Generation and Separation of Mesoscale Eddies from Surface Ocean Fronts

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Motivation

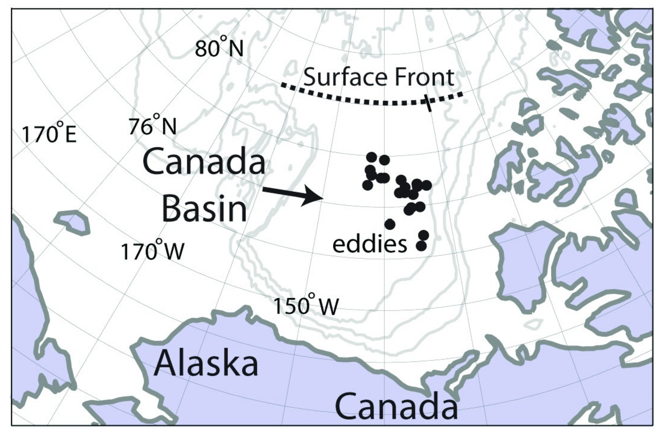

Fig. 1. Locations of observed eddies in the Beaufort gyre (black dots) and of the surface density front (dashed line).

The analysis in this paper is motivated by observations of a large number of energetic sub-mixed layer eddies in the Arctic Ocean's Canada Basin (Fig. 1). The anomalous water mass signature of these eddies suggests that they are generated at a surface density front observed around 80^0 N and extending approximately in the zonal direction (Fig. 1).

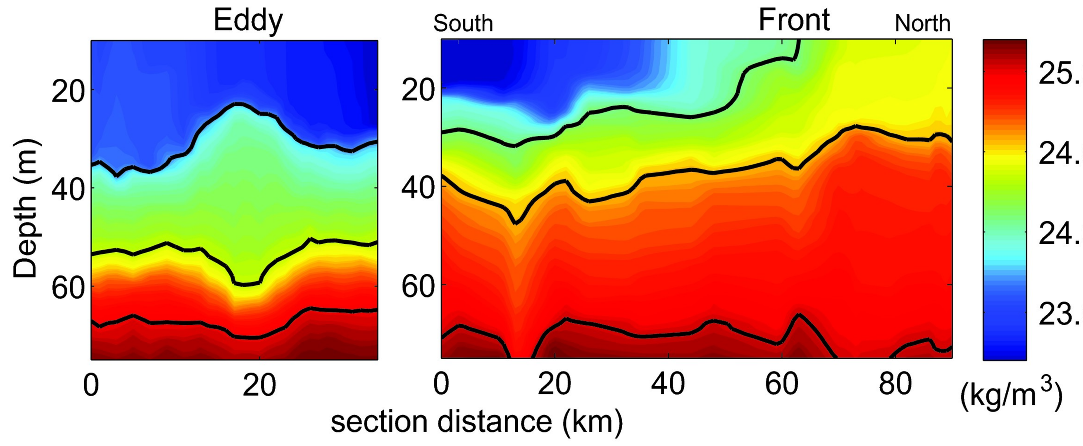

Fig. 2 **(a)** An observed vertical profile of a typical anticyclonic sub-mixed layer eddy and **(b)** a surface density front (from Ice Tethered Profilers deployed in the Arctic Ocean) .

How could eddies appear at such long distances away from their formation region?

Methodology

A general circulation ocean model (MIT GCM) is used to simulate the relaxation of the surface density front from its initial state and the accompanying eddy shedding.

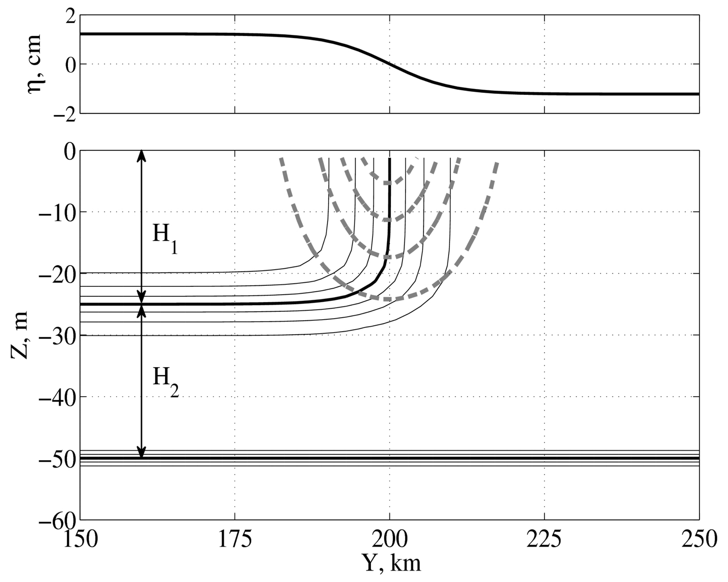

Fig. 3. Initial frontal configuration. (Top) the elevation of the free surface η. (Bottom) solid black – isopycnals with 0.125kg/m3 spacing; dashed gray – along-front velocity with 2 cm/s spacing.

<u>Numerical Model Set-up</u>

- Primitive equation model with no sub-grid parameterizations
- No buoyancy or momentum restoring applied
- Domain size: 400m x 300km x 400km. Vertical resolution: 2.5m (varying), horizontal: 0.5km
- BC: periodic in X-dir, no-flux at Y-dir boundaries, no stress and free slip at top and bottom
- Dissipation used for numerical stability: $K_v=10^{-5}$ m²/s, $K_h=2$ m²/s

Numerical Simulations of frontal instabilities

The front is unstable and its growing meanders lead to the production of eddies. Dominating structures are dipoles with a surface cyclone and an underlying anticyclone shifted horizontally. Mergers of same sign vortices as well as the absorption of eddies by the slumping front trap most of the eddies to the frontal area. Self-propagating dipoles are observed to propagate far from the front on rare occasions.

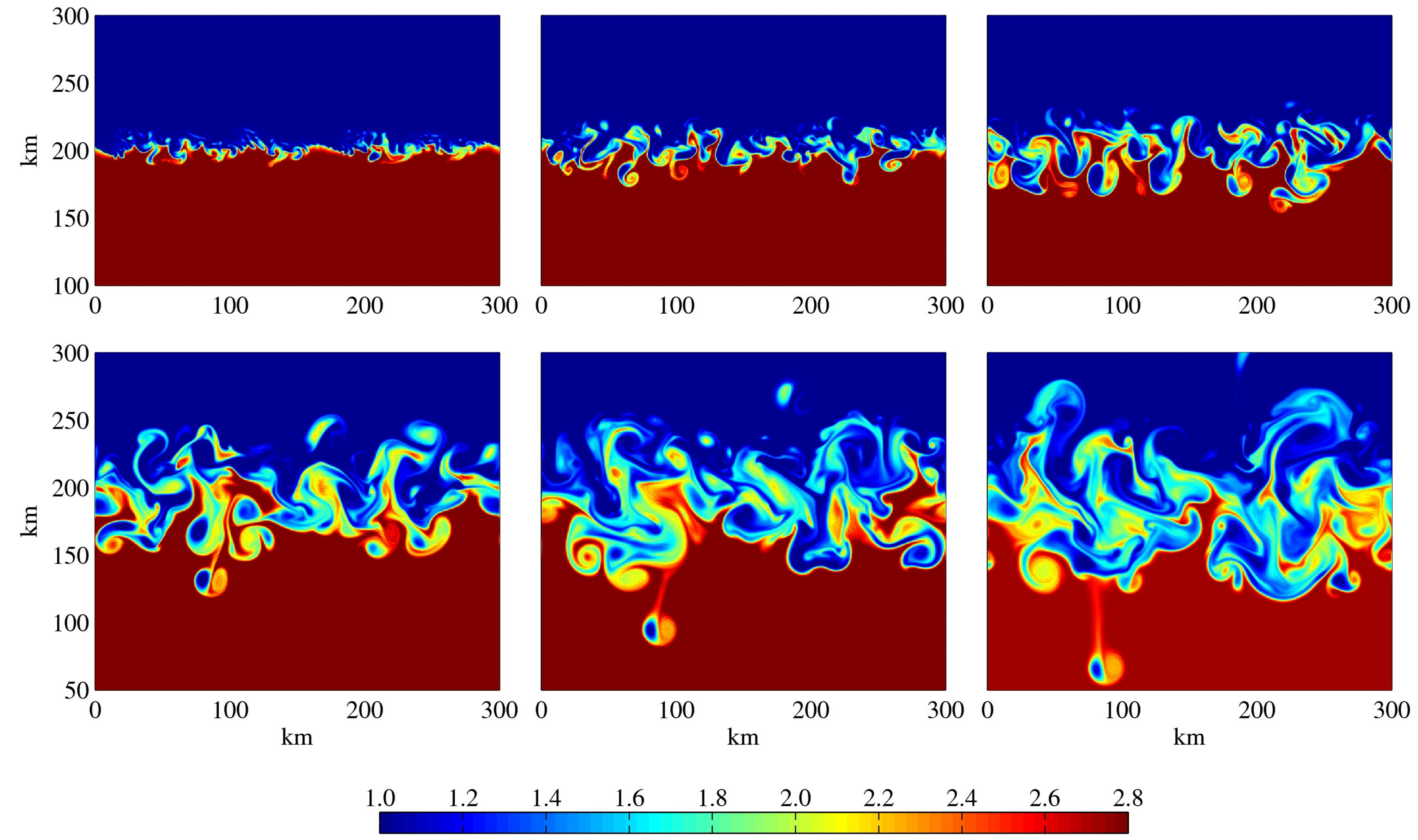

Fig. 4. The time evolution of the frontal instabilities (the simulations performed for ~60 model days). Colors show the potential vorticity in layer 2, normalized by its value on the deep side of the front. Note the formation of the dipoles at the early stage, and a later separation of a dipole from the front.

Dynamical model of a dipole pair

- Anticyclone is formed as frontal meanders bring low PV waters across the deep side of the front. Cyclones have origin near the center of the front, in the high PV region of isopycnal outcropping.
- 2.5-layer quasi-geostrophic model is used to separate the velocity contributions from individual eddies in a dipole.

$$\begin{cases} \nabla^2\psi_1 + F_1(\psi_2-\psi_1) = S_1\delta(\boldsymbol{r}) \\ \nabla^2\psi_2 + F_2(\psi_1-\psi_2) - F_3\psi_2 = S_2\delta(\boldsymbol{r}-\boldsymbol{\Delta}) \end{cases}$$

1) Circulation in the bottom layer due to the top <u>cyclone</u>

$$\psi_2 = S_t F_2 \frac{K_0(r/\lambda_1) - K_0(r/\lambda_2)}{\lambda_1^{-2} - \lambda_2^{-2}}$$

2) Circulation in the top layer due to the bottom <u>anticyclone</u>

$$\psi_1 = S_b F_1 \frac{K_0(r/\lambda_1) - K_0(r/\lambda_2)}{\lambda_1^{-2} - \lambda_2^{-2}}$$

Ratio of self-propagating velocities depends on the PV anomaly (Fig. 5) in each eddy

$$\varepsilon = \frac{U_1}{U_2} = \frac{S_b F_1}{S_t F_2} = \frac{S_b H_2}{S_t H_1}.$$

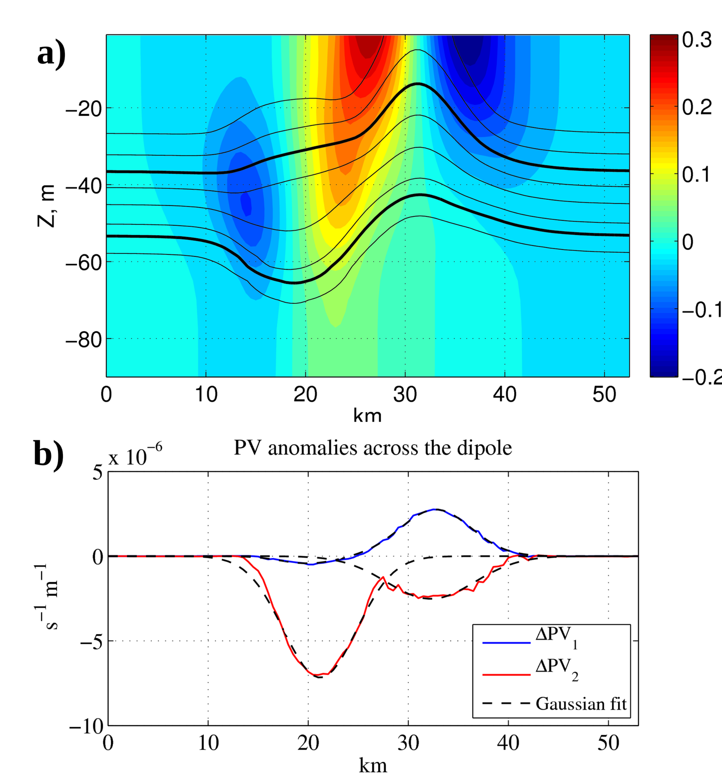

Fig. 5. Sections through the center of a dipole. **(a)** Colors – velocity out of the board; contours – isopycnals. **(b)** PV anomalies in layer 1 (blue) and layer 2 (red).

Dipole trajectories

Dipoles propagate on circular trajectories with a radius determined by the ratio of self-propagating velocities ε.

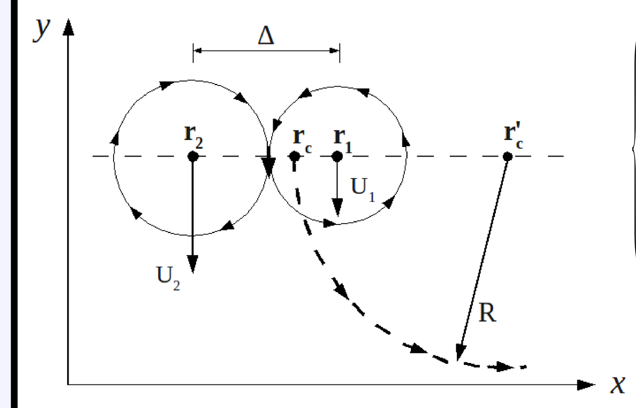

Fig. 6. Schematic showing dipole parameters and its trajectory.

Kinematic equations describe the motion of each vortex in a dipole with coordinates $\mathbf{r}_{1,2}$ and a location of its center $\mathbf{r}_c$:

$$\begin{cases} \dot{\boldsymbol{r}}_1 = \frac{U_1}{\Delta}\boldsymbol{k}\times(\boldsymbol{r}_2-\boldsymbol{r}_1) \\ \dot{\boldsymbol{r}}_2 = \frac{U_2}{\Delta}\boldsymbol{k}\times(\boldsymbol{r}_2-\boldsymbol{r}_1) \end{cases}$$

$$\boldsymbol{r}_c = \frac{U_2\boldsymbol{r}_1 + U_1\boldsymbol{r}_2}{U_1+U_2} \sim 2\Delta\frac{U_1U_2}{U_2^2-U_1^2}\begin{bmatrix} \sin\omega t \\ \cos\omega t \end{bmatrix}$$

Where $\omega = \frac{U_2-U_1}{\Delta}$ is the frequency.

Balanced dipoles (ε=1) have trajectory radius R=∞ and thus propagate on straight lines: $R = \frac{2\Delta}{\varepsilon - 1/\varepsilon};\ \varepsilon = \frac{U_1}{U_2}.$

Statistical properties of dipoles

Eddy separation from the slumping front are rare, and only balanced dipoles were observed to escape.

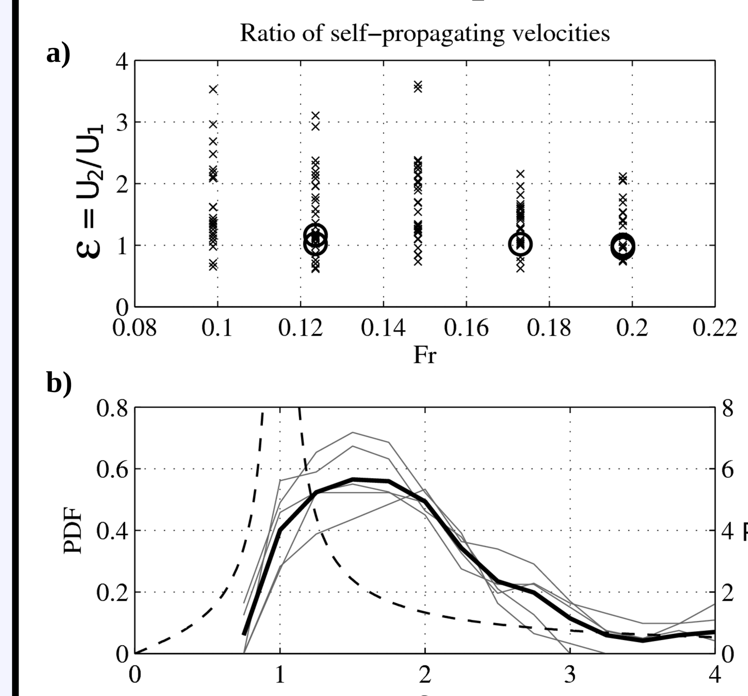

Fig. 7. **(a)** ε-ratio of dipoles for fronts with different Froude number; circles mark escaped dipoles **(b)** The probability density function of ε (solid) and the dependence of the trajectory radius R on ε (dashed).

- A total of ~130 dipoles were identified along with their essential parameters: size, PV anomalies, and Δ.
- A dynamical model is then used to split the velocity contribution of each eddy in a dipole, thus obtaining ε.
- Only dipoles with ε~1 were observed to escape the influence of the front
- The probability density function (PDF) of ε is mostly independent of the frontal Froude number.

Conclusions and references

Frontal instabilities lead to the production of eddies, amongst which self-propagating dipoles are common features. As the front slumps, most of the eddies recirculate back, with only balanced dipoles found to separate. The probability for the production of balanced dipoles from frontal meanders remains relatively small, independent of the frontal strength.

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