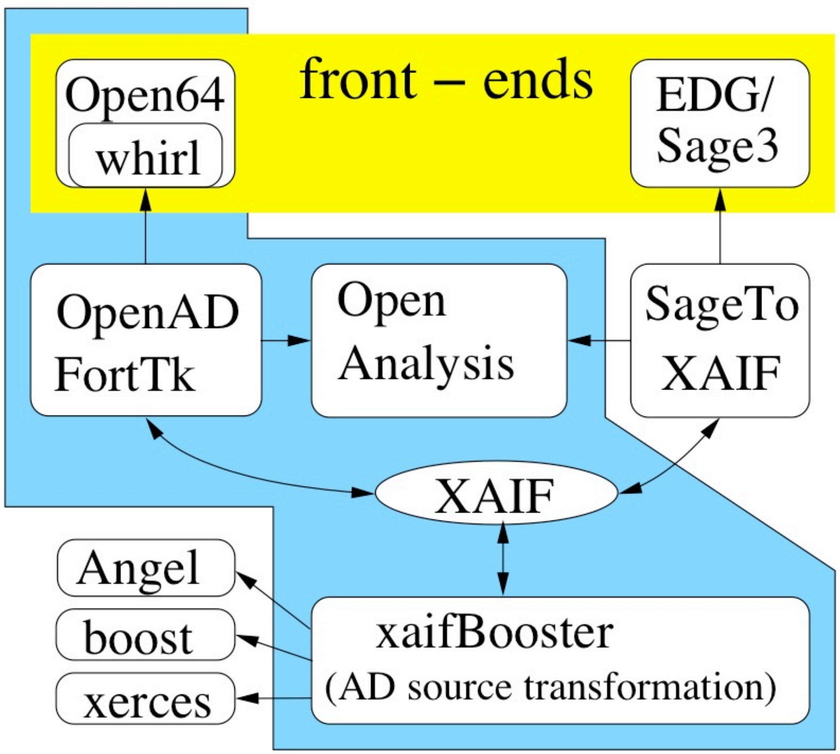


Bathymetry of model domain.
Each distinct pixel is on cell

OpenAD: a new open-source automatic differentiation tool

http://www.mcs.anl.gov/OpenAD

@ *ANL:* ***J. Utke***, B. Norris, M. Strout, P. Hovland
@ *Rice:* N. Tallent, G. Mellor-Crummy, M. Fagan
@ *MIT:* P. Heimbach, C. Hill, C. Wunsch
@ *RWTH:* ***U. Naumann***

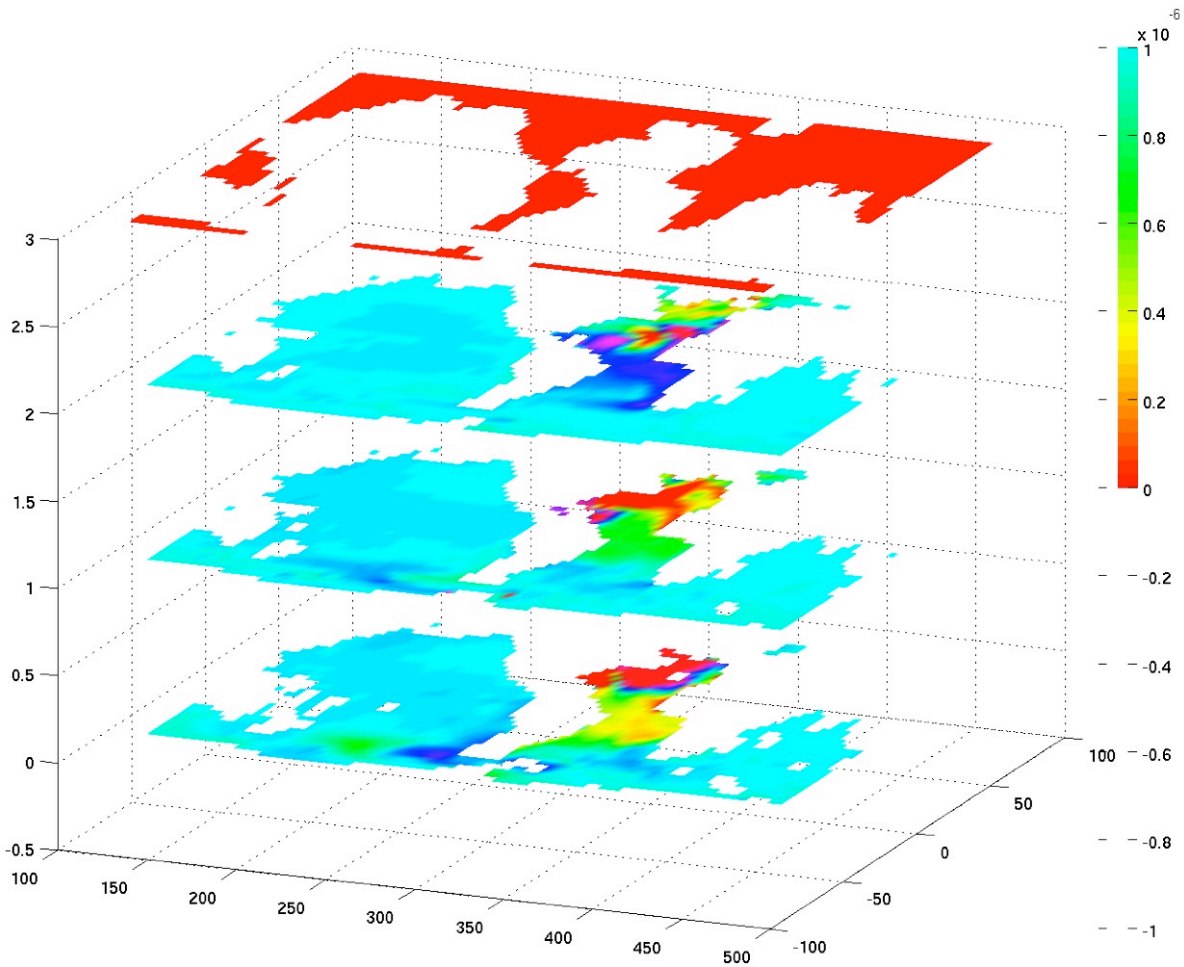


Tool design emphases:

- modularity
- flexibility
- use of open-source components
- new algorithmic approaches

• XML-based language-independent transformation
• basic block preaccumulation
• other optimal elimination methods
• control flow & call graph reversal
• taping & hierarchical checkpointing

Atlantic meridional heat transport: 10-year sensitivities at 4^{o} resolution (OpenAD)



First ***MITgcm*** application using ***OpenAD***, and with implemented checkpointing at the time-stepping level (now running at 1^{o})

Extend adjoint integration of heat flux sensitivities backward in time (here at coarser resolution).

Confirms role of propagating waves (Rossby waves, Kelvin waves) over these time scales in fast signal propagation over long distances.