Baroclinic instability and eddy fluxes in a seasonally ice-covered ocean

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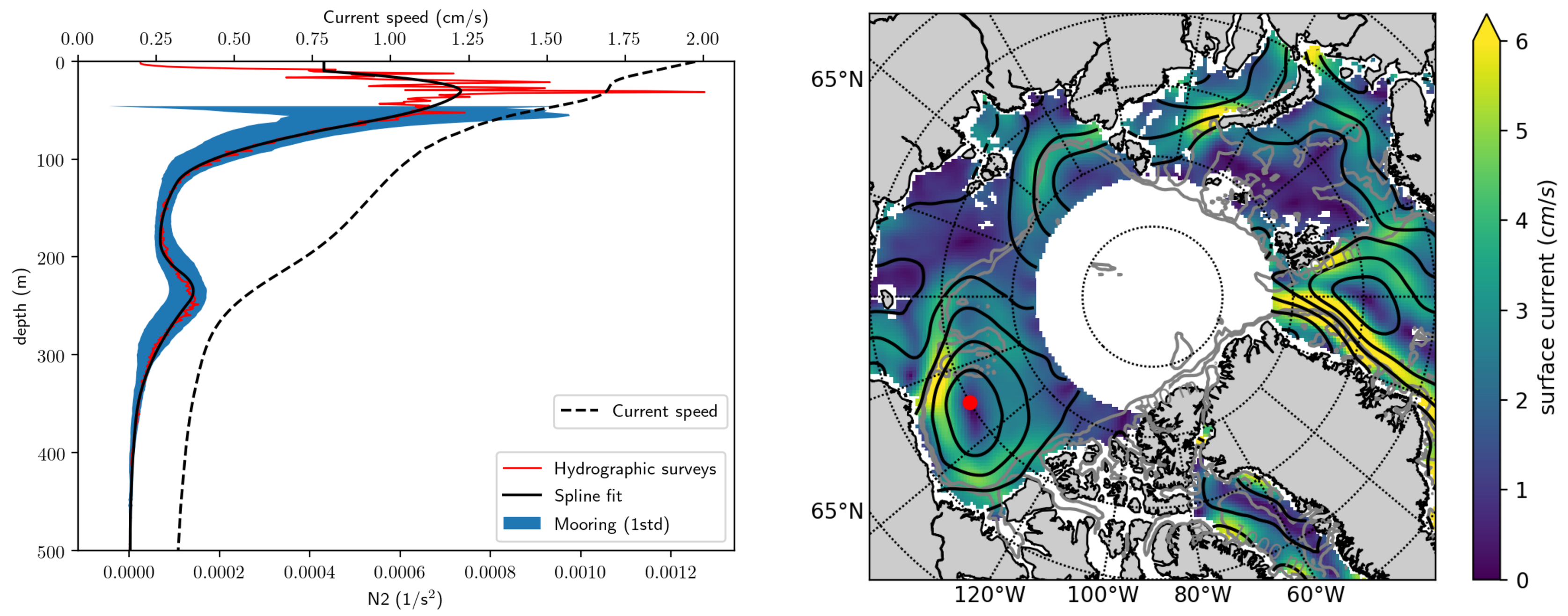
Abstract

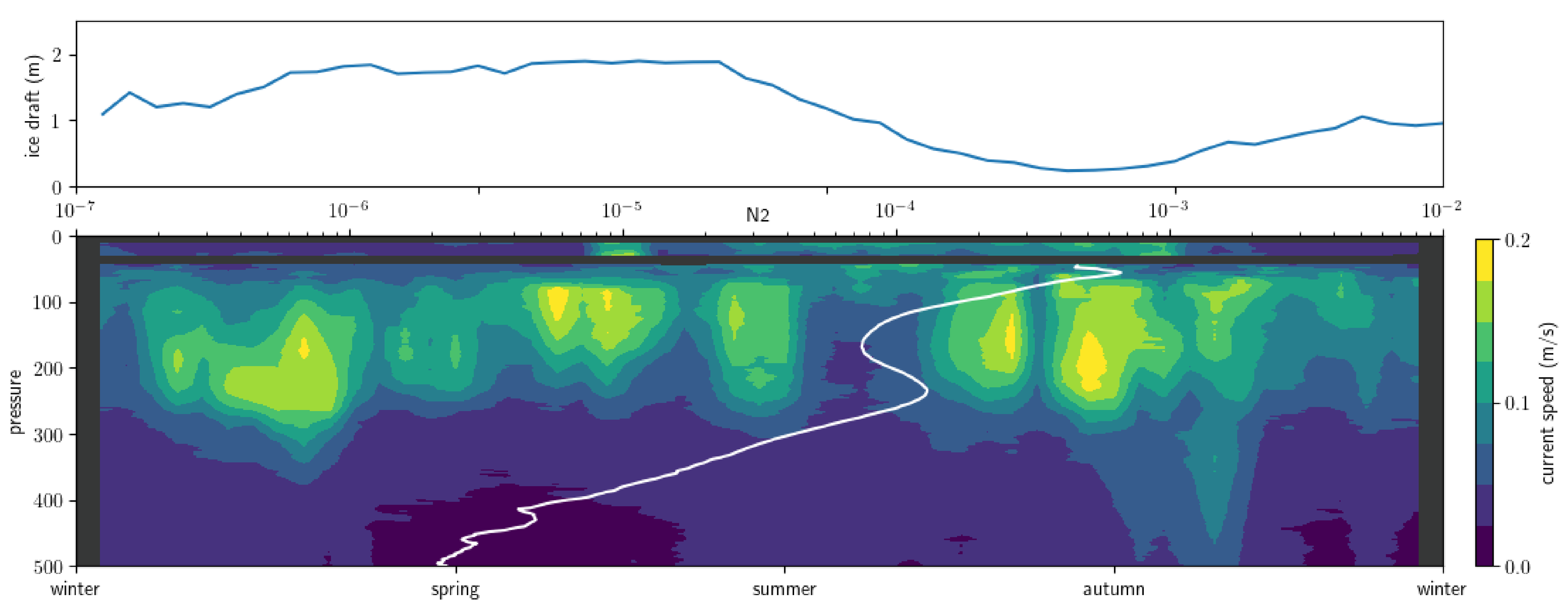
We address the origin and seasonal evolution of the eddy field in the Arctic. The origin of both mixed layer and halocline eddies is found in the development of baroclinic instability. The formation and evolution of mixed layer eddies is strongly modulated by the seasonal cycle in the ice cover.

Observations



Left: Brunt-Vaisala Frequency squared N^2 (solid) and current speed (dashed) in the central Canada Basin (red mark). Right: 2003-2014 Beaufort Sea mean surface currents.

Baroclinic eddies play an important role in regulating the large scale circulation, momentum transfer, the transport and mixing of water masses and heat, and biology. The development of baroclinic eddies depends on a combination of the destabilizing effect of the velocity shear and the stabilizing effect of stratification [2, 4, 11]. In the presence of ice, friction at the ice-ocean interface provides an additional stabilizing effect: energy and vorticity are dissipated within the Ekman layer generated by the interaction of the currents with a solid boundary [3, 1, 12, 6, 5, 7].



Observations of ice draft (top), current speed (bottom, color) and mean Brunt-Vaisala frequency (bottom, white line) in the central Canada Basin.

The origin of Arctic eddies is unclear: are they generated everywhere, or only in the more unstable coastal currents and then advected into the central basin [7]? Arctic eddies are also characterized by a peculiar subsurface velocity maximum [6, 13].

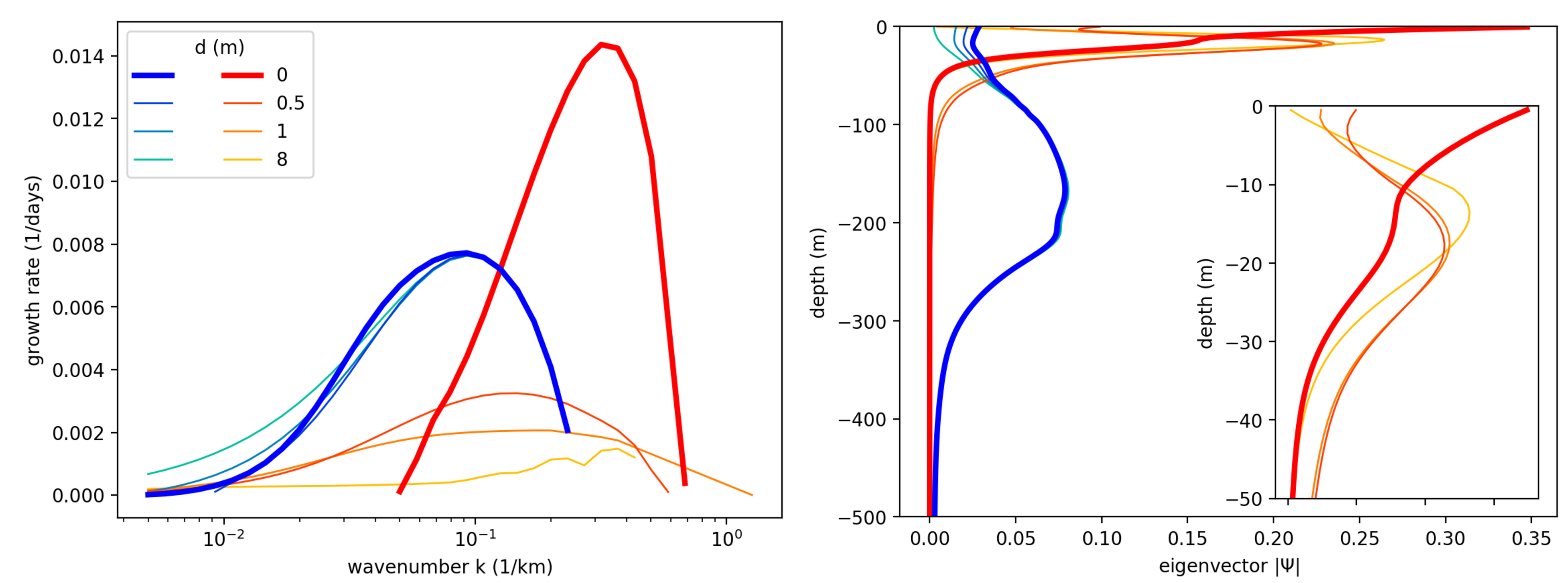
Observations of currents in the central Canada basin (bottom panel, color) show a strong seasonality in eddy activity in the mixed layer, with low speeds in winter and a more active eddy field in summer. In contrast, halocline eddies, extending from below the mixed layer up to 250 m depth, do not show any detectable seasonality. The vertical structure of the eddies is apparently related to the presence of two peaks in stratification, as can be seen by the vertical profile of the Brunt-Vaisala frequency (white line [13]. The presence of mixed layer eddies seems related to the ice cover (top panel).

Can we explain the origin and seasonal variability of Arctic eddies with baroclinic instability and surface friction?

Mooring data were collected and made available by the Beaufort Gyre Exploration Program based at the Woods Hole Oceanographic Institution (`http://www.whoi.edu/beaufortgyre`) in collaboration with researchers from Fisheries and Oceans Canada at the Institute of Ocean Sciences.

Surface currents are obtained by satellite altimetry, for details see T. W. K. Armitage et al. *Arctic sea surface height variability and change from satellite radar altimetry and GRACE, 2003-2014*. Journal of Geophysical Research: Oceans, 121(6):4303–4322, 2016.

Baroclinic eddies



Growth rates (left) and vertical structure of the perturbations (right) for the mixed layer (red) and halocline (blue) eddies. Selected values of Ekman layer depth d.

— Theory —

The evolution of instabilities is governed by the linearized quasi-geostrophic dynamics

$$\frac{\partial q}{\partial t} + \bar{U}\cdot\nabla q = 0$$

$$q = \nabla^2\Psi + \frac{\partial}{\partial z}\left(\frac{f_0^2}{N^2}\frac{\partial \Psi}{\partial z}\right)$$

where Ψ is the streamfunction and q is the potential vorticity. Both β_0 and the background vorticity gradient $\nabla\bar{q}$ are assumed to be zero.

Friction is modeled by the presence of an Ekman layer the top and at the bottom of the domain. Boundary conditions are then imposed by matching the interior vertical velocity to the Ekman pumping w_E

$$-\frac{f_0}{N^2}\left[\frac{\partial}{\partial t}\frac{\partial \Psi}{\partial z} + \bar{U}\cdot\nabla\left(\frac{\partial \Psi}{\partial z}\right)\right] = \underbrace{\frac{d}{2}\nabla^2\Psi}_{w_E}$$

where d is the Ekman layer depth. The right hand side models the dependence of the Ekman pumping w_E on the geostrophic relative vorticity $\nabla^2\Psi$ or, equivalently, the dissipation of vorticity in the Ekman layer. Larger ice concentrations and thicknesses, able to sustain larger internal stresses, are modeled by larger Ekman layer depths.

— Results —

The growth rate and vertical structure of the two fastest growing instabilities are shown above.

Mixed layer eddies (red) are strongly affected by friction with the ice. An Ekman layer depth of 0.5 m is sufficient to reduce the growth rate from 0.014 per day ($T = 71$ days) to 0.003 per day ($T = 333$ days), with higher friction dampening the growth of instabilities even more. At the same time, the length scale increases by a factor of four from 2.5 km to almost 10 km. The vertical structure clearly shows the effect of dissipation, with increased friction driving the mode to zero at the surface.

In contrast, halocline eddies (blue) are barely affected by friction: a small reduction in the surface representation of the mode is visible, but the bulk of the perturbations, lying below 50 m, is unchanged. Similarly, both the growth rate and the characteristic length scale are essentially unchanged at 0.008 per day ($T = 125$ days) and 11 km.

Both the origin and seasonal variability of Arctic eddies can be explained by baroclinic instability: eddies can be locally generated, with mixed layer ones quickly dissipated by the interaction with the ice during winter.

— Dissipation or preexisting eddies —

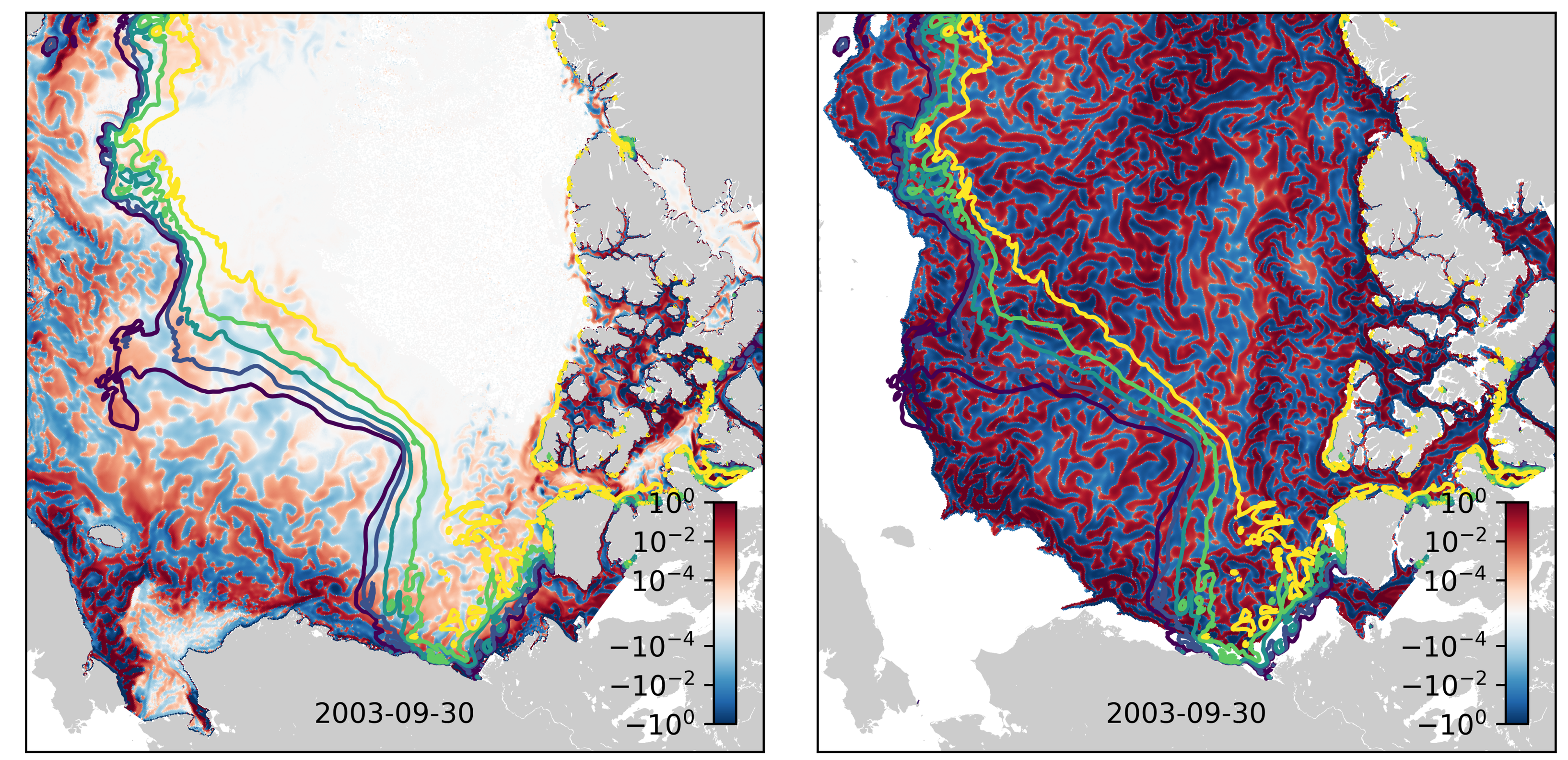
How about preexisting eddies generated, e.g., in ice free regions? Their spindown time scale can be estimated by energetic consideration as

$$T_\nu = \frac{K}{\dot{W}} = \frac{H}{d}f^{-1}$$

where K is the kinetic energy of the eddy, $\dot{W}$ is the power dissipated by friction, H is the depth of the eddy and d is the Ekman layer length scale. If we consider a characteristic vertical scale $H \approx 30$ m, characterizing the surface eddies, and an Ekman layer depth of order 1 m, the resulting time scale is about 2 days, with larger Ekman layer depths dissipating eddies even faster.

Mixed layer eddies cannot travel long distances while in contact with the ice cover. In contrast subsurface eddies, insulated from the ice cover, can propagate far from the region where they are generated.

Model



Relative vorticity field ($\times 10^7$) at 17 m (left) and 97 m depth (right); logarithmic color scale. Ice concentration contours range from 95% (yellow) to 85% (purple), every 2.5%.

Baroclinic instability results are local and based on linear assumptions. In order to gain further insights about the spatial and temporal evolution of the eddy field as a function of the ice cover we resort to a Pan-Arctic eddy resolving, 4 km resolution, multi-decadal run based on NEMO-LIM3.

Two snapshots of the vorticity field for September 2003 are shown above. As predicted by the theory, mixed layer eddies (left) rapidly disappear in the presence of ice, with relative vorticity dropping by more than five orders of magnitude across the marginal ice zone. In contrast, halocline eddies (right) are unaffected by the presence of ice.

Conclusions

Observations, baroclinic instability calculations and numerical models show that

- Mixed layer eddies are strongly affected by the presence of the ice cover. Even moderate friction reduces growth rates to levels too low for eddies to actually develop. When developed over the summer or in ice free regions, eddies will be dissipated on a time scale of a few days.
- Halocline eddies are unaffected by the presence of the ice, and can potentially travel long distances without being dissipated.

Our analysis suggests that increasingly ice free summers will result in important changes in the state of the Arctic. The time scales characterizing baroclinic instability are less, but of the order of, the seasonal cycle, suggesting that eddies are actually growing exponentially over most of the summer. Even a moderate extension of the ice-free season will result in a large increase in the eddy activity in the mixed layer, with consequences on mixing of heat at the ocean surface, and on the regrowth of the ice cover the following winter.

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