

We thank the reviewers for the time and effort they spent reviewing this manuscript. Their feedback has helped improve the manuscript. Detailed responses to each comment are provided below.

Response to Reviewer #1

The paper investigates an observed asymmetry in the response of coastal currents to fluctuating wind stress over a coastal bank offshore of Korea. Observations are supplemented with a realistic model in which the asymmetry persists. Using momentum balance analysis and an idealized model, the authors identify spatial differences in mass divergence driven by Ekman transport as the primary mechanism underlying the observed asymmetry. The findings are then generalized, accounting for differences in offshore circulation and wind patterns, suggesting that such asymmetries may not be limited to the study area. The paper is well-conceived, and the text and figures are generally clear. However, there are some structural inconsistencies and potential clarifications that warrant reconsideration.

1. The introduction of observations and the realistic model is a bit unclear.

Are the observations used from moorings? Is the surface bin from all stations a depth average between 0 and 1 (0.5) meters? During which period were the moorings deployed? Are the peaks in PSD statistically significant? And do the other stations differ significantly in terms of PSD from “B” and “F”?

The realistic ROMS model used is not introduced in detail; some fundamental properties and perhaps notes on previous validation efforts would be appropriate, especially given that they are from different runs than those in the cited paper.

Response: All observations were obtained from ADCP moorings. Measurements were taken at a depth of 4 m below the surface at all stations, except for station E, where measurements were taken at 2 m depth. The deployment periods for each mooring were as follows:

A: 2019-03-27 to 2019-09-26

B: 2019-03-20 to 2019-09-19

C: 2019-03-19 to 2019-10-09

D: 2019-03-27 to 2019-10-17

E: 2019-03-27 to 2019-10-17

F: 2019-03-21 to 2019-09-20

The spectral peak at a 7.5-day period in the PSD was evaluated using a Monte Carlo significance test with 1000 iterations. The 7.5-day peak is statistically significant at the 95% confidence level at all stations. However, the prominence of this peak varies among stations. At station D, the PSD is broadly distributed without a distinct peak, while at station E the 7.5-day peak is not clearly pronounced. The remaining stations exhibit a clear peak at a 7.5-day period.

The section describing the realistic model has been revised as follows:

2.2 Realistic model

A previously developed realistic model was used to complement the limited observational coverage and to examine the full spatial variability of coastal currents (Jung and Cho, 2020). The model domain is identical to that of Jung and Cho (2020), except that the coastline and bathymetry along the southern coast of the Korean Peninsula are represented using less smoothing. The previous model successfully reproduced the upwelling pattern in the study area when compared with in situ observations. The initial conditions were taken from the output of the previous model. The model was initialized from the 2015 output of the previous simulation and integrated through 2019. Tidal forcing was omitted to isolate the wind-driven dynamical response of coastal currents over the bank. All other model configurations, including atmospheric forcing and open boundary conditions, are identical to those used in the previous study. Additional details of the model configuration can be found in Jung and Cho (2020).

2. The results and discussion may be restructured for easier readability.

Could the sections on adding offshore circulation and the sensitivity analysis be moved to the results section? In addition to these parts seeming well-suited to the results section, I believe the inclusion of so many figures distracts from other major discussion points. Much of the text in this section could remain relatively unchanged in the results section.

Response: We thank the reviewer for this constructive comment. In the revised manuscript, the relevant text and figures have been moved to the Results section.

MINOR:

1. Have the observed current velocities and directions been correlated to the wind stress? Are all of these correlations significant? Are the peaks seen significant?

Response: The alongshore wind and observed currents, both defined as 20° counterclockwise from the east-west direction, are correlated and statistically significant ($p\text{-value} < 0.05$) at all stations except station E. The correlation coefficients at stations A, B, C, D, and F are 0.44, 0.57, 0.59, 0.46, and 0.42, respectively.

2. There seems to be greater asymmetry in the observed locations than in the area averages. Is this due to sampling bias, some onshore-offshore gradient, or something else?

Response: The greater asymmetry at the observation locations likely reflects a combination of factors. It may partly arise from asymmetric bathymetry and the distribution of the observation locations. In addition, spatial averaging over a broader area tends to smooth out local variability, thereby reducing the apparent asymmetry in the area-averaged results.

3. Is the spin-up period of the idealized model sufficiently long? Has this been tested?

Response: Yes. This was tested and it was confirmed that the kinetic energy reached an almost steady state.

4. Any particular reason for writing the advection terms in the momentum equation in their conservative form? Are these the ones used for the computation? Could these equations be moved to the methods?

Response: Yes, the advection terms in the ROMS momentum equations are written and computed in flux form (conservative form). Since the equations and the related description are relatively concise, we have retained them in the Momentum balance section for clarity.

5. Interesting point on the variability of the Ekman layer and its potential impact on the observed asymmetry. Do sufficient observations or realistic model runs exist to investigate whether there could be significant seasonality or, in general, how representative the observational period presented is in this regard?

Response: Although the realistic model simulation produced results for the

entire year, the observational data are available only for spring and summer. Therefore, we are unable to determine whether the observed asymmetry exhibits seasonal variability or how representative the observed period is.

6. Interesting discussion on coastal waves and their potential impact, or lack thereof. I was wondering whether the interaction between the flow around the bank and the bank itself, potentially also influenced by wind stress, could excite topographic Rossby waves in your simulations (and observations) and thus be a third feasible explanation for the asymmetry? The topographic Rossby waves could, in theory, cause an asymmetric response under either wind direction. A depth-integrated PSD or wavelet analysis could perhaps help shed light on this.

Response: We thank the reviewer for this constructive and insightful comment. In response to the reviewer's suggestion, we further analyzed the depth-averaged PSD. The results show a single dominant peak at 8 days, consistent with the surface current variability. Based on the conditions of the idealized model along the bank edge (depth of 30 m, buoyancy frequency of 0.02 s^{-1} , and bottom slope of 0.0026), the estimated periods of the topographic Rossby waves (TRWs) under stratified conditions are approximately 1 day and 0.6 days for wavelengths of 50 km and 100 km, respectively. In addition, using the bottom drag coefficient ($5 \times 10^{-4}\text{ m s}^{-1}$) applied in the idealized model, the corresponding spin-down timescale along the bank edge is approximately 0.7 days, suggesting that freely propagating TRWs would be strongly damped in this region. While TRWs may, in principle, be weakly excited and respond in a quasi-steady manner to alongshore wind forcing, their contribution is expected to be small. Therefore, TRWs are unlikely to contribute significantly to the observed asymmetry in surface currents over the bank.

The following paragraph has been added to the discussion section:

Lines 304-315: Another potential source of the asymmetry is topographic Rossby waves (TRWs), which can be generated through the interactions between the flow and bottom topography and may contribute to the asymmetric current responses. Under the conditions of the present idealized model along the bank edge (depth of 30 m, buoyancy frequency of 0.02 s^{-1} , and bottom slope of 0.0026), the estimated TRW periods under stratified conditions (e.g., Ku et al., 2020; Rhines, 1970) are approximately 1 day and 0.6 days for wavelengths of 50 km and 100 km, respectively.

However, the power spectral densities (PSDs) of surface currents (Figures 13 and 14) and depth-averaged currents (not shown) consistently exhibit a single dominant peak at approximately 8 days, with no significant energy at shorter

periods, including the intrinsic TRW timescales. In addition, given the bottom drag coefficient ($5 \times 10^{-4} \text{ m s}^{-1}$) used in the idealized model, the associated spin-down timescale along the bank edge is approximately 0.7 days, indicating that freely propagating TRWs would be strongly damped in this region.

These results suggest that, although TRWs may be weakly excited and respond in a quasi-steady manner to alongshore wind forcing, their contribution is minimal. Therefore, TRWs are unlikely to play a dominant role in the observed asymmetry.

References:

Ku, A., Seung, Y. H., Jeon, C., Choi, Y., Yoshizawa, E., Shimada, K., Cho, K.-H., and Park, J.-H.: Observation of Bottom-Trapped Topographic Rossby Waves on the Shelf Break of the Chukchi Sea, *Journal of Geophysical Research: Oceans*, 125, e2019JC015436, <https://doi.org/10.1029/2019JC015436>, 2020.

Rhines, P.: Edge-, bottom-, and Rossby waves in a rotating stratified fluid, *Geophysical Fluid Dynamics*, 1, 273–302, <https://doi.org/10.1080/03091927009365776>, 1970.

Some of the font sizes in the figure labels are a bit small.

Response: Thank you for pointing this out. We have increased the font sizes in Figures 2, 4, 6, 7, 9, 10, and 12.

Response to Reviewer #2

I have read the manuscript by Jung et al. entitled “Asymmetric response of coastal currents to oscillating wind stress over a coastal bank”. The manuscript is generally well-written and makes for an interesting read. Nevertheless, I have some issues with the interpretation of the model results, which I think could be made more insightful, as well as a question regarding the set-up of the idealized model. I also have some suggestions for further sensitivity experiments. I recommend a major revision.

Major Concerns:

1. Idealised model set-up: The way the model is currently set-up, the depth contours converge on the western side of the bank (and also diverge from the eastern side). This means the topography near the coast is very steep on either side of the bank so that the depth contours around the bank, in effect, run into a vertical wall. I am wondering how realistic this is? Looking at Figure 1, there seems to be quite a wide shelf between the coast and the 30m isobath that is missing from the idealized model set-up, and it is on this shelf region that the observations have been taken. On the other hand, on the western side of the bank, there does seem to be a convergence of the isobaths so that the topography at the coast looks to be quite steep, certainly steeper than on the eastern side of the bank. As I discuss under point 2 below, I am suggesting that the convergence of the isobaths on the western side of the bank might be of dynamical importance.

Response: We thank the reviewer for this comment. We agree that the idealized bathymetry does not reproduce all aspects of the observed topography, particularly the broader shelf region present on the eastern side of the bank. The purpose of the idealized configuration was to isolate the intrinsic variability of the currents over the bank while retaining its primary geometric characteristics, featuring a shallow bank center surrounded by deeper water.

Despite the simplification, both the realistic and idealized simulations consistently exhibit enhanced variability in the western region of the bank, suggesting that the idealized configuration captures the key processes relevant to this study. As discussed below, this geometric feature contributes to enhanced mass convergence or divergence, depending on the wind direction, and to the concentration of energy, resulting in stronger variability in the western region under both wind conditions.

2. To my mind, the most obvious explanation for the asymmetry in the current

variability between the western and eastern sides of the coastal bank is that the western side is downstream in the sense of coastal trapped wave propagation and, in particular, shelf wave propagation. The convergence of the depth contours on the western side of the bank seems likely to lead to a concentration of energy in this region, and hence larger amplitude variability. This concentrating effect on the western side of the bank can be seen in Figure 6, especially in the sea level plots and is consistent with what I suggest above. The fact the time scale of the wind stress variability is long compared to the propagation time for coastal trapped waves to pass around the bank is not important – think of the arrested topographic wave of Csanady (1978, JPO). What I am suggesting here is much simpler than is discussed on lines 264-271 and does involve any interaction between coastal trapped waves and the mean flow.

Response: We thank the reviewer for this insightful comment. We fully agree that the arrested topographic wave (ATW) framework of Csanady (1978) provides a useful perspective for interpreting the spatial asymmetry observed over the bank. In particular, our additional analyses indicate that the western region acts as a convergence zone for energy flux, which is consistent with the reviewer's suggestion that the concentration of energy leads to enhanced variability. At the same time, our results suggest that mass convergence and divergence driven by Ekman transport over the bank topography play an important role in generating the initial disturbance in the western region. We have revised the manuscript to clarify this combined interpretation and better relate our findings on Ekman-driven mass transport to the ATW framework suggested by the reviewer.

The following discussion has been added to the revised manuscript:

Lines 277-290: Although the depth-averaged wind stress is spatially symmetric across the bank, the resulting Ekman transport produces an asymmetric response because the mass transport over the shallower region becomes more aligned with the wind direction under the influence of strong bottom stress. This generates pronounced mass convergence and divergence in the western region during westward and eastward winds, respectively.

The momentum balance analysis presented above shows a geostrophic balance in the cross-shore direction, while the alongshore momentum balance is maintained among wind stress, bottom stress, PGF, and Coriolis force, which is consistent with the arrested topographic wave (ATW) framework (Csanady, 1978). Under these conditions, the disturbance generated by the mass convergence or divergence in the western region is subsequently governed by ATW dynamics, which describes the disturbance spreading out as a form of

spatial diffusion. Because the topography converges toward the west, depth-integrated energy fluxes propagating westward converge strongly in the western region under both eastward and westward wind conditions. Thus, the enhanced variability observed in the western region reflects the spatial redistribution of energy. Within the ATW framework, energy flux convergence does not imply continuous local energy accumulation. Rather, it identifies a region where the continuously supplied energy flux must be balanced by enhanced dissipation. This balance is achieved through intensified current variability and associated sea level gradients in the western region.

Reference:

Csanady, G. T. (1978). The arrested topographic wave. *Journal of Physical Oceanography*, 8(1), 47-62.

3. Lines 275-276: In keeping with what I write above, I do not think I agree with the statement that “the wind-driven response is more likely governed by locally forced time-dependent dynamics than by wave-related processes”. Surely if the dynamics was local and frictionally dominated, there would be no asymmetry in the response to wind forcing between the eastern and western sides of the bank?

Response: We agree with the reviewer that the statement may be confusing. We have revised the sentence to better clarify the point discussed in that section. Also, the revised discussion now adopts the ATW-based interpretation described in our response above.

The revised sentence is as follows:

Lines 301-303: Thus, although transient or weakly trapped wave responses cannot be ruled out, the wind-driven response over the shallow bank is more likely governed by local dynamics associated with the bank topography rather than by propagating wave processes.

4. Figure 6: I wonder why the panels (a)/(c) and (b)/(d) in Figure 6 are not more closely mirror images of each other? In particular, there is a rectified flow offshore and I wonder why that is there and how it is generated? The nonlinear terms, as shown, for example, in Figure 9, do not seem large, suggesting that the model is behaving linearly, in which case one would expect the plots in panels (b) and (d) to be simply the opposite (multiplied by minus one) of what is shown in panels (a) and (c). Is it possible that the model has not been run long

enough to be in an oscillating equilibrium? With regard to this point, are the rectified features in Figure 6 still present in the sensitivity experiment that was run using the smallest amplitude for the wind stress mentioned on line 251, or if the model is run using even smaller amplitude for the wind stress?

Response: We thank the reviewer for this comment. First, regarding model equilibrium, the simulations reach a repeatable oscillatory state after the first wind cycle, indicating that they have been run for a sufficiently long period to attain equilibrium. Second, the lack of mirror symmetry between the panels arises from the geometric constraints of the system. Specifically, the presence of the coastline and meridional variations in bathymetry generates sea-level gradients that are not mirror-symmetric under opposite wind directions. Consequently, the interaction between the spatially uniform wind stress and these geometrically controlled sea-level gradients determines the direction and magnitude of the surface currents, resulting in a rectified offshore flow. Finally, this feature is also evident in the experiment with a smaller wind-stress amplitude.

5. Suggestions for further sensitivity experiments with the idealized model: (i) run with reduced and increased bottom friction for comparison (see Specific Comment 3 below); (ii) run with uniform density to assess any role for the density stratification; (iii) since the local time dependence seems to be quite small in the momentum balance, and in view of the “saturation” comment on line 248, I suggest carrying out runs using steady wind stress in each of the eastward and westward directions. These runs may also help to answer my point 4. above.

Response: We thank the reviewer for these helpful suggestions. We conducted additional sensitivity experiments, which improved our understanding of the system’s dynamics. Here, we summarize the results of these experiments.

First, experiments with weaker and stronger bottom friction show that current variability and cross-shore sea level gradients in the western region become stronger as bottom friction decreases. Conversely, stronger bottom friction leads to a more diffused response with weaker sea level gradients. These results are consistent with the ATW framework, in which friction controls the spatial adjustment of the response.

Second, we performed an experiment with uniform density. The asymmetric response over the bank remained present, indicating that stratification is not essential for the asymmetry itself.

Finally, we conducted experiments with steady westward and eastward wind stress. In both cases, the alongshore surface currents reached nearly steady

values comparable to the peak currents in the oscillatory wind experiments with 8-day and 12-day forcing periods. However, the eastward wind case showed less stable variability in surface currents.

Specific Comments:

1. Figure 2: What are the correlations between the alongshore currents and the alongshore wind shown in the figure and how significant are these correlations?

Response: The alongshore currents and the alongshore wind show statistically significant correlations ($p\text{-value} < 0.05$) at all stations except station E. The correlation coefficients at stations A, B, C, D, and F are 0.44, 0.57, 0.59, 0.46, and 0.42, respectively.

2. When discussing equation (1), it would help to refer to Figure 1b.

Response: We thank the reviewer for this suggestion. In the revised manuscript, Figure 1b is referred to when discussing the idealized bank bathymetry.

3. Line 110: How is bottom friction parameterized? This information needs to be included.

Response: Bottom friction is parameterized using a linear bottom stress formulation, where the stress is proportional to the velocity. A related description has been added to Section 2.3 in the revised manuscript as follows:

Lines 117-119: Bottom stress was parameterized using a linear formulation, in which the stress was assumed to be linearly proportional to velocity and the bottom drag coefficient was set to $5 \times 10^{-4} \text{ m s}^{-1}$.

4. Equation (2): How is z defined here? Does z increase upwards or downwards? Where is $z = 0$? I also suggest to plot the temperature profile.

Response: In this study, the vertical coordinate z is defined as positive upward, where $z=0$ represents the undisturbed sea surface. The vertical profile of temperature has been added as Figure 3b in the revised manuscript.

5. Line 138: Why does the realistic model exhibit such large velocities in the western region, almost twice the velocities seen in the observations?

Response: The overestimation of velocity magnitudes in the realistic simulation

compared to observations likely stems from the simplified representation of complex topographic features. Specifically, factors such as the smoothing of bathymetry in the model grid, the choice of parameterizations, or unresolved small scale coastline variations could contribute to the enhanced current speeds. Additionally, tidal current may reduce wind driven subtidal flow in the observation (Kim et al., 2013).

Reference:

Kim, C.-S., Cho, Y.-K., Choi, B.-J., Jung, K. T., & You, S. H. (2013). Improving a prediction system for oil spills in the Yellow Sea: Effect of tides on subtidal flow. *Marine pollution bulletin*, 68(1-2), 85-92

6. Line 160: Are two wind cycles enough?

Response: Yes, two wind cycles are sufficient because the model reaches a repeatable oscillatory state after the first wind cycle.

7. Line 163: The sea level distributions in Figure 6 do not look that “asymmetric” to me. See Major Concern 4 above.

Response: Thank you for pointing this out. Please refer to our response to major concern 4 above.

8. Equations (3) and (4): The uv terms are missing brackets.

Response: We thank the reviewer for careful reading. The missing brackets for the uv terms have been corrected in the revised manuscript.

9. Lines 199-202: It is written that the “depth-averaged wind stress is symmetric between the two regions”. In that case, how can the resultant Ekman transport produce stronger convergence/divergence in the western region given the definition of the Ekman transport in terms of the wind stress? See also lines 299-301.

Response: This is because the direction of mass transport varies depending on the depth. Please refer to our response to major concern 2. We have revised the corresponding text in the revised manuscript.

Lines 208-210: Although the depth-averaged wind stress is symmetric between

the two regions (Figs. 9b and 10b), the resulting Ekman transport produces stronger convergence during westward winds and stronger divergence during eastward winds in the western region because the mass transport over the shallower region is more closely aligned with the wind direction.

Lines 338-340: This contrast arises because Ekman transport over the shallower region is more closely aligned with the wind direction, resulting in stronger convergence during westward winds and stronger divergence during eastward winds in the western region.

10. Line 248: The “saturation” mentioned here suggests that experiments using steady wind forcing, as suggestion in Major Concern 5 above, would be useful.

Response: Thank you for this suggestion. Please refer to our response to major concern 5.