How Coastal Currents form Oceanic Vortices in Bays explained with Eddy Simulations around Kamchatka

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ABSTRACT

In the ocean, the creation of eddies is often the result of turbulence in a current, which makes it almost impossible to predict at which location an eddy will form. However, there exist examples in which an eddy forms many times at the same position. Such an example is the Kamchatka Eddy, which can be observed almost every winter south of the Kamchatka peninsula in the Northwest Pacific. The regular formation of this eddy indicates that localised eddy sources exist that make the eddy formation process predictable. To test this hypothesis, I implemented several ocean models in the computation fluid dynamics tool `fluid2d`. My numerical experiments check the influence of bays in a coast for the creation of oceanic vortices by an alongshore current. I found that inside a bay, big and stable vortices are created by the current. The formation process of these vortices is explained in this article, based on the results of my numerical simulations. My findings suggests that the three bays at the east coast of Kamchatka constitute eddy sources that feed the Kamchatka Eddy.

1. Introduction

In the Northwest Pacific Ocean near the Russian peninsula Kamchatka, an interesting phenomenon can be observed. A big anticyclonic eddy appears almost every year in winter at a fixed position south of the peninsula [Solomon and Ahlnäs (1978), Stabeno et al. (1994), Yasuda et al. (2000), Isoguchi and Kawamura (2003), ISS Crew (2012)]. This oceanic vortex is known as the Kamchatka Eddy. It stays at its position without decreasing for several months. It is remarkable that an eddy of this size forms so regularly and exists so steadily. The process behind this phenomenon has so far not been explained and is therefore the objective of my study, which answers the question: Can the particular eastern coastline of Kamchatka play a role in the creation of the Kamchatka Eddy?

The Kamchatka current, like oceanic currents in general, can form meanders, become unstable and shed eddies. Since the creation of eddies results from a turbulent process, it is usually impossible to predict where a new eddy will form. This is contrary to the Kamchatka Eddy, which forms every time at about the same position. Therefore, it is likely that localised sources exist that feed the Kamchatka Eddy. My hypothesis is that the three bays in the eastern coastline of Kamchatka constitute such eddy sources.

The here presented study tests this hypothesis and explains how coastal bays influence the creation of vortices when a current flows along a coast with bays. To do this, I implemented several 2D fluid models in the hydrodynamical simulation framework `fluid2d` by Roullet (2017). My numerical models increase in their complexity, from rather simple to almost realistic. The common element of all the models is an oceanic current flowing along a coast with a bay; the current is created by a constant surface forcing. The more complex models take also Earth rotation and non-uniform ocean depth into account.

The models used in this study are presented in detail in Section 2. Then Section 3 presents the affirmative results I obtained; also those models are presented which proved not suitable for testing the hypothesis. Finally Section 4 contains a discussion of the results, links them to the particular situation of Kamchatka, and answers the abovementioned question.

2. Method: Numerical Models

To study the influence of coastal bays on the creation of oceanic vortices, I implemented three models in the computational fluid dynamics tool `fluid2d`. My models are inspired by the real situation of the Kamchatka current. As explained by Isoguchi and Kawamura (2002), the Kamchatka current is a western boundary current flowing in

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southwestward direction close to the eastern coastline of the Kamchatka peninsula. This coastline features three almost semi-circular bays with capes between them.

My first numerical model uses a north–south periodic domain which allows to have a quasi-infinite current. It is desirable to have an infinite current, because on a finite domain, the current has to make a turn when it reaches the end of the domain. In such a turn, the current tends to get turbulent. The turbulence would complicate the study of the interaction between the current and a bay. This bay is modelled as a semi-circle removed from the straight coastline. The coastline is also north–south periodic, as a necessity of the periodic domain. Furthermore, the periodicity requires that the Coriolis parameter is constant. Without loss of generality, the Coriolis parameter can be set to zero, compare (1) in the following.

I implemented the here-described situation using the *Euler* model of `fluid2d`. The software solves numerically the vorticity equation

$$\frac{\partial \omega}{\partial t} + \mathrm{J}(\psi, \omega) = F(x,y)\,, \tag{1}$$

where the vorticity ω is the Laplacian of the streamfunction ψ [Roullet (2017)] and $F(x,y)$ denotes a constant (but non-uniform) surface forcing. This forcing creates the current along the western boundary of the domain.

For the more realistic experiments, I use the *quasi-geostrophic* model of `fluid2d`. In this model, the vorticity contains contributions of the Coriolis parameter $f(y) = f_0 + \beta y$, the ratio between bathymetry $H_B(x,y)$ and ocean depth H, and the barotropic Rossby radius R_d [Salmon (1998)]:

$$\omega = \nabla^2 \psi - R_d^{-2} \psi + f + f_0 \frac{H_B(x,y)}{H}\,. \tag{2}$$

The evolution equation is still (1). Note that this model is either on the β-plane or on the f-plane (for $\beta = 0$).

On the β-plane, the model cannot be periodic in the direction of the current, so another approach is needed to have a western boundary current. There are two possibilities – one is easy to understand, one is easy to implement. The first one consists of forcing a current along the coast as in the Euler model and then gently diminishing it as it reaches the southern end of the domain. This is done by a buffer zone, in which the vorticity is smoothly forced to the value of the background vorticity f (plus possibly bathymetry). However, having a realistic buffer zone requires a fine tuning of parameters. Otherwise the buffer will impact too much the interesting part of the domain, namely where the current interacts with the bay.

This fine tuning is not required for the second approach, which uses a gyre or double-gyre model and thus comes close to the real situation [Isoguchi and Kawamura (2002)]. Wind-driven oceanic gyres feature naturally a western intensification on the β-plane, as explained by Stommel (1948). That means, a strong current flows along the western boundary of the domain. As it is shown later in Section 3b, such a model requires also bottom topography to model realistically the situation directly at the western coast. Therefore, I set the height of the bathymetry $H_B(x,y)$ such that it represents the continental shelf with its slope towards the abyssal ocean of depth H.

The values of the important parameters entering in the quasi-geostrophic model are presented in Table 1. They are given in the units of kilometer and day (d). I implemented the simulation with these units, because they give reasonable values for the lengths, times and velocities appearing in the experiment ($10\,\mathrm{cm\,s^{-1}} = 8.64\,\mathrm{km\,d^{-1}}$). For the Euler model, it is not necessary to specify the units, since none of the parameters presented in Table 1 appear in the formulation of the model. Therefore, the results of this experiment can be scaled to any situation and can be useful to explain similar phenomenon in other places, too.

TABLE 1. Typical values of the important parameters in the ocean around Kamchatka; used in the quasi-geostrophic model.

Parameter	Value
f_0	$10\,\mathrm{d^{-1}}$
β	$1.2 \times 10^{-3}\,\mathrm{km^{-1}\,d^{-1}}$
R_d	$2000\,\mathrm{km}$

3. Results

Part *a* of this section describes what I observed with the three numerical models that give useful results. Part *b* explains why two other models fail to explain the creation of vortices influenced by a bay.

a. Creation of vortices in a bay

My numerical experiments with the Euler model prove that a bay in the coast enables the creation of big, stationary vortices. These vortices form inside the bay and can reach a diameter comparable to the size of the bay. The process of vortex creation influenced by the bay is explained by the snapshots of vorticity shown in Fig. 1. As a first step, the coastal current becomes unstable near the bay. This is different from the case of a current along a straight coast, where an instability can happen at any position. The instability deflects the current from its straight path into the bay. This deviated part of the current is trapped in the bay and circulates in there. During its circulation, it aggregates more vorticity from the current flowing along the coast. This aggregation makes the vorticity patch grow to a big vortex. The vortex grows up to the size of the bay and stays within the bay for a long time. In contrast: vortices formed outside of the bay are advected by the current and do not stay at a fixed position. It is

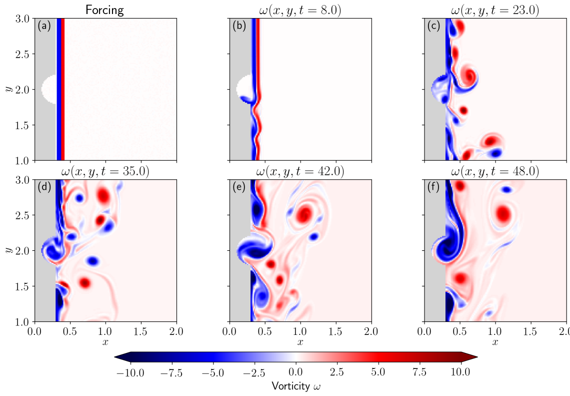

FIG. 1. This time series of vorticity (b–f) shows the creation, trapping and growing of a vortex in a bay. The vortex draws its energy from a current flowing straight down along the coast due to a constant forcing (a). Although the forcing imposes a straight path, the current deviates from this and flows into the bay (b). This bay traps the vorticity patch, which then aggregates more vorticity from the permanent current and thereby grows (c,d). As a result, the vortex in the bay grows bigger than those away from the coast (e). Also, the trapped vortex stays fixed at its position for a long time (f). (Note that the colour bar applies to frames (b–f); the colours in (a) are only for illustration purposes.)

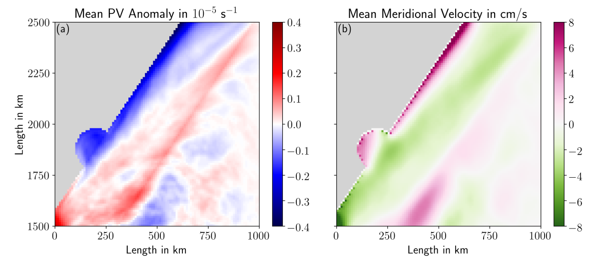

FIG. 2. The formation of an anticyclonic vortex in a bay is shown by 2500-day time averages of the double-gyre model with a continental shelf. (a) The time mean of PV (potential vorticity) anomaly shows that a patch of negative vorticity (blue) exists over a long time in the bay. (b) The time mean of meridional velocity shows the big southward flowing current (green) in parallel to the coast along the shelf. The current deviates from this path and enters in the bay, it turns around, and follows the shape of the bay, creating the anticyclonic vortex in the bay.

thus shown that a bay in the coast influences the creation of vortices in a current by determining their position and size.

I obtain the same result by considering a quasi-geostrophic model on the f-plane with an explicitly forced current. Also in this model, the presence of a bay in the coast leads to the creation of a big, stationary vortex in the bay. However, my numerical experiments show that this is no longer true if the current is forced explicitly and $\beta \neq 0$. On the β-plane, it is necessary to consider a more realistic model with a current induced by wind forcing flowing along the continental shelf.

In a wind-forced double-gyre model with a continental shelf, an alongshore current tends to create big, stationary vortices due to a bay. This is proven by Fig. 2, which shows the anomaly of PV (potential vorticity) and the meridional velocity. Both quantities are averaged over a long-time model run. In my model (as in reality), the current flows along the continental shelf and thus in a distance from the coast. It approaches the coast where the bay is and circulates inside the bay, thereby creating a vortex of negative circulation. This vortex fills out the whole bay and stays stably inside there over a long time. In consequence, the vortex is clearly visible in the time mean of PV anomaly. Therefore, the bay induces the formation of a big, stationary vortex at a fixed position.

b. Models ruled out by this study

To observe the creation of vortices in the bay, it is necessary to include the continental shelf in the gyre model. If instead a uniform depth of the basin ($H_B \equiv 0$) is used, the western boundary current behaves very differently. Instead of flowing across the bay and then recirculating within it, the current follows the coastline closely (Fig. 3a). It goes around the cape at the upstream end of the bay, retraces the curvature of the bay, and leaves the bay downstream. When the current left the bay, it does not come back and so it cannot form a vortex in the bay. I thus conclude that the gyre model without a continental shelf is not a suitable approach to study the coastal dynamics of a western boundary current.

Another model that proved unable to give realistic results is the explicitly forced current on the β-plane (Fig. 3b). The β-plane is defined by a PV background decreasing linearly in north–south direction. Onto this background vorticity, the explicit forcing adds a perturbation, because vorticity is velocity shear and the current is localised. This perturbation excites a wave in the PV, which propagates along the lines of iso-PV (bottom of Fig. 3b). Thereby it produces additional vorticity sheets of alternating sign next to the explicitly forced current (top and centre of Fig. 3b). This sequence of alternating vorticity is unstable and breaks up into small vortices constantly. Therefore, it is not possible to study solely the interaction between a current and coastal features with this model.

4. Discussion and Conclusion

I found that a bay in a coast is a source of oceanic vortices. A boundary current along a coast with embayments does not randomly shed vortices, but predominantly near and in the bays. Also the size of these vortices is determined by the size of the bay. My numerical experiments showed this in different settings: for an idealized quasi-infinite current in an Euler model; for a current close to a coast on the f-plane; and for the western boundary current of a Stommel-gyre if the continental shelf is taken

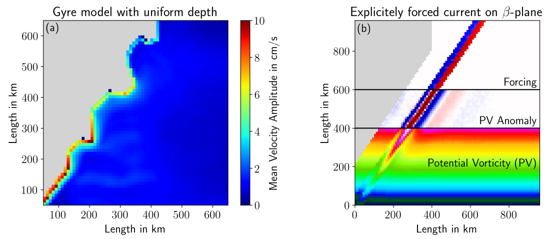

FIG. 3. (a) In the gyre model with uniform ocean depth, the current cannot create vortices inside the bays, because it follows exactly the coastline. This close retracing of the coastline is not what is observed in reality at Kamchatka, although the shape of the coast and the mean velocity are similar to those of the actual Kamchatka situation. (b) In the β-plane model with a current forced explicitly, the current is in a realistic distance from the coast (upper part). However, after a spin-up phase (half a year), sheets of alternating vorticity appear east of the actual current (middle part). Explanation: the forcing perturbs the PV background; this perturbation propagates eastward (lower part) and makes it impossible to study the pure current along the coast.

into account. These results suggest that the three bays at the east coast of Kamchatka (K) constitute eddy sources which feed the big K Eddy. This can explain why the K Eddy exists over such a long time and how it always forms in the same area.

A serious limitation of my models is their intrinsic 2D nature. This is justified by the observation that eddies near K have a deep structure [Isoguchi and Kawamura (2003)]. But the 1-layer 2D models make it impossible to describe the deep Kuril–Kamchatka trench, which exists in the area of the eddy formation [Isoguchi and Kawamura (2003)]. It might have an influence on the K Eddy.

Furthermore, the models I studied have a forcing that is constant in time. Therefore, my simulations cannot explain why the eddy formation happens predominantly in winter. It is probably because the K current is strongest in winter, but the precise influence of this temporal variation needs further examination.

Some more questions are left unanswered by my study. How do the eddies travel from the bays to the formation site of the K Eddy? Why does the K Eddy stay at its position and not somewhere else? And what makes the K Eddy cease finally? Theses questions can be the starting point for further research with numerical experiments, with satellite measurements, or with *in situ* data.

Finally, note that my first model makes no assumptions that are particular for K. Thus, my simulation can by used to explain phenomenons in any part of the world ocean. My results show step-by-step the formation of a circular eddy induced by an oceanic current flowing across a coastal bay (Fig. 1). It is likely that the same formation process also happens along other coastlines. This opens the door for future research, trying to find such sites in the oceans and looking at the implications of this. After all, eddies are an important player in many oceanic processes, cf. Talley et al. (2011), so it is crucial to understand their formation in detail. The author of this article hopes humbly to bring the scientific community closer to this goal with the here presented study.

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