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SJTU

Effects of inclusion of adjoint sea ice rheology on estimating Arctic ocean-sea ice state

Guokun Lyu and Meng Zhou

School of Oceanography, Shanghai Jiao Tong University, Shanghai, China

Guokun.lyu@sjtu.edu.cn

In collaboration with Armin Koehl, Nuno Serra, and
Detlef Stammer at university of Hamburg

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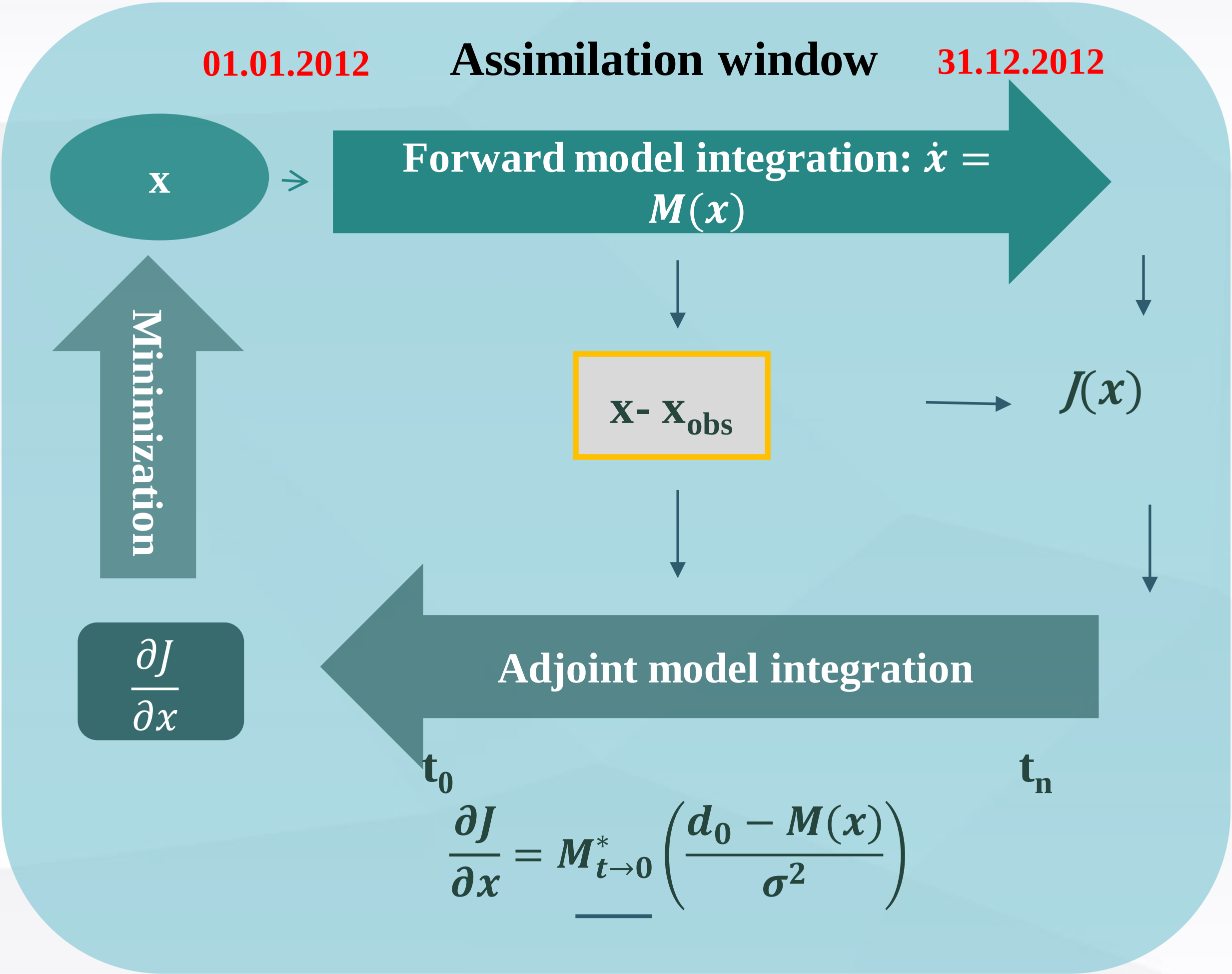
Background and Motivation

Schematic of the adjoint method



Control variables x:

- Initial state in 2012: T/S/SIC/HEFF
- Daily atmospheric forcing:
  - 2-m air temp
  - U/V wind
  - Longwave/Shortwave
  - Specific hum

Background and Motivation

Sea-ice dynamics: $$m\frac{d\vec{u}}{dt} = -mf\vec{k}\times\vec{u} + \tau_a + \tau_w - mg\nabla P(0) + \nabla\cdot\sigma$$

Viscous-Plastic (VP) Rheology:

Stress tensor: $$\sigma_{ij} = 2\eta\varepsilon_{ij} + [\zeta-\eta]\varepsilon_{kk}\delta_{ij} - \frac{P}{2}\delta_{ij}$$

Shear Viscosities: $$\zeta = P/_{2\Delta}$$

Bulk Viscosities: $$\eta = P/_{(2e^2\Delta)}$$

$$\Delta = \left[(\varepsilon_{11}^2+\varepsilon_{22}^2)(1+e^{-2}) + 4e^{-2}\varepsilon_{12}^2 + 2\varepsilon_{11}\varepsilon_{22}(1-e^{-2})\right]^{\frac{1}{2}}$$

Ice pressure: $$P = P^{*}\mathrm{H}\times\exp(-C^{*}\times(1-A))$$

Ice strain rate: $$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

e=2.0: Eccentricity of the yield curve describing the viscous-plastic rheology
$P^* = 2.5*10^4$: Ice compressive strength constant
C^*=20.0: Ice strength decay constant

- Sea ice adjoint sensitivity:
  - Heimbach et al., 2010, OM
  - Kauker et al., 2009, GRL
  - Koldunov et al., 2013, CD
  - **Toyoda et al., 2019, MWR**
- State estimation:
  - ECCOV2~ECCOV4
  - Fenty and Heimbach, 2013, JPO
  - Koldunov et al., 2017, TC
  - **Lyu et al., 2021, QJRMS**
  - Nguyen et al., 2021, JAMES

Effects of Inclusion of Adjoint Sea Ice Rheology on Backward Sensitivity Evolution Examined Using an Adjoint Ocean–Sea Ice Model

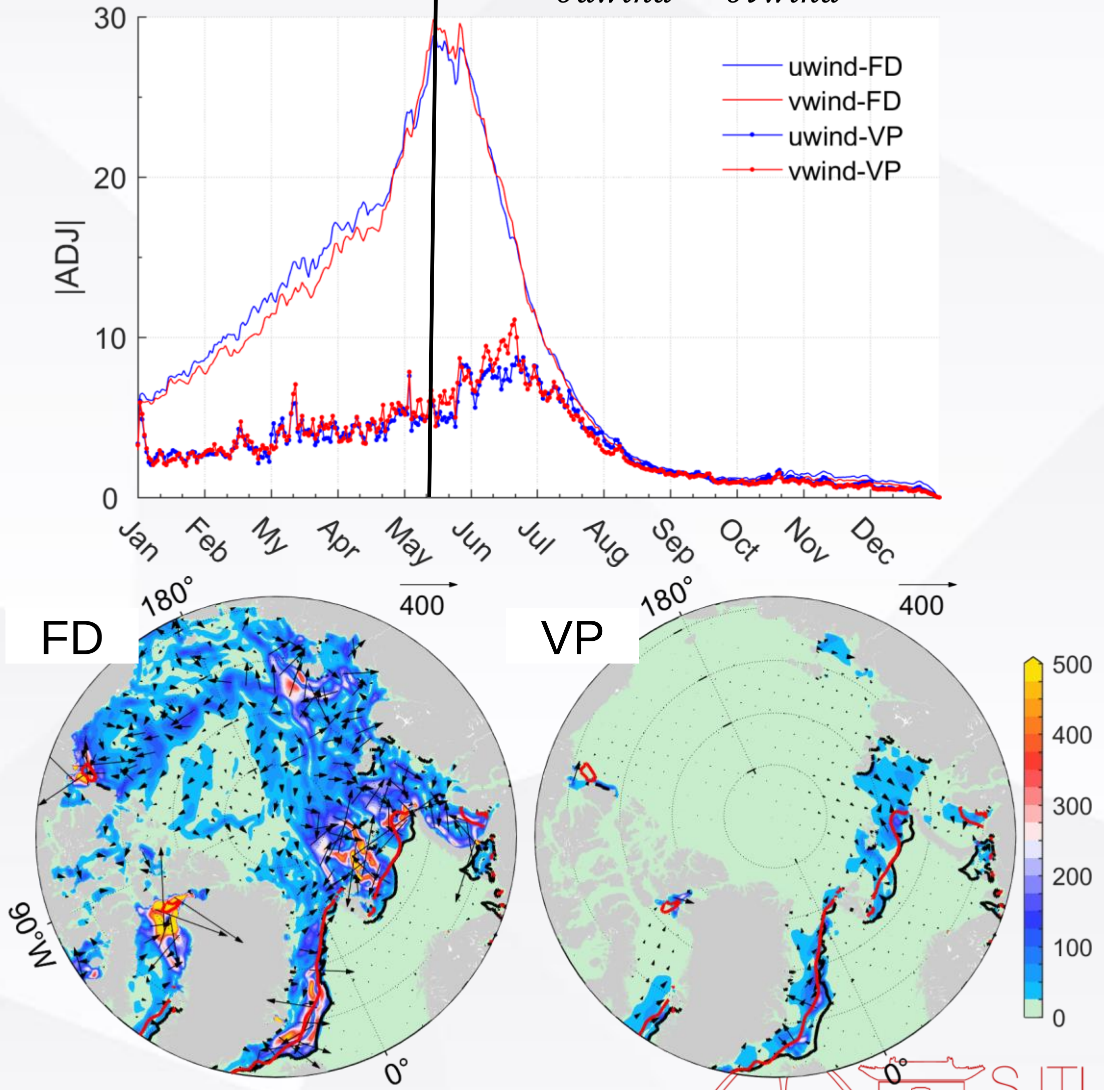
TAKAHIRO TOYODA, NARIAKI HIROSE, L. SHOGO URAKAWA, HIROYUKI TSUJINO, HIDEYUKI NAKANO, NORIHISA USUI, YOSUKE FUJII, KEI SAKAMOTO, AND GORO YAMANAKA

Meteorological Research Institute, Japan Meteorological Agency, Tsukuba, Japan

Background and Motivation

- Stabilizing the adjoint of ice Rheology :
  - Remove the adjoint sensitivity of shear/bulk viscosity (ζ/η)to strain rate (ε) (Toyoda et al., 2019, MWR)
  - Filter the adjoint of ice velocity in the adjoint of sea ice dynamics

Temporal and spatial $\frac{\partial J}{\partial uwind}$ & $\frac{\partial J}{\partial vwind}$



Questions：

Q1: Can we further improve sea ice-ocean state estimation with adjoint of sea ice rheology?

Q2: What are the impacts on the sea ice retreat process?

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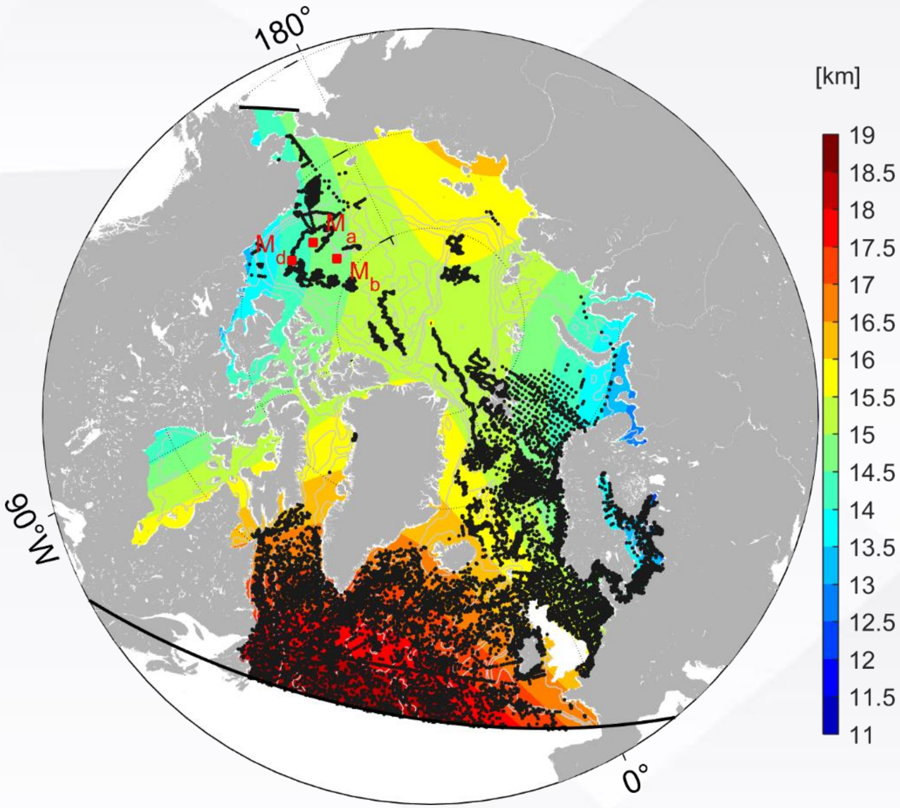
Content

1. Experiment Setups : Models

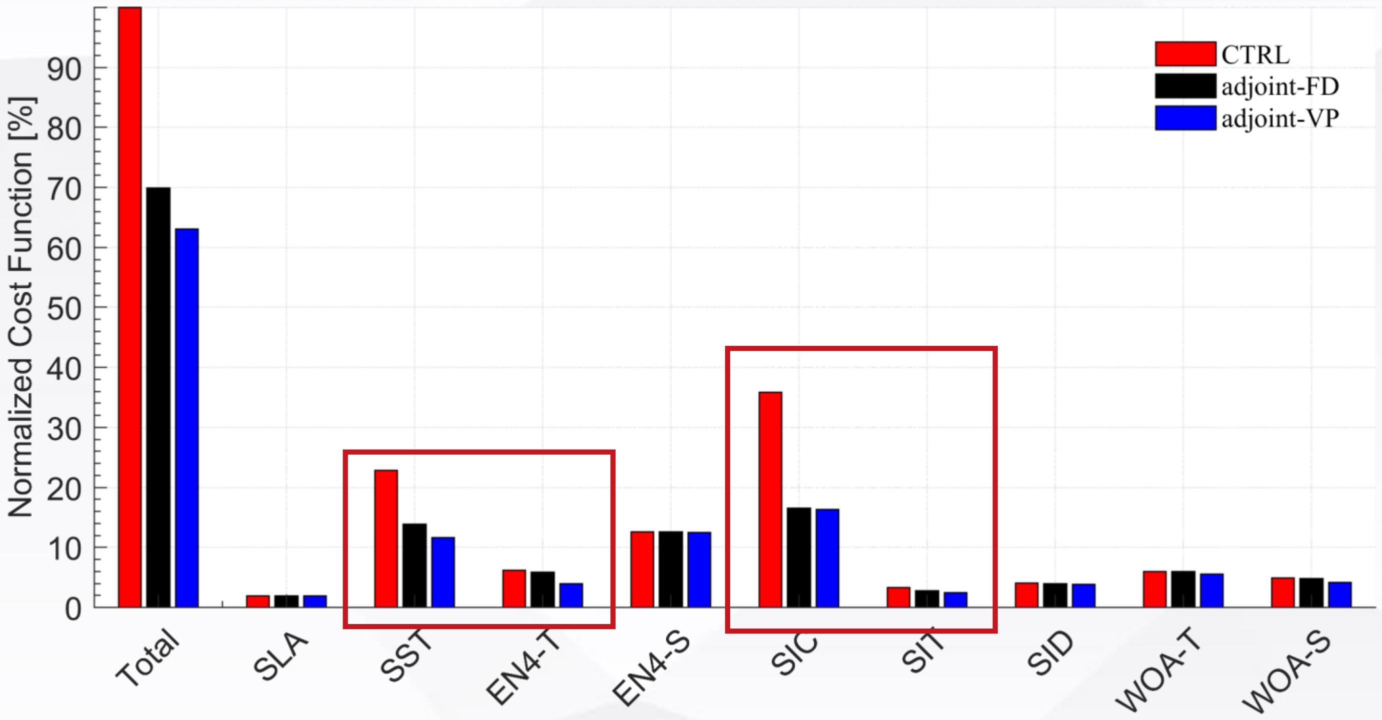


Model domain, resolution (shading), available profiles (dots), and BGEP moorings (red rectangles)

- Based on **ECCO framework**
- A Pan-Arctic Ocean-Sea ice model configuration:
  - ✓ MITgcm+dynamic-thermodynamic sea ice model (Hilber et al ,1979)
  - ✓ Resolution: ~16 km + 50 levs
  - ✓ The adjoint model: generated by TAF (Gering et al., 1998)

- **Assimilated measurements:**
  1. Ice concentration: AMSRE, AMSE2, SSMI;
  2. Ice thickness : SMOS/CRYsat
  3. Along-track SLA, MDT
  4. Profiles from EN4, UDASH, moorings from BGEP, Bering Strait
  5. SST; WOA18
- **Assimilation experiments:**
  - ✓ Control run: **CTRL**
  - ✓ Adjoint of free drift model: **adjoint-FD**
  - ✓ Adjoint of VP rheology : **adjoint_VP**

2.1 Results: cost function reduction



Adjoint_VP 31 iterations

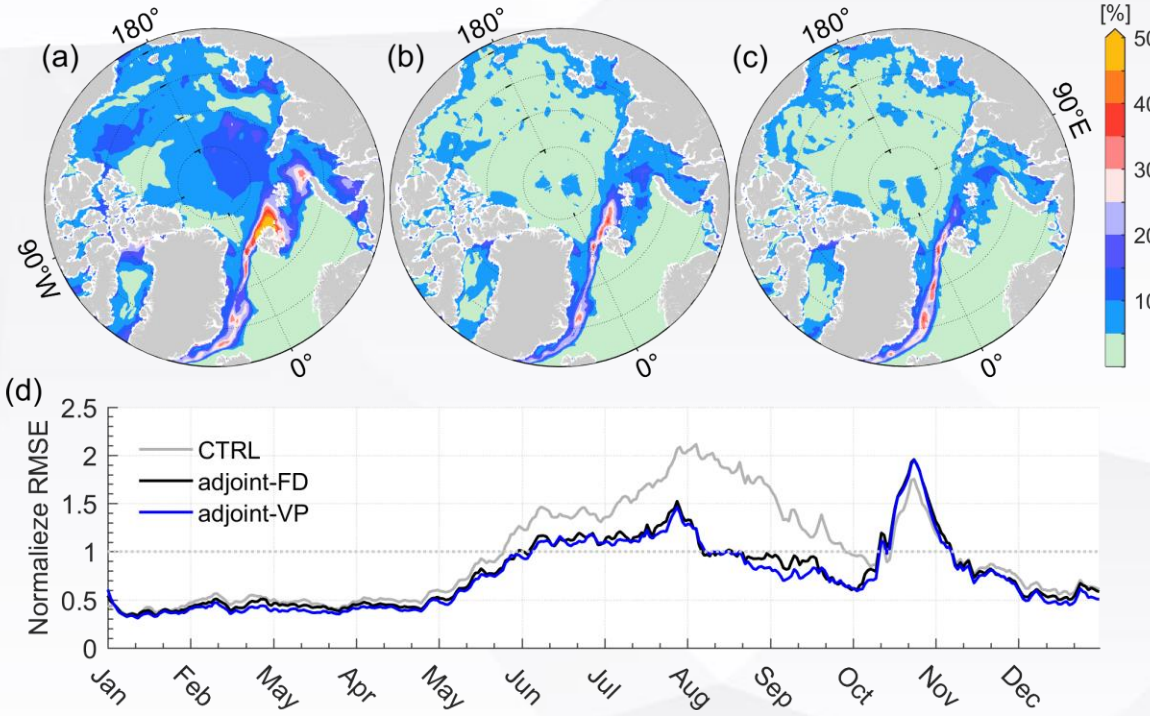
Adjoint_FD 12 iterations

- ➢ more iterations can be performed, resulting in more cost reduction (7-8%).

2.1 Results: RMSEs of SIC & SIT

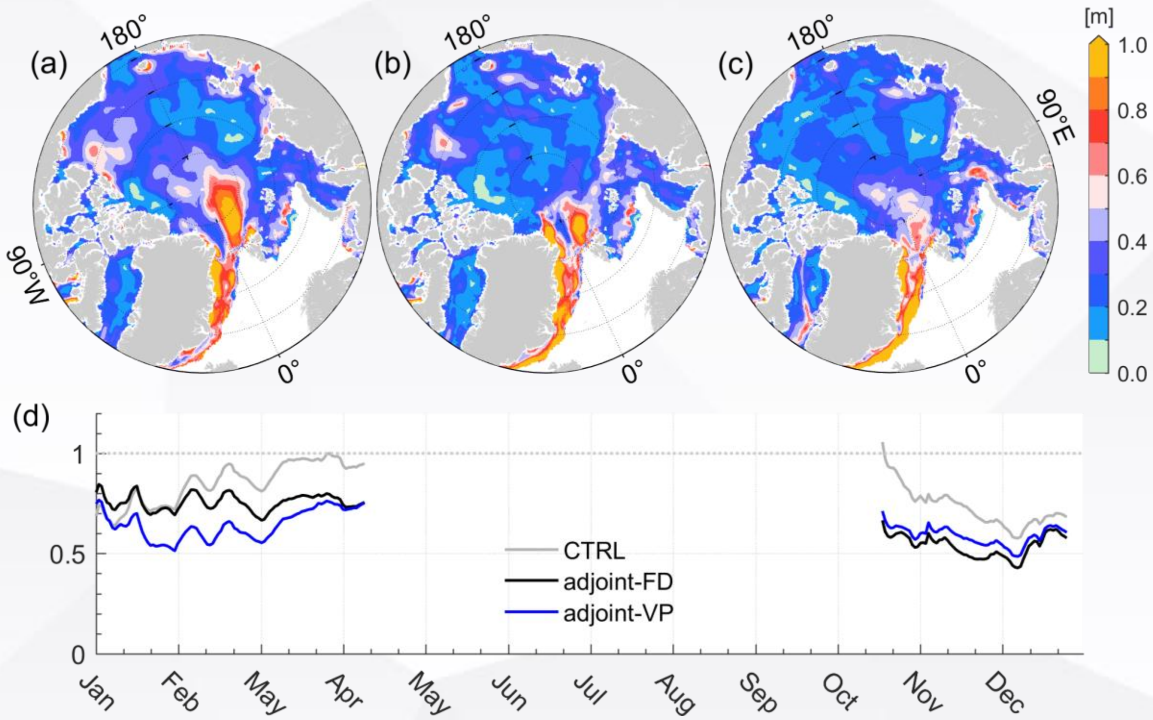
Root Mean Square Errors of SIC

CTRL Adjoint-FD Adjoint-VP



Root Mean Square Errors of SIT

CTRL Adjoint-FD Adjoint-VP



RMSEs of	SIC (%)	and	SIT (m)
Ctrl	6.22		0.37
Adjoint-FD	4.30		0.34
Adjoint-LSR	4.28		0.34

2.1 Results: Water Temperature over top 50m

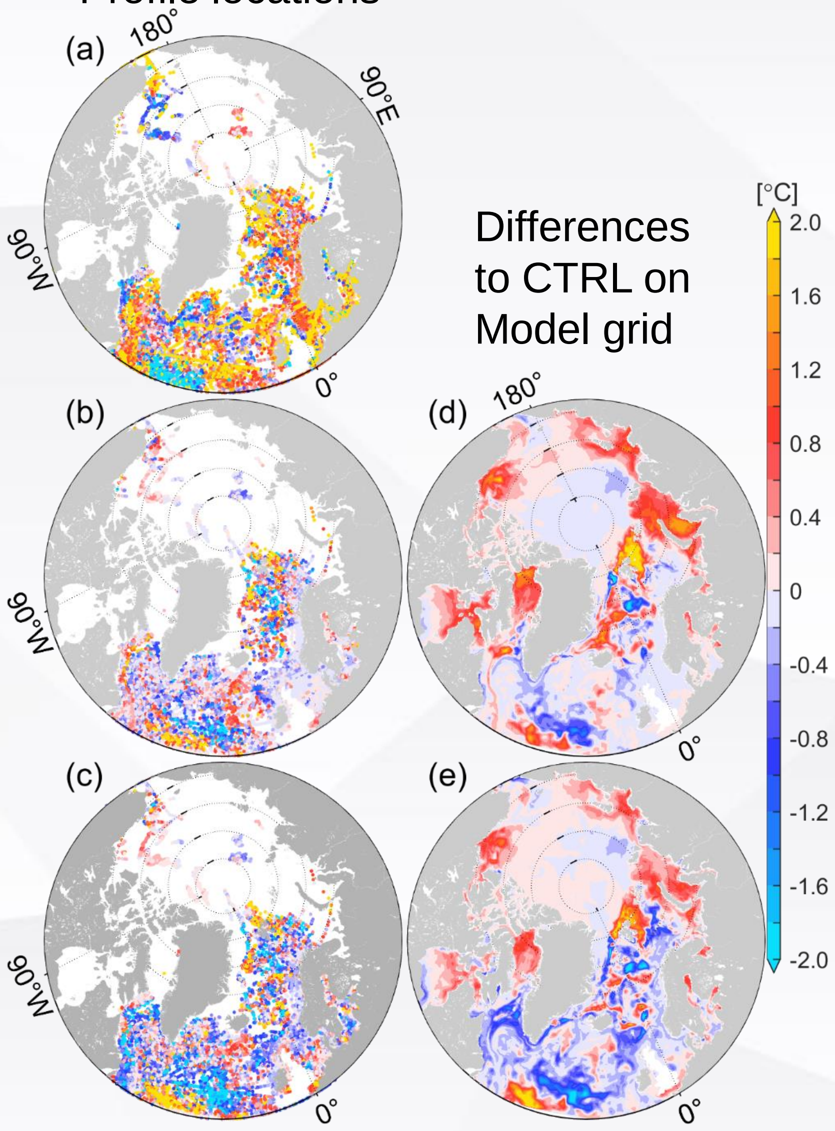
Profile locations

CTRL- Obs
RMSEs 1.25 °C

FD-CTRL
RMSEs: 1.18 °C

LSR-CTRL
RMSEs: 0.98 °C

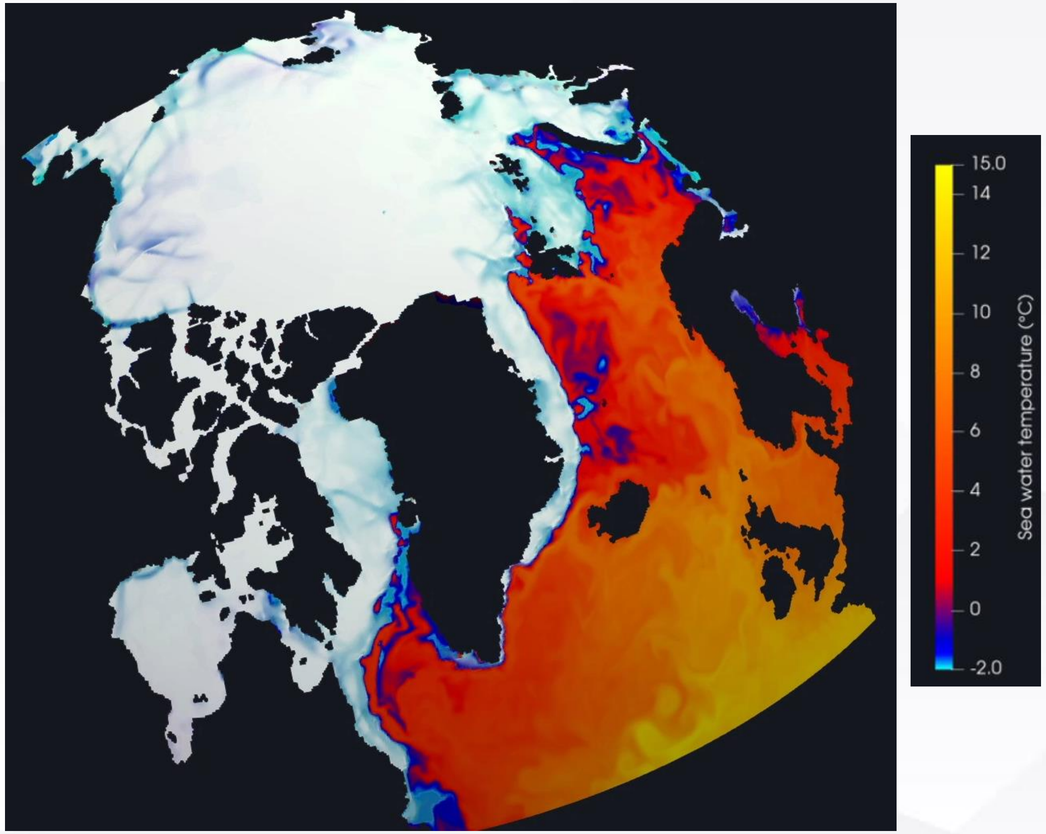
Differences to CTRL on Model grid



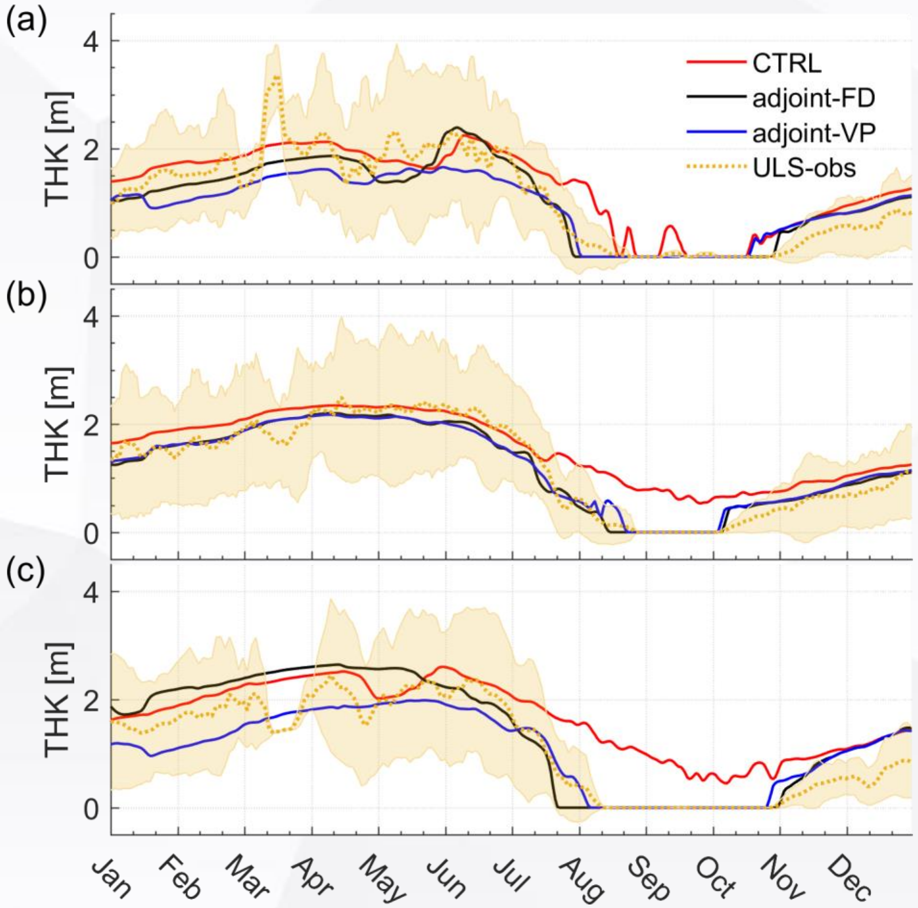
- Adjoint-VP results smaller temperature errors
- Ice-covered region: they are similar, due to the very-well representation of SIC changes.
- Ice-free regions, north Atlantic Ocean, LSR results in further error reduction, due to the more iterations.

2.2 Results: Spatial-temporal sea ice variability

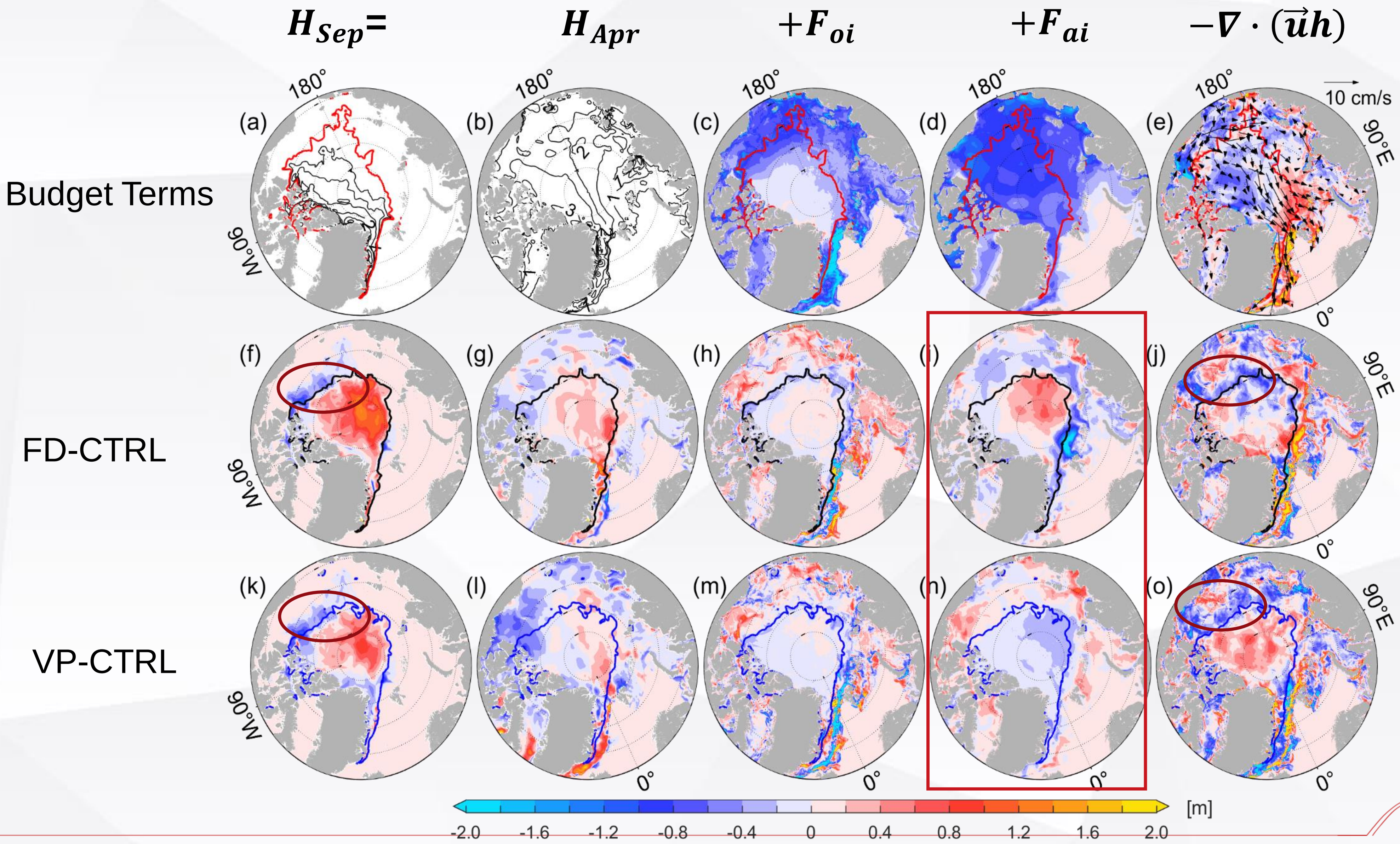
Sea ice concentration & thickness



Up-looking-Sonar SIT in M_a, M_b, M_d from Beaufort Gyre Exploration Project

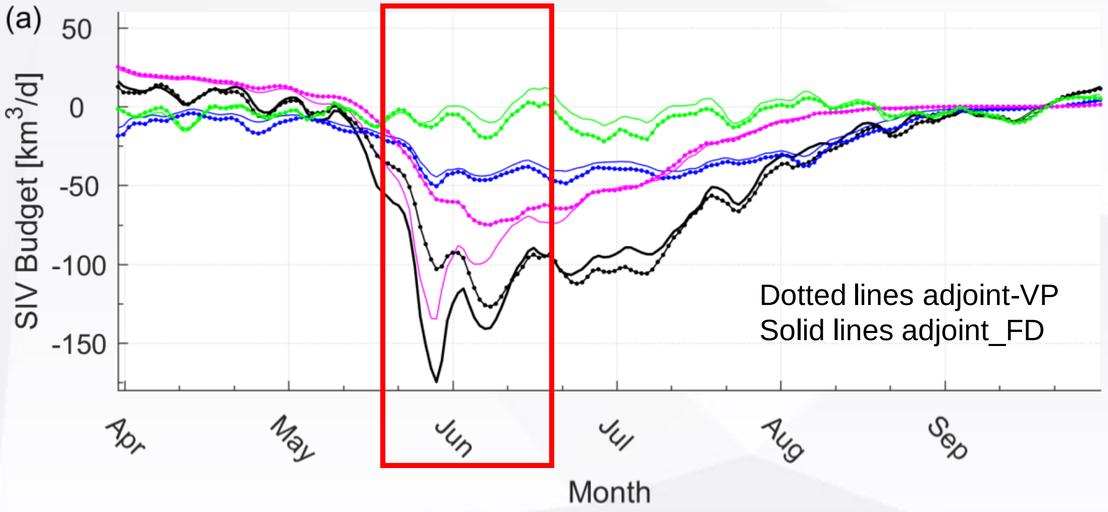


2.2 Results: Spatial pattern of sea ice retreat

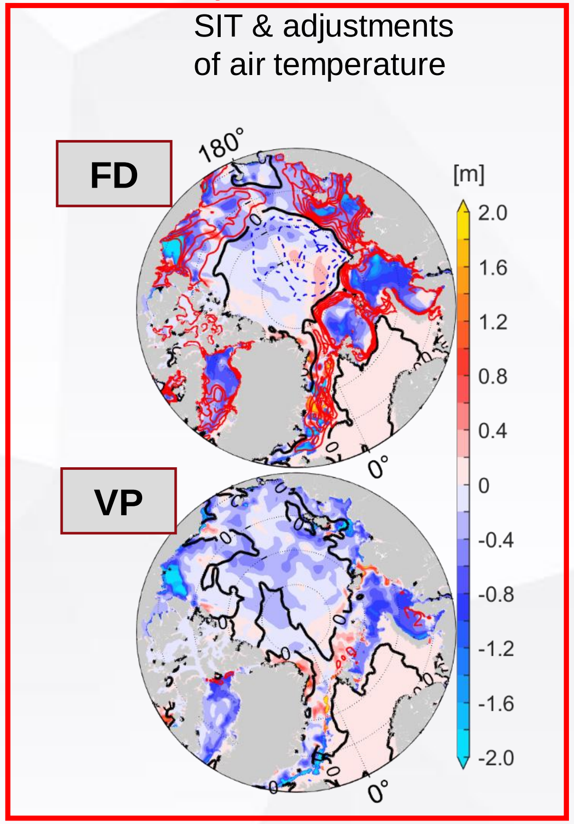


- Ice advective flux shapes September effective thickness pattern
- Differences of central Arctic Ocean ice thickness is related to F_{ai} and $_{Fadv}$

$$\frac{\partial SIV}{\partial t} = -\nabla \cdot (\vec{u}h) + F_{oi} + F_{ai} + F_{res}$$



Changes from 20.May-15.June



- adjoint-FD melts more ice over the marginal seas through strong temperature adjustments (>10 °C)
- Adjoint-VP leads to temperature adjustments <2 °C, is more reasonable.

3. Conclusions and Outlook

We improved the adjoint of sea ice rheology (VP), tested its impacts on ocean-sea ice state estimation.

- Including adjoint of ice rheology allows more iterations to be performed, and further reduces the total cost （7-8%）.
- Analyzing the sea ice retreat process, we note that is more reasonable.

Enables estimating parameters, e.g.,
e=2.0: Eccentricity of the yield curve describing the viscous-plastic rheology
P* = 2.5*10^4: Ice compressive strength constant
C*=20.0: Ice strength decay constant