Exploring the role of the "Ice-Ocean governor" and mesoscale eddies in the equilibration of the Beaufort Gyre: lessons from observations

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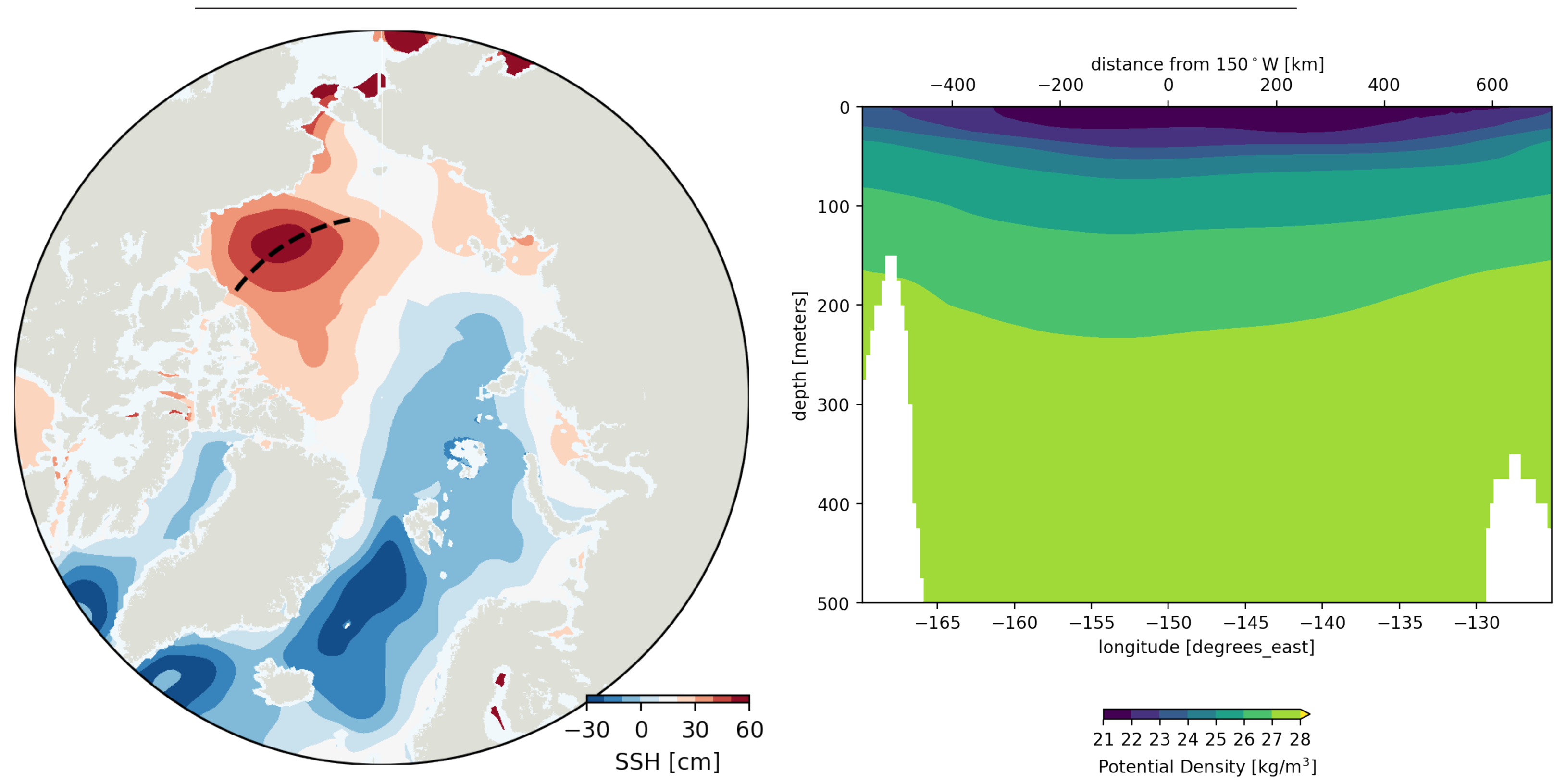
Abstract

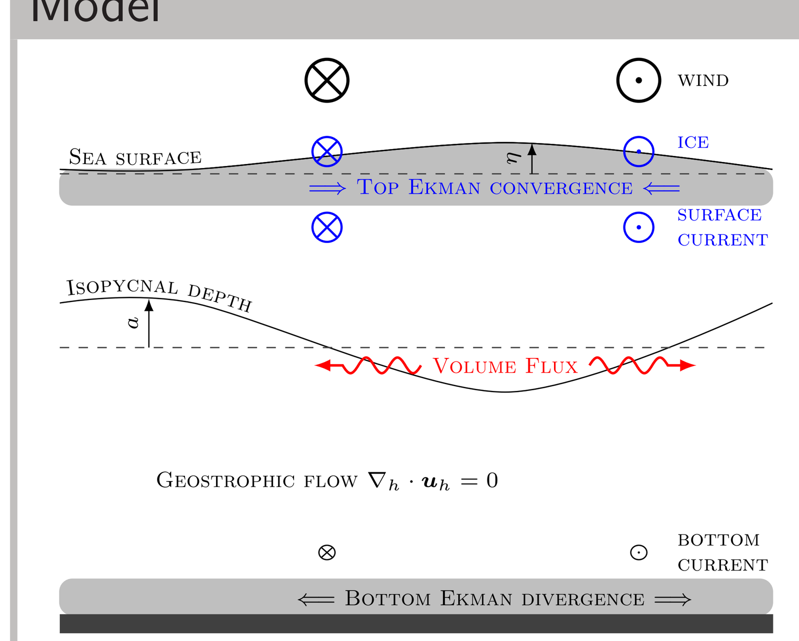
Observations of Ekman pumping, sea surface height anomaly, and isohaline depth anomaly over the Beaufort Gyre are used to explore the relative importance and role of (i) feedbacks between ice and ocean currents, dubbed the "ice–ocean governor" [2] and (ii) mesoscale eddy processes in the equilibration of the Beaufort Gyre. A two-layer model of the gyre is fit to observations and used to explore the mechanisms governing the gyre evolution from the monthly to the decennial time scale. The ice–ocean governor dominates the response on interannual time scales, with eddy processes becoming evident only on the longest, decadal time scales.



The doming of satellite-derived Sea Surface Height in the Canada Basin (red region) marks the persistent anticyclonic circulation of the Beaufort Gyre, one of the main features of the Arctic Ocean (2003-2014 mean, data from [1] and the World Ocean Atlas).

A section across the Beaufort Gyre Region at 75°N (black dashed line in the left panel), shows how the doming up of the sea surface height toward the center of the gyre is reflected in the bowing down of isopycnals. The stratification is dominated by salinity variations and concentrated close to the surface, with potential densities ranging from a mean value of $1021\,\mathrm{kg\,m^{-3}}$ at the surface to close to $1028\,\mathrm{kg\,m^{-3}}$ at a depth of about 300 m, and remaining almost constant below that.

Model



$$\frac{d(\eta - a)}{dt} = K\frac{a}{L^2} - \underbrace{\overline{w}_{Ek}}_{\text{Top Ekman}}$$

$$\frac{da}{dt} = -K\frac{a}{L^2} + \underbrace{\frac{d}{2f}\frac{g\eta + g'a}{L^2}}_{\text{Bottom Ekman}},$$

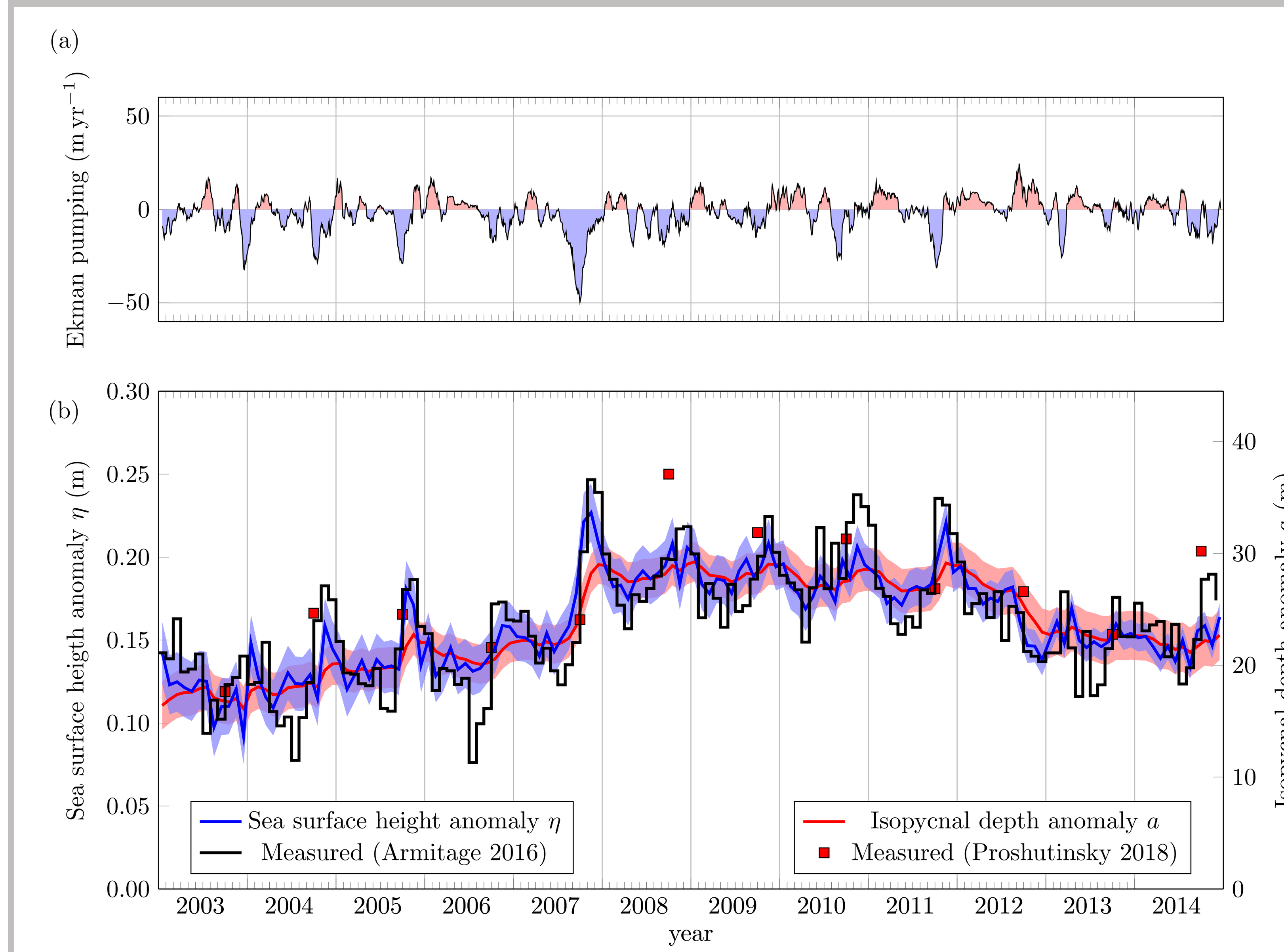
Schematic of the idealized two-layer model: the wind- and ice-driven Ekman flow (blue) drives variations in the layer thicknesses or, equivalently, in the sea surface height η and isopycnal depth a. The interior is assumed to be in geostrophic balance, and eddy processes (red) result in a volume flux flattening the isopycnal slope. L is a characteristic length scale, and is set to 300 km (see section in the box above).

We consider the surface stress $\boldsymbol{\tau}$, to have a wind-driven $\boldsymbol{\tau}_a$ and an ice-driven $\boldsymbol{\tau}_i$ component, weighted by the ice concentration α

$$\boldsymbol{\tau} = (1-\alpha)\underbrace{\rho_a C_{Da}|\boldsymbol{u}_a|\boldsymbol{u}_a}_{\boldsymbol{\tau}_a} + \alpha\underbrace{\rho C_{Di}|\boldsymbol{u}_i - \boldsymbol{u}_g|(\boldsymbol{u}_i - \boldsymbol{u}_g)}_{\boldsymbol{\tau}_i},$$

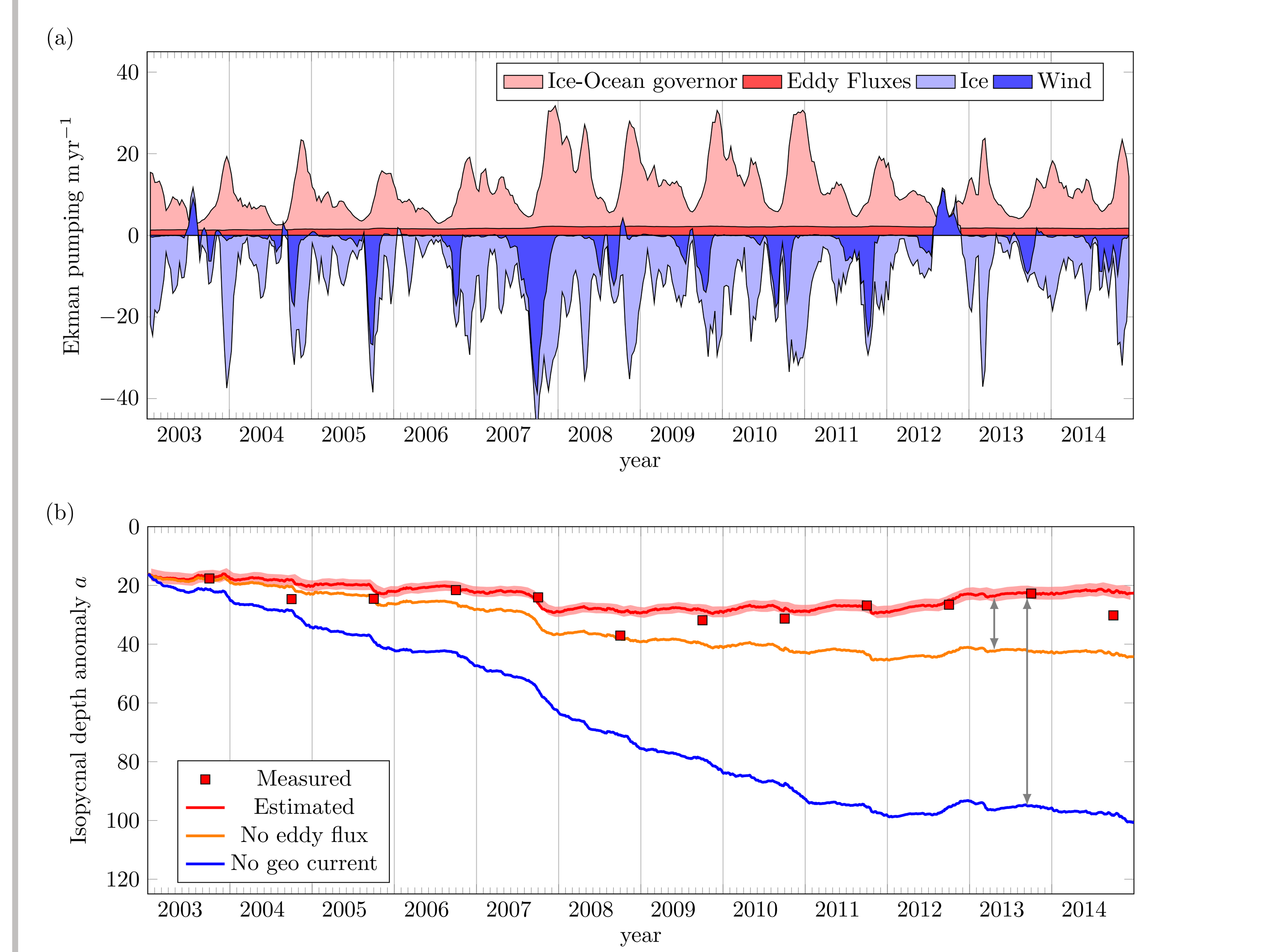
where $\boldsymbol{u}_a$, $\boldsymbol{u}_i$ and $\boldsymbol{u}_g$ are the observed wind, ice and surface geostrophic current velocities respectively, Note how the geostrophic surface currents $\boldsymbol{u}_g$ act as a negative feedback on the ice-driven component [see 2].

Observations



Observations of monthly mean Ekman pumping (black, top panel) and mean sea surface height anomaly measured over a length scale $L = 300\,\mathrm{km}$ from the center of the Beaufort Gyre (black, bottom panel) are assimilated in the idealized model. Blue and red filled areas in the top panel denotes upwelling and downwelling respectively. Red marks in the bottom panel shows the 30 psu isohaline depth anomaly estimated from hydrographic data for August-September-October of each year [5]; in the Arctic, isohaline depth can be considered a good approximation to isopycnal depth because the ocean stratification is mostly due to salinity variations. The estimated sea surface height anomaly (blue), isopycnal depth anomaly (red), eddy diffusivity $K = 218\,\mathrm{m^2\,s^{-1}}$ and reduced gravity $g' = 0.065\,\mathrm{m\,s^{-2}}$ (corresponding to $\Delta\rho = 6.8\,\mathrm{kg\,m^{-3}}$) are in agreement with observations. In particular, the estimated sea surface height anomaly (blue) captures a large part of the observed seasonal cycle variability (black) as well as its long-term increase after 2007 (RMSE $= 0.02\,\mathrm{m}$, $R^2 = 0.68$). The estimated bottom Ekman layer thickness is $d = 58\,\mathrm{m}$, and includes the effects of bottom bathymetry. Shaded blue and red regions in the bottom panel show the uncertainty of the model estimation (one standard deviation).

Conclusions



To better understand the relative role of the ice-ocean governor and eddy diffusivity in the equilibration of the gyre, we compute the contribution of the geostrophic current to the ice-ocean stress as

$$\boldsymbol{\tau}_{ig} = \boldsymbol{\tau}_i - \boldsymbol{\tau}_{i0},$$

where $\boldsymbol{\tau}_{i0}$ is the ice-ocean stress neglecting the geostrophic current, i.e., computed by setting the surface current to zero. We also define the Ekman pumping associated with each component as

$$w_a = \frac{\nabla \times ((1-\alpha)\boldsymbol{\tau}_a)}{\rho f} \qquad w_i = \frac{\nabla \times (\alpha\boldsymbol{\tau}_i)}{\rho f}$$

$$w_{i0} = \frac{\nabla \times (\alpha\boldsymbol{\tau}_{i0})}{\rho f} \qquad w_{ig} = \frac{\nabla \times (\alpha\boldsymbol{\tau}_{ig})}{\rho f},$$

so that the total Ekman pumping is

$$w_{Ek} = w_a + w_i = w_a + w_{i0} + w_{ig}.$$

We also note that the eddy flux term $K\frac{a}{L^2}$, having units of m/year, can be expressed as an equivalent Ekman pumping and compared with the other Ekman velocities.

The figure above shows a) Ekman pumping associated with wind forcing w_a (dark blue) ice forcing w_{i0} (light blue), eddy fluxes $K\frac{a}{L^2}$ (dark red) and the Ice-Ocean governor w_{ig} (light red). The mean Ice-Ocean governor term w_{ig} is six times larger than the mean eddy fluxes term Ka/L^2. b) hypothetical isopycnal depth anomaly under different scenarios: red line and red marks are the same as in the figure in the left box, with the red shaded region denoting one standard deviation. The orange curve represents the evolution of the isopycnal obtained by neglecting eddy diffusivity in the model. The blue curve is obtained by neglecting the ice-ocean governor. The error introduced by not including the ice-ocean governor is much larger (gray arrows), with an increase in isopycnal depth anomaly of more than ten times the actual one over the 12-year period considered.

References

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