Jet Propulsion Laboratory
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Analyzing Causation Using ECCO’s Adjoint

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“A near-uniform fluctuation of ocean bottom pressure and sea level across the deep ocean basins of the Arctic Ocean and the Nordic Seas”

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[Fukumori et al, 2015, *Prog. Oceanogr.*, ***134***, 152-172.]

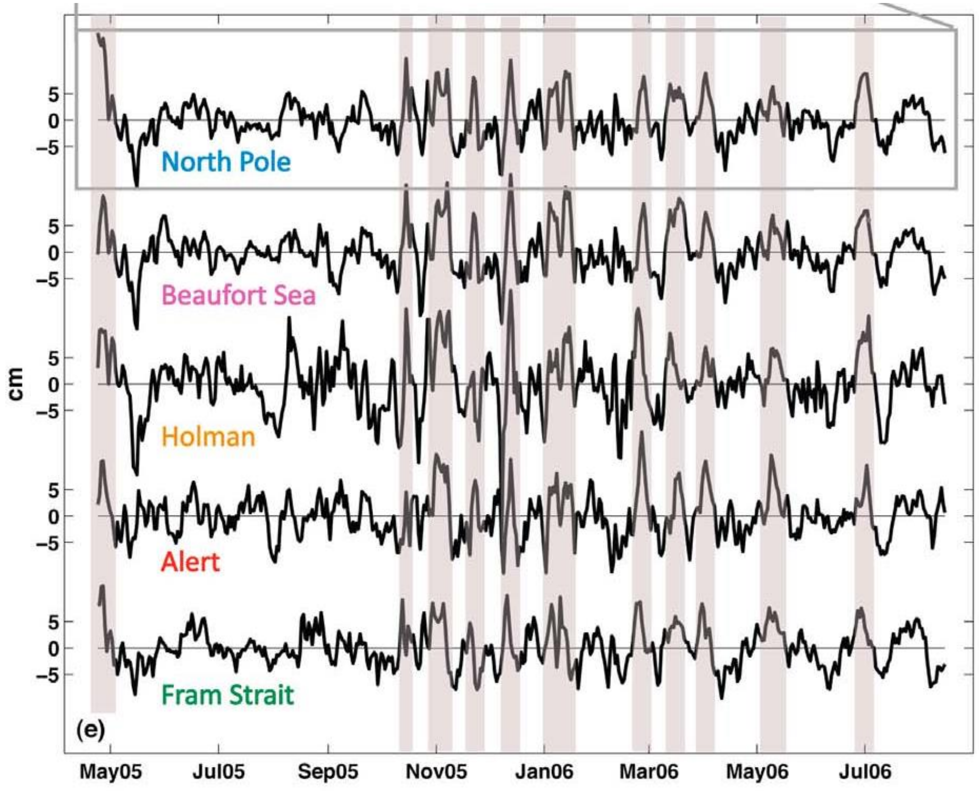
Background

Ocean bottom pressure (OBP) varies coherently across the Arctic Ocean, correlated with meridional winds in the Nordic Sea.

[Peralta-Ferriz et al., 2011, *Geophys. Res. Lett.*, ***38***, *L14606.]*

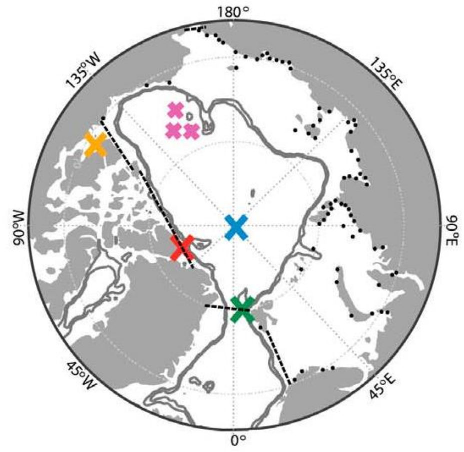
OBP time-series

±5 cm

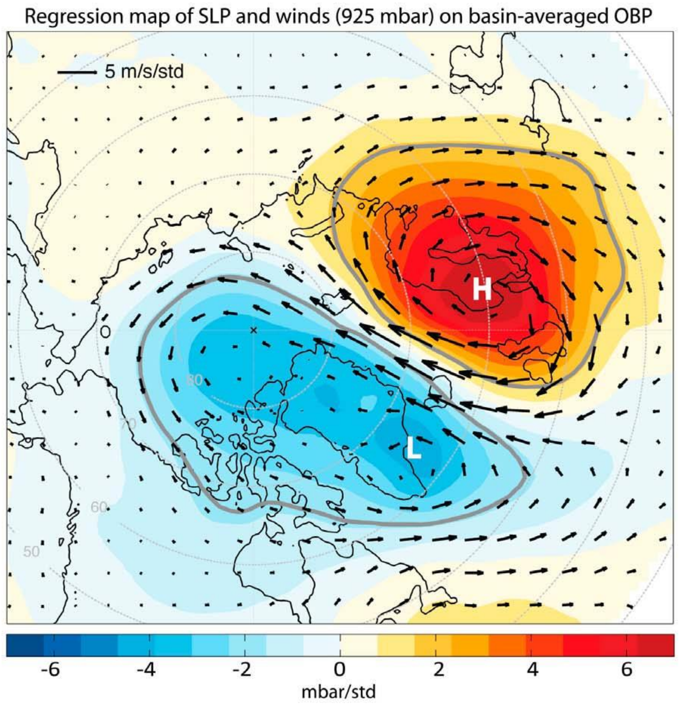


May 05

Jul 06



Regression with winds (vector) and atmospheric pressure (color)



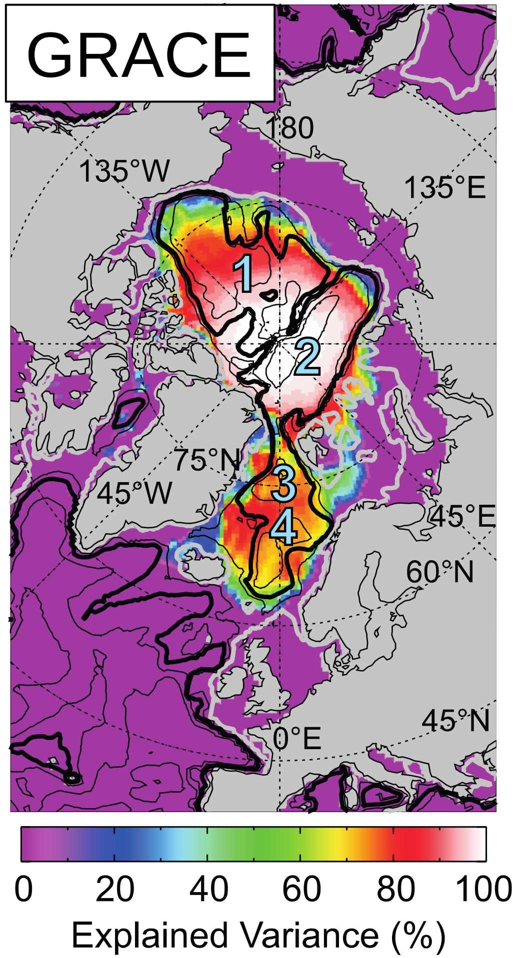
ECCO’s Consistency with Observations (1/2)

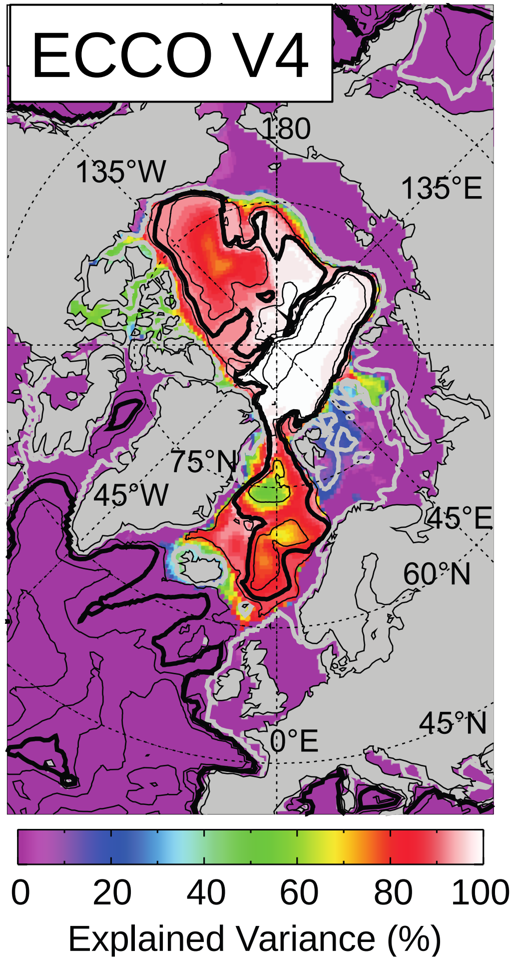
Ocean bottom pressure (OBP) varies near-uniformly across the deep ocean basins of Arctic Ocean and the Nordic Seas similarly for observations (GRACE) and ECCO (V4).

Explained Variance:

$$1 - \frac{var(a - b)}{var(a)}$$

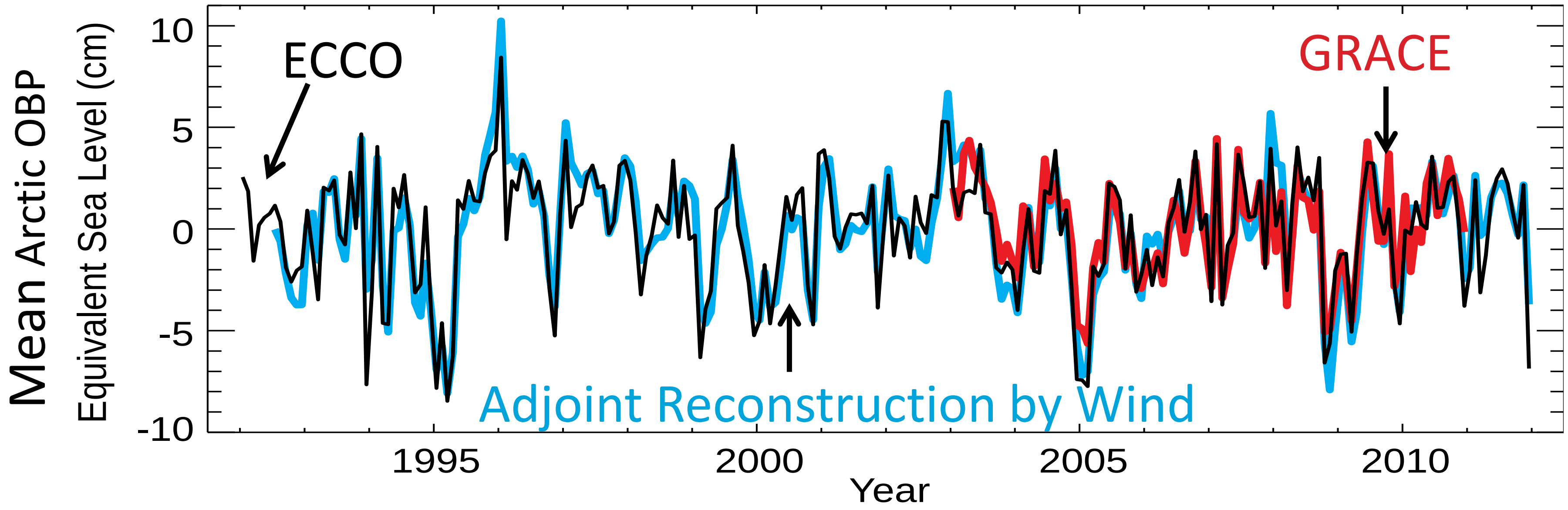
a = OBP at each location
b = OBP at the North Pole





ECCO's Consistency with Observations (2/2)

ECCO's OBP varies coherently with observations (GRACE).



Adjoint Gradient Decomposition/Reconstruction

OBP at time t

Forcing

$$\delta J(t) \approx \boxed{\sum_{i}\sum_{\mathbf{r}}\sum_{\Delta t}} \frac{\partial J(T)}{\partial u_i(\mathbf{r}, T-\Delta t)} \delta u_i(\mathbf{r}, t-\Delta t)$$

Type (i), location ($\mathbf{r}$), and lag (Δt) of forcing

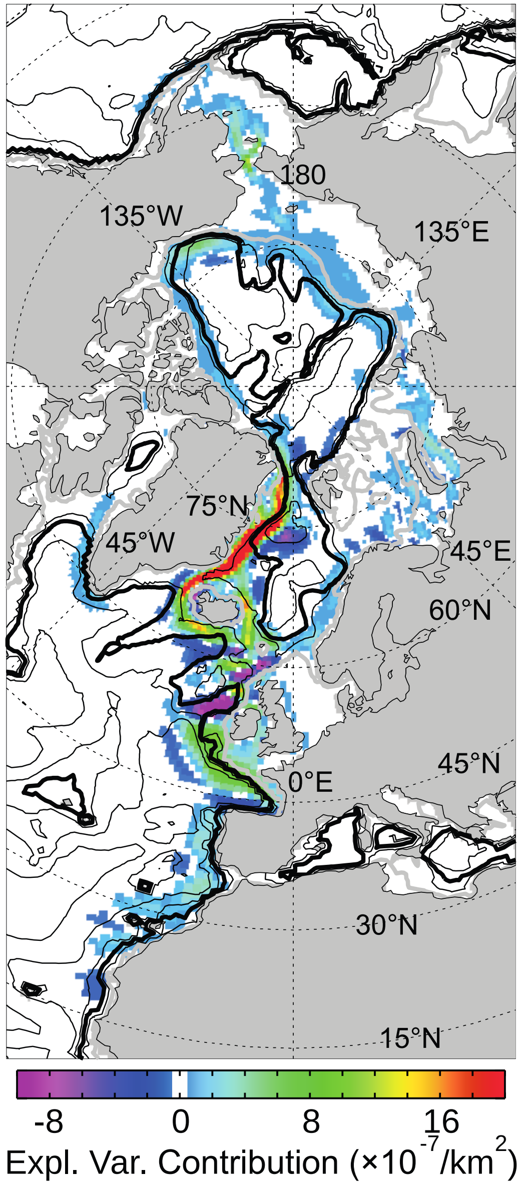
Adjoint Gradient

Causation (1/4)

The Arctic's coherent ocean bottom pressure (OBP) variation is driven by winds on the continental slope.

Arctic OBP variance explained by winds at different locations.

$$1 - \frac{var\left(J - \sum_{i=wind} \sum_{\Delta t} \frac{\partial J}{\partial u_i} \delta u_i(\mathbf{r}, t - \Delta t)\right)}{var(J)}$$

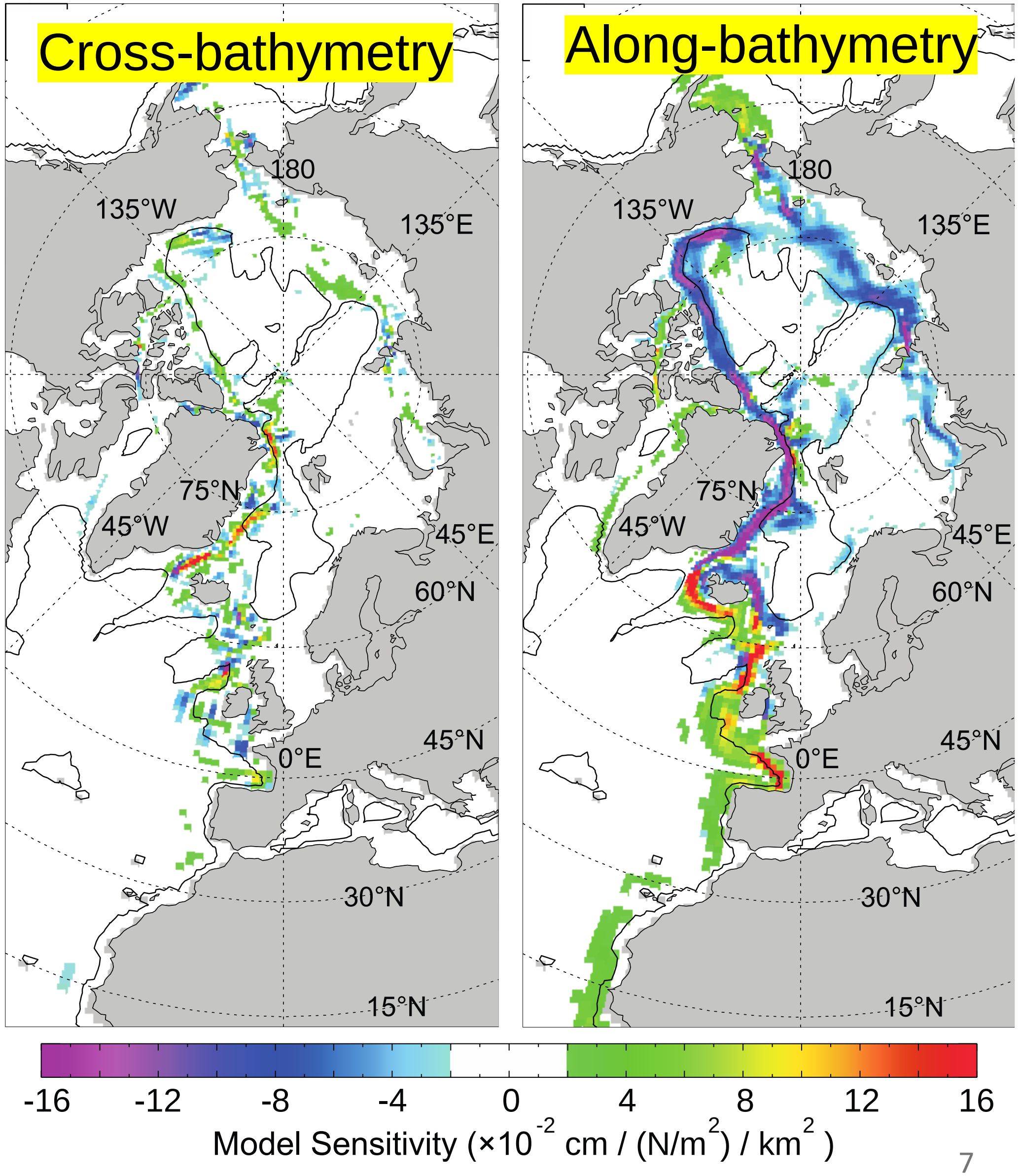


Causation (2/4)

Along-slope winds in opposite directions inside and outside the Arctic are responsible for the OBP variation.

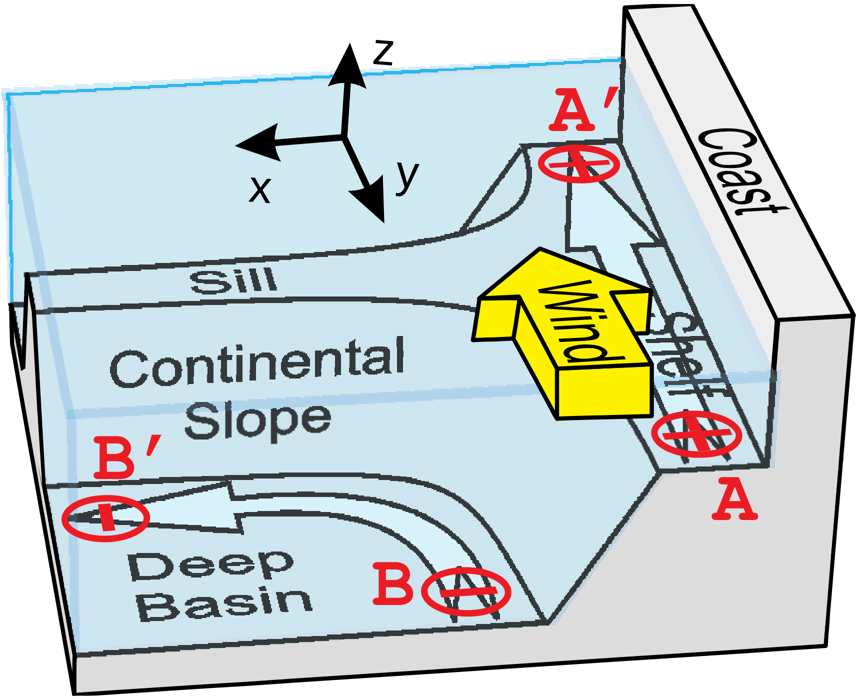
Sensitivity of Arctic OBP to winds at 4-weeks lag (Δt).

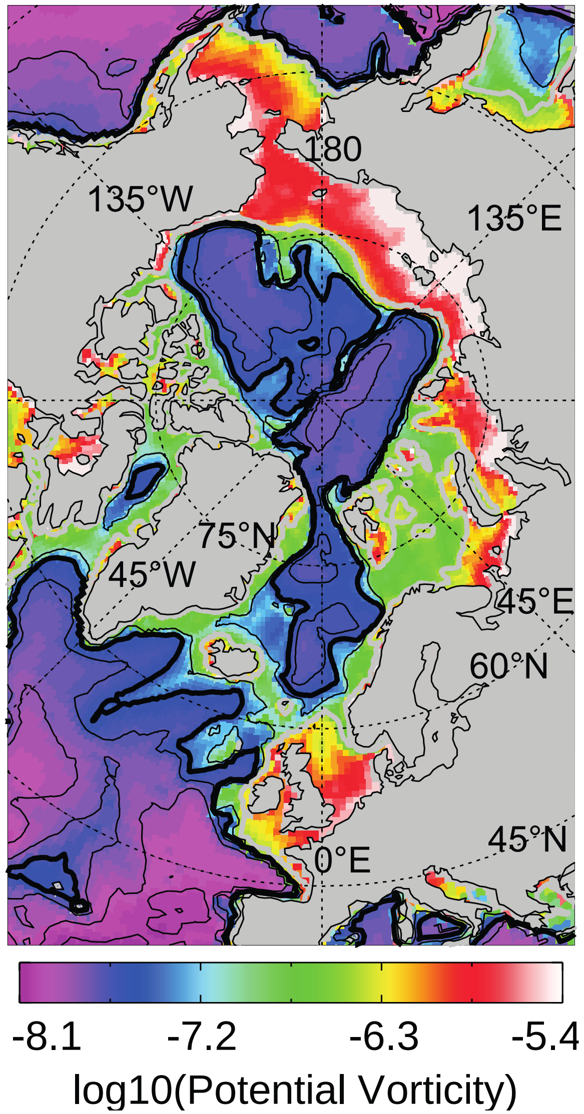
$$\frac{\partial J(T)}{\partial u_{wind}(\mathbf{r}, T-\Delta t)}$$



Causation (3/4)

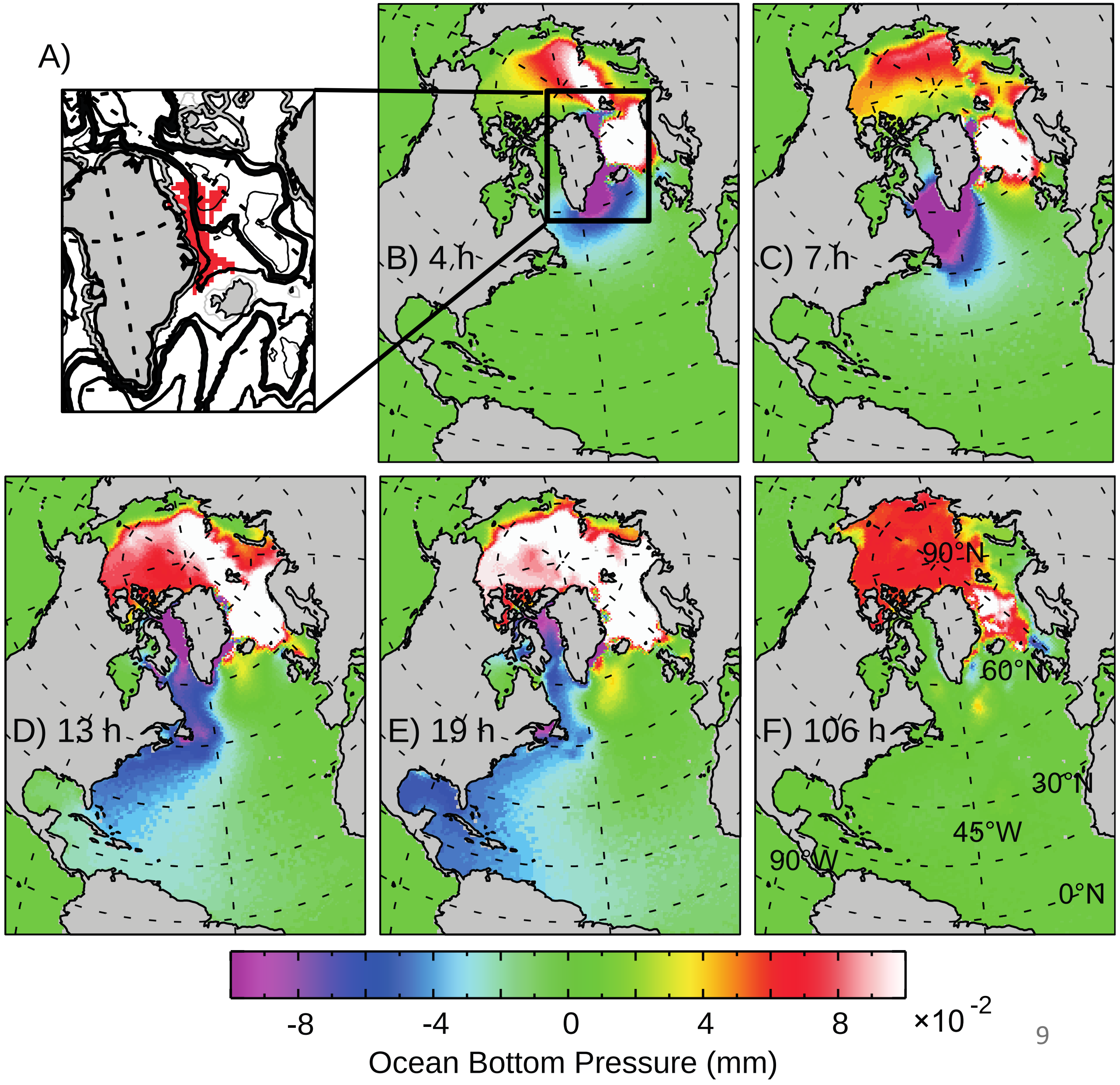
Wind-driven coastally-trapped waves that bifurcate at the shallow straits allow anomalies to persist in the deep Arctic basins shielded by steep gradients of planetary potential vorticity *f/H*.





Causation (4/4)

Change in OBP resulting from wind perturbation is consistent with bifurcating coastally-trapped wave theory.



Summary

1. A **near-uniform barotropic fluctuation** dominates sea level and ocean bottom pressure variations across the interconnected **deep ocean basins of Arctic Ocean and the Nordic Seas**,
2. The fluctuation is driven by **winds along the continental slope** of the Arctic and its neighboring region,
3. The winds drive **coastally trapped waves** that **bifurcate** at the Arctic's shallow straits and become confined in the Arctic's deep ocean basins of **near-uniform planetary potential vorticity**,
4. Model **adjoints** provide effective means **to identify and to quantify causal mechanisms**.

“Correlation does not imply causation”,

but adjoints do.

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