Investigating the Mechanisms of Sea Level Change using 30+ Years of Satellite Altimetry and the ECCO Ocean State Estimate

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Overview

We outline a new effort to study mechanisms of sea level change. While global mean sea level rise is largely attributable to increases in ocean heat content and mass linked to global warming (**Fig. 1**), the expression of these changes across the ocean is heterogeneous and remains incompletely understood (**Fig. 2**). Regional variations often arise from redistribution of heat, freshwater, and mass rather than net changes in their global budgets. Identifying the regions and mechanisms through which global warming influences sea level is essential for advancing physical understanding and predictive capability.

We leverage the Estimating the Circulation and Climate of the Ocean (***ECCO***; https://ecco-group.org/) ocean state estimate, which integrates the ***complete altimetry record*** along with other diverse suite of observations, to identify the ***origin, pathways, and mechanisms*** of large-scale oceanic changes in ***heat, freshwater, and mass*** that have contributed to over 30+ years of observed sea level rise.

ECCO: Dynamic Computation Reimagined

As a least-squares fit of a theoretical model to observations, ECCO's close agreement with data (**Figs. 1 & 2**) validates its governing equations. Beyond analyzing its state, we examine ***ECCO's model itself***—the dynamical framework that defines the physical relationships among variables—to investigate the mechanisms driving sea level change.

ECCO's ***adjoint model*** provides a powerful means to identify the drivers of sea level change (**Eq 1**). Illustrative examples include the causes of sea level rise in the Beaufort Sea (**Figs. 3 & 4**; *J. Phys. Oceanogr., 2021, **51**, 3217-3234*) and in the South Pacific Ocean (**Fig. 5**).

Complementary approaches—such as ***passive tracers***, their ***adjoints***, ***perturbation experiments***, and ***property budget analyses***—will also be employed to elucidate the mechanisms of sea level change across the globe. Many of these tools are now available in ***EMU***, ECCO's new modeling utility.

EMU (ECCO Modeling Utilities)

EMU is a ***freely available***, ***menu-driven***, ***containerized*** implementation of the ECCO model and its adjoint (**Table 1**), enabling analyses of the model's physics without requiring modeling expertise.

The tools are invoked by a single command, ***emu,*** which guides the users through their investigation. EMU includes programs for reading, plotting, and analyzing its results in popular scientific languages (e.g., Matlab, Python, IDL). EMU can be installed using the shell script ***emu_setup.sh,*** available at

https://github.com/ECCO-GROUP/ECCO-EIS/

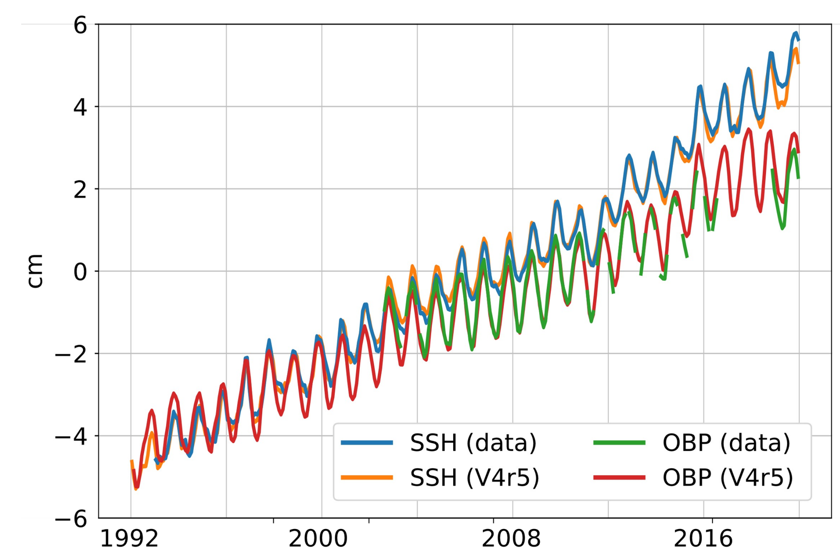

Fig. 1 Global mean time-series of sea level and ocean bottom pressure (in equivalent sea level) of ECCO V4r5 in comparison to observations.

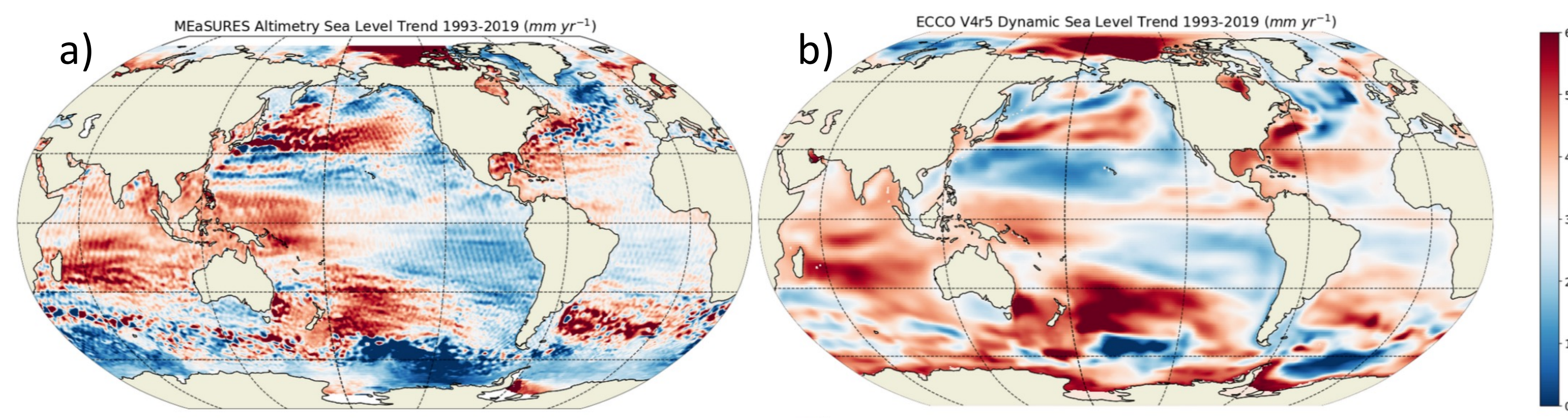

Fig. 2 Regional sea level trend: a) Altimetry, b) ECCO V4r5.

$$J(t) \approx \sum_{i} \sum_{\mathbf{r}} \sum_{\Delta t} \frac{\partial J(t_g)}{\partial \phi_i(\mathbf{r}, t_g - \Delta t)} \delta\phi_i(\mathbf{r}, t - \Delta t)$$

type *location* *lag* *adjoint gradient*

Eq. 1 ***Adjoint Gradient Decomposition***
Quantities of interest *(J)* can be expanded linearly with respect to independent forcings (ϕ) using the adjoint model.

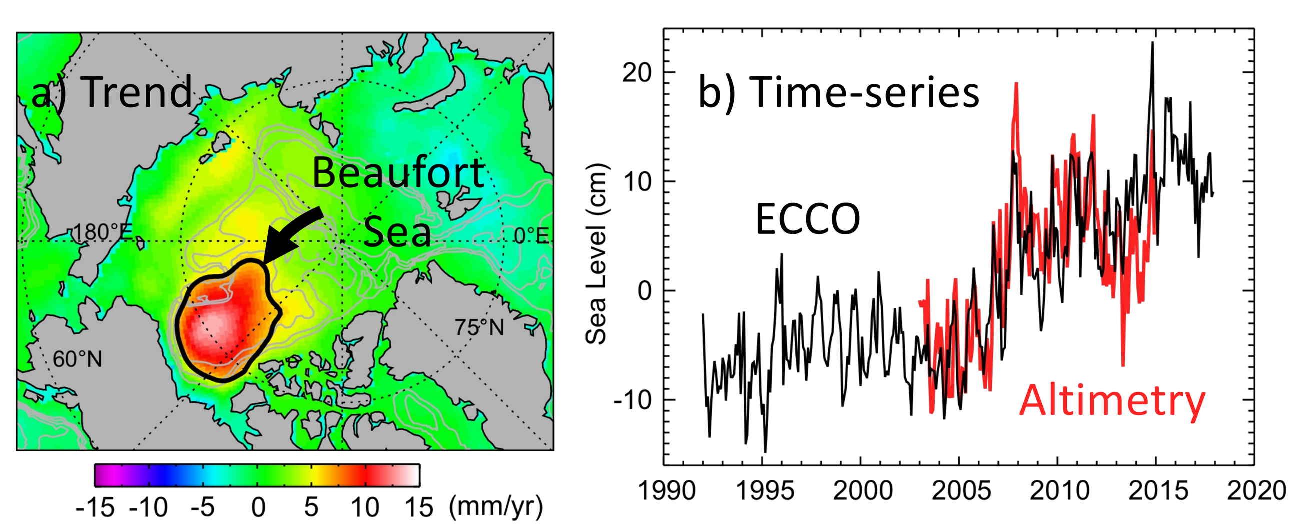

Fig. 3 a) Sea-level trend and b) Time-series of Beaufort Sea mean sea level.

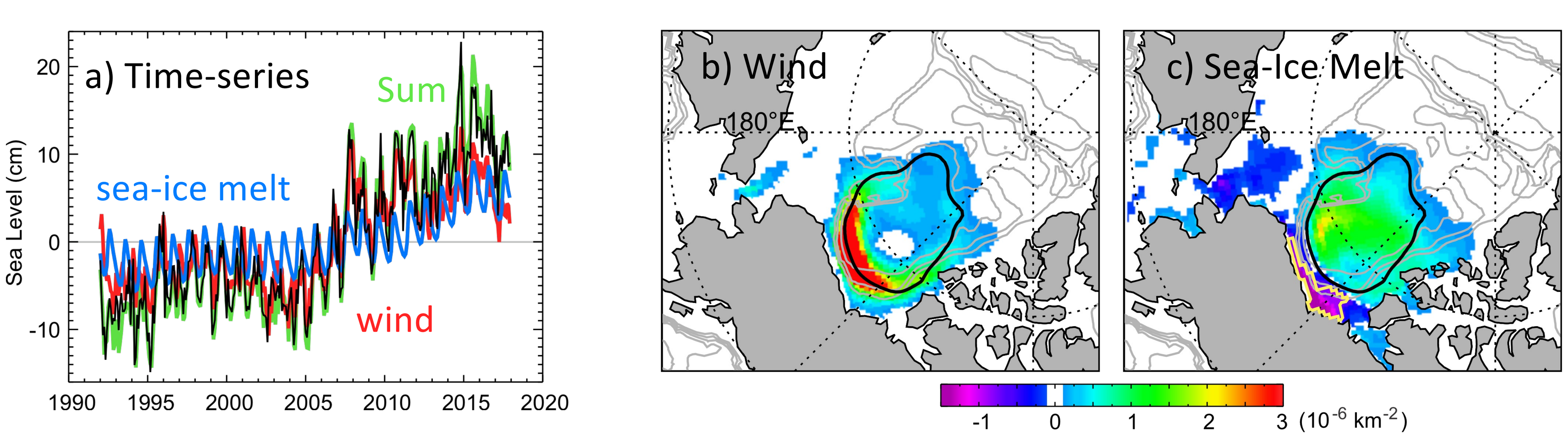

Fig. 4 Attribution of Beaufort Sea mean sea level change based on Eq 1:
a) Time-series, b) & c) Explained variance per unit area by wind and sea-ice melt.

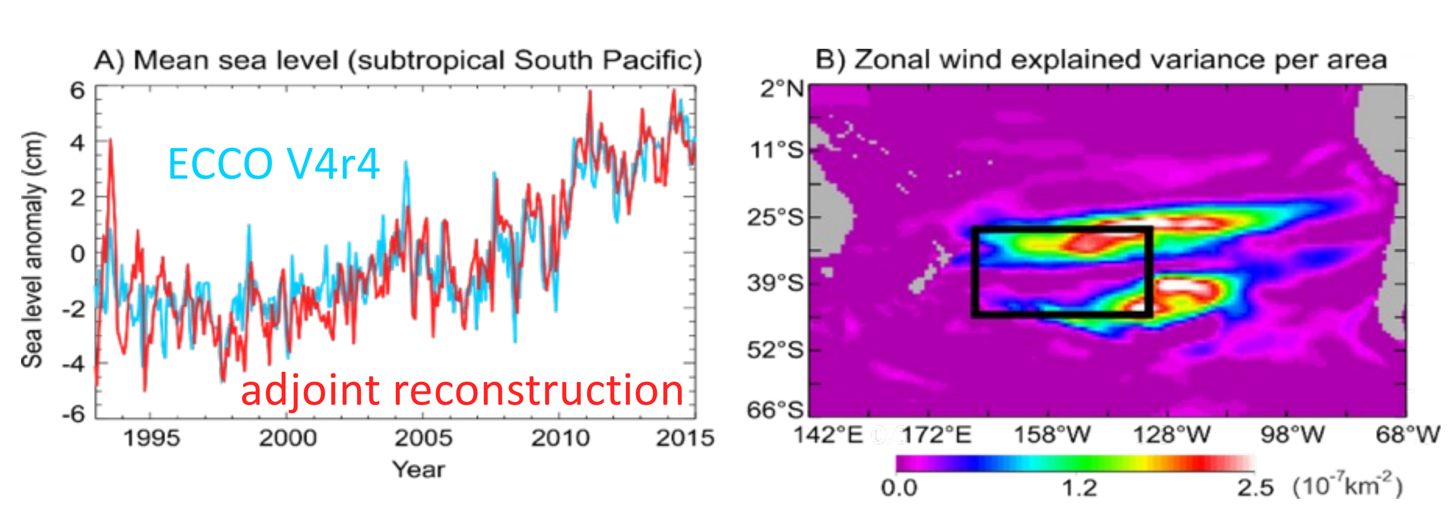

Fig. 5 Analyzing subtropical South Pacific mean sea level change with Eq 1: A) Time-series (non-seasonal), B) Explained variance per unit area by zonal wind.

	Tool	Description
1	Sampling	Evaluates time-series of model state and control.
2	Forward Gradient	Computes model's response to change in forcing.
3	Adjoint	Computes model's sensitivity to forcing (adjoint gradient).
4	Convolution	Evaluates convolution of adjoint gradients with forcing (Adjoint Gradient Decomposition).
5	Tracer	Computes evolution of passive tracer and its adjoint.
6	Budget	Evaluates budget time-series.
7	Modified Simulation	Re-runs model with modifications (e.g., forcing, output).
8	Attribution	Evaluates state times-series by control type.
9	Auxiliary	Generates user input files for other EMU tools.

Table 1 ***ECCO Modeling Utilities (EMU)***