Circulation in the Eastern Bering Sea: Inferences from a 2-kilometer-resolution model

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Abstract. A 2 kilometer-resolution model of the eastern Bering Sea is developed to capture dynamical processes on the scale of the Rossby radius of deformation on tidal to seasonal time scales. The model spans the region from 178°E to the Alaskan coast and from roughly 50° to 66°N, including the Aleutian Islands in the south and the Bering Strait in the north. The high resolution throughout ensures that the mesoscale dynamics of significant subregions of the domain, such as the Aleutian Island passes, Bering Sea slope, and the shelf canyons are captured simultaneously without the concern for loss of interconnectivity between regions. Simulations are performed for the ice-free season (June-October) of 2009 forced with tides and atmospheric forcing. The model compares favorably with observations from AVHRR and Envisat satellites, Argo drifters and Bering Sea shelf moorings. The mesoscale dynamics of the mixing and exchange flow through the eastern Aleutian Island passes, which exhibit strong diurnal and two-week variability are well represented. The two-week oscillation in volume flux through the largest of these passes (Amukta Pass) is found to be out of phase with the transport through the neighboring passes (e.g. Seguam Pass, Samalga Pass). Mesoscale structure is also found to be ubiquitous along the mixing front of the cold pool. Structures at the scale of $O(20\text{ km})$ persist and play a role in determining the pattern of erosion of the water mass as the shelf warms and mixes. On the Bering Sea shelf, tidal motions are dominant and variability on the horizontal scale of the first-mode internal tide develops ($O(30\text{ km})$) from the shelf break to the onshore edge of the Bering shelf cold pool.

1. Introduction

The continuous advancement in computational capabilities provide ocean modelers the opportunity to simulate the physics of the oceans with ever-increasing resolution and/or scale. Problematic boundary conditions can be moved farther away from the region of interest and dynamics that previously were unresolved or only coarsely resolved can now be
30 captured. This increase in computational capacity is particularly beneficial in applications where finer-scale processes determine important dynamics of a system at a larger scale and where the system exhibits interconnectivity such that modeling subregions of the domain individually with open boundary conditions is tenuous. The eastern Bering Sea is one such region (Fig.1). Large scale currents of the North Pacific and Gulf of Alaska
35 coastal currents connect with the Bering Sea basin and shelf through narrow island passes [Stabeno *et al.*, 2005; Clement-Kinney and Maslowski, 2012]. The influx of the North Pacific waters and strong tidal mixing in the vicinity of these passes set up currents that traverse the Aleutian Island Arc and then extend northwestward in an unstable and intermittent current along the length of the Bering shelf slope. Slope-shelf exchange is
40 influenced by the presence of deep canyons along the shelf break [Clement-Kinney *et al.*, 2009]. Strong tides on the southern shelf make the outer shelf islands (the Pribilof Islands) regions of rectified currents and intense mixing that influence water column structure in some cases over 100 km away. Furthermore internal tides may propagate across the Bering Sea basin from strong generation sites like the Aleutian Islands [Cherniawsky *et al.*, 2001;
45 Cummins *et al.*, 2001] and possibly the shelf break and canyons to influence the structure and patterns of variability across the Bering Sea shelf. The model effort discussed here

focuses on resolving these processes over the entire eastern Bering Sea so that a more accurate description of the dynamics of the system over the ice-free season can be obtained.

A general understanding of the mean circulation in the eastern Bering Sea has developed
50 through observations and modeling [e.g., *Stabeno et al.*, 1999; *Reed and Stabeno*, 1999; *Ladd and Stabeno*, 2009; *Clement-Kinney et al.*, 2009; *Zhang et al.*, 2010; *Danielson et al.*, 2011; *Panteleev et al.*, 2012]. The basin circulation is generally a cyclonic gyre. In the south, along the north slope of the Aleutian Island ridge, is the eastward flowing Aleutian North Slope Current (ANSC, Figure 2). This flow turns sharply northwestward
55 becoming the Bering Slope Current (BSC) upon reaching the Bering Sea shelf in the southeast corner of the basin. The area along the slope is noted for enhanced eddy variability on the scale of 20-100 km, detected in altimetry, satellite radiometer imagery, and drifter motions [*Sinclair and Stabeno*, 2002]. Exchange with the North Pacific occurs through numerous Aleutian Island passes with source waters from the North Pacific gyral
60 circulation (the Alaskan Stream), and the fresher Gulf of Alaska shelf current (the Alaska Coastal Current).

Mean flows on the Bering Sea shelf are northward and generally strongest near the Bering Strait. Inflow onto the shelf occurs through Unimak Pass west of Unimak Island and the tip of the Aleutian Peninsula, in the south, and by exchange with basin waters
65 along the 1200 km shelf-slope boundary. Each winter a seasonal ice sheet forms extending southward over a large portion of the Bering Sea shelf. During years in which spring winds from the north predominate, the ice cover can reach south of the Pribilof Islands and persist there into May [*Stabeno et al.*, 2012a]. A bottom cold pool is formed when the ice retreats and stratification is established primarily through surface heat fluxes on

70 the southern shelf. Both salinity and temperature maintain strong stratification on the northern shelf [*Stabeno et al.*, 2012b]. Particularly on the southern Bering Sea shelf, tides are energetic leading to formation of a mixing front in the summer at approximately the 50 m isobath [*Kachel et al.*, 2002].

Dynamics in some parts of the Bering Sea are significantly influenced by processes
75 occurring on tidal time scales and on spatial scales on the order of a few kilometers. For example, the eastern passes that connect the North Pacific ocean with the Bering Sea basin are typically only tens of kilometers wide but experience very strong tidal forcing. The energetic mixing and exchange flows they introduce into the system determine the characteristics of the ANSC [*Kowalik*, 1999; *Reed and Stabeno*, 1999; *Cummins et al.*,
80 2001; *Ladd et al.*, 2005; *Foreman et al.*, 2006; *Nakamura et al.*, 2010]. Mixing can be so vigorous that it may potentially mix growing phytoplankton out of the euphotic zone, thereby reducing production, which can explain low chlorophyll areas around the islands seen in satellite color imagery [*Ladd et al.*, 2005].

The scale of dominant baroclinic eddies in the Bering Sea, the Rossby radius of deformation,
85 tion, is estimated to be as small as 20 km [*Chelton et al.*, 1998; *Ladd et al.*, 2005]. However modeling studies of the Bering Sea circulation published to date have generally lacked the resolution to represent oceanic phenomena at this scale. Recent studies have nonetheless provided new and important information on mean transports, and seasonal and interannual variability in the ocean circulation and ice extent and concentration. Among recent
90 contributions, *Danielson et al.* [2011] provided model-data comparisons in the Bering Sea using a 35-year simulation obtained with an 10-km resolution ROMS-based coupled ice-circulation model of the North-East Pacific, and focused on monthly to decadal vari-

ability in the area. *Danielson et al.* [2012] used the same model along with an idealized barotropic representation of the Bering Sea shelf to study the differences in onshelf transport produced by northwesterly versus southeasterly winds. *Zhang et al.* [2010] utilized a coupled ice-circulation model with spatially varying resolution covering the entire Arctic and parts of Pacific and Atlantic Oceans north of 39°N. They focused on the response of the ice extent and concentration to atmospheric forcing. The model had 2-km resolution along the Alaskan coast, but only 12-km along the Aleutian Islands chain. *Panteleev et al.* [2006, 2012] assimilated in-situ and satellite observations in their approximately 20-km resolution semi-implicit model to constrain mean transports and seasonal variability in the entire Bering Sea. *Hu and Wang* [2010] developed a 9-km resolution model of the Bering Sea, based on the Coupled Ice-Ocean Model (CIOM) and studied effects of tidal and wave-induced mixing on stratification in the area of the cold pool on the Bering Sea shelf. In a series of works involving multi-year simulations with a 9-km resolution model including the Arctic and parts of the Pacific and Atlantic Oceans, *Clement et al.* [2005]; *Clement-Kinney et al.* [2009], and *Clement-Kinney and Maslowski* [2012] studied circulation in the northern Bering Sea, inter-annual variability of Aleutian throughflows, and integrated volume, heat, and freshwater transports over the Bering Sea basin and shelf. *Ezer and Oey* [2010] studied the effect of the Alaskan Stream on the Bering Sea variability using a 5- to 8- km resolution model, which however did not include the atmospheric, ice or tidal forcing. *Ezer and Oey* [2013] characterized the flow through the various Aleutian Island passes using the same model. An earlier study by *Hermann et al.* [2002] involved development of a model focusing on eddy variability in the southeastern Bering Sea using a model with maximum resolution of 4 km. *Mizobata et al.* [2008] also explored eddy

variability at the shelf break (using a model with 5 km horizontal resolution) to try to determine the relationship between eddy activity and on-shelf fluxes.

Internal tides in the Bering Sea have yet to be thoroughly described. Perhaps in part this is because modeling their generation and propagation requires high resolution over a large domain. *Cummins et al.* [2001] studied the generation of the M_2 internal tide over the Aleutian ridge using seven years of Topex/Poseidon altimetry and a barotropic tidal model. They found intensive generation over Amukta Pass from where the internal tide propagates both into the Pacific Ocean and Bering Sea. *Cummins et al.* [2001] additionally studied propagation of the internal tide in the Pacific using a two-dimensional (latitude vs. depth) baroclinic tidal model. Based on the satellite altimetry analysis [*Cherniawsky et al.*, 2001], the internal tide amplitude and phase structures in the Bering Sea were more complicated than in the Pacific, possibly affected by the internal tide generation over the Bering Sea slope.

The goal of this study is to explore aspects of the dynamics of the eastern Bering Sea that a 2-km horizontal resolution model affords. Simulations are performed for the ice-free season from June through October of 2009. The overall performance of the model is evaluated by comparison with observations from thermal imaging and altimeter satellites, shelf moorings and Argo drifters. Particular attention is focused on 1) the dynamics of the exchange flow between the complex of passes in the region of Amukta Island, 2) the mesoscale structures associated with the erosion of the cold pool, and 3) the signature of internal tides on the middle to outer shelf.

2. Model Setup

Simulations are performed using a hydrostatic primitive equation model with a terrain following vertical coordinate, namely, the Regional Ocean Modeling System (ROMS rev.585 <http://www.myroms.org>). In this model setup the advection of momentum and tracers are handled with a 3rd-order upwind scheme and 4th-order centered vertical scheme [Shchepetkin and McWilliams, 2005]. Vertical mixing is parameterized with the Mellor-Yamada level 2.5 closure [Mellor and Yamada, 1982] with modifications due to [Kantha and Clayson, 1994]. Mixing of momentum along s-coordinate surfaces is treated as a harmonic viscosity with a coefficient of $5 \text{ m}^2\text{s}^{-1}$. There is no explicit horizontal diffusivity for temperature or salinity. Surface fluxes are parameterized using the COARE algorithm of Fairall *et al.* [2003] as implemented in the ROMS. Bottom stress is parameterized as quadratic with a roughness length of 0.02 m.

The model domain spans the region from 178°E to 157°W and from roughly 50°N to 66.4°N (Figure 1). The bathymetry is interpolated to the model grid from the Alaska Region Digital Elevation Model (ARDEM - <http://mather.sfos.uaf.edu/~seth/bathy>) with some smoothing applied where necessary to reduce terrain-following-coordinate pressure gradient errors around the Aleutian Islands and along the Bering Sea slope. The bathymetry is also made to smoothly match that of the global model that supplies the boundary conditions along each model edge. Model grid spacing is approximately 2 km in the horizontal with forty-five vertical levels stretched such that resolution is higher near the surface and bottom.

Initial fields are produced by melding fields obtained from the $1/12^\circ$ resolution Navy HYCOM global model (HYCOM GLBa0.08 Chassignet *et al.* [2007], <http://www.hycom.org>) and BESTMAS regional simulations [Zhang *et al.*, 2010] for June

160 1st, 2009. The BESTMAS solution is used over the Bering Sea shelf and smoothly matched
with the HYCOM initial condition at the shelf break. Early experiments showed that while
HYCOM produced a decent initialization for the North Pacific and Bering Sea basin, it
failed to represent accurately the vertical temperature structure on the shelf at the start
of June 2009. It was found that by using initial fields from BESTMAS on the shelf, the
165 seasonal evolution of temperature in this region could be more accurately modeled than
using HYCOM fields because BESTMAS incorporates a more sophisticated representa-
tion for sea ice than the global HYCOM model. It is possible that BESTMAS represents
more accurately the spring melting processes on the shelf and better captures the cold
pool formation in the spring of 2009 [*Zhang et al.*, 2012]. The model simulation discussed
170 here is for the period from June 1st through October 31st 2009.

Open boundary conditions for horizontal velocity, potential temperature, and salinity
are specified as a combination of Orlanski radiation and nudging (on a 3 day time scale for
inflow) to the HYCOM global model solution which is provided as a series of snapshots
once a day. Inertial oscillations in such a time series are aliased and appear as oscillations
175 with a 2.5 day period. The four-day low-pass filter is applied to the HYCOM fields to
reduce this effect. The boundary condition for turbulent kinetic energy is an Orlanski
radiation condition without nudging. In addition to these boundary conditions a band of
increased horizontal viscosity and diffusivity (a 'sponge') is applied within 50 km of the
western boundary of the model domain to damp erroneous boundary effects that would
180 otherwise develop in the model. A gravity-wave radiation condition is used for sea surface
height [*Chapman*, 1985] in conjunction with a Flather condition for the barotropic velocity
components [*Flather*, 1976]. Additionally, tidal forcing is applied at the model boundaries

using four tidal constituents (K_1 , O_1 , M_2 , S_2). Tidal amplitudes and phases are obtained from the OSU tidal inversion global model solution (TPXO) [Egbert and Erofeeva, 2002].

185 The atmospheric forcing for the model is provided by the North American Regional Reanalysis (grid 221) [Mesinger et al., 2006]. However it is found that with these fluxes the Bering Sea shelf tends to 'overheat' in the model. To ameliorate this problem, incoming surface solar radiation is reduced by 25% for the duration of the simulation. This can be justified considering the documented over-insolation attributed to the NARR at high
190 latitudes during summer months [Walsh et al., 2009].

3. Model Verification

3.1. Large-scale Circulation Patterns

The model captures the mean structure of currents in the eastern Bering Sea region (Figure 2). This includes the Alaskan Stream (AS), the ANSC, the BSC, the Anadyr Current and the Bering Strait outflow. South of the Aleutian Arc, the AS and the Alaska Coastal Current (ACC) merge, flowing westward. This current interacts with
195 the various island passes leading to reduced surface current magnitude west of Amchitka (179.9 °W), Amukta (171.9 °W) and Unimak (161.2 °W) passes. The diminished surface current west of Amukta pass is consistent with drifter and altimeter observations from 2001-2004, noted by Stabenog and Hristova [2014]. To the north of the island chain, the eastward flowing ANSC exhibits increased intensity to the east of Amukta and Amchitka
200 passes associated with the net northward transport through the passes from the Pacific. The ANSC between 167°W and 170 °W is narrow, about 30 km wide. It turns sharply northwestward at Bering Canyon to form the broader and weaker BSC. This current flows northward generally following the contours of the shelf break but also exhibits eddy

formation and weak westward recirculation. The strongest shelf current, the Anadyr
Current, flows northeastward along the Northern Siberian coast and is most intense in
the seasonal average between the coast and St. Lawrence Island.

Several weaker shelf flows also appear in the seasonal average. The approximately 5
cm s⁻¹ northward flow along the 50 m isobath coincides with the average position of the
inner shelf tidal mixing front. The recirculating currents around the Pribilof Islands may
be tidally rectified flows [Kowalik, 1999] or associated with mixing fronts that develop
in the shallow waters surrounding the islands. A weak easterly flow along the Aleutian
Peninsula is a result of inflow of fresher Alaska Coastal Current water through Unimak
Pass.

On shorter time scales, the current structure on the shelf is in part determined by the
passage of weather systems over the summer season. A comparison of low-pass filtered
meridional currents between model and an upward pointing ADCP (RDI Workhorse) at
the C55 mooring location (see Figure 1) offers further corroboration of the quality of the
model solution (Figure 3). Data was collected at this mooring and at the S55 mooring
as part of the Bering shelf portion of the Bering Ecosystem Study (BEST -data courtesy
of K. Aagaard, NSF Grant ARC-0732428) from 2008 through 2010. The data when low-
pass filtered using a 3.25 day Hanning window, reveals current direction shifting mostly
in response to wind events. Currents tend to be intermittent and weak with frequent
reversals. The currents most often vary in response to the local wind forcing (Fig.3c)
but not always. A strong northward flow event on August 8th 2009 develops during a
relatively calm period. In this situation, the passage of a weather system to the south

of the C55 mooring location causes a large scale setup of sea surface height that drives a geostrophic current.

3.2. Surface temperature and stratification

The progression of ocean warming and cooling from June to November can be observed in monthly averages of SST obtained from a synthesized satellite product [OSTIA *Stark*
 230 *et al.*, 2007] (Figure 4, top). The OSTIA product maps daily SST at approximately a 5 km resolution based on an optimal interpolation of infrared and microwave sensors. As summer progresses surface temperatures increase, reaching a peak in August before increased winds and surface cooling lead to decreasing temperatures in the fall. The satellite data shows that SST in the immediate vicinity of the Aleutian Islands is colder
 235 than the surrounding waters, which must be due to strong tidal mixing. The water along the northern Siberian coast becomes colder than the surrounding shelf waters due to late-summer upwelling.

The model SST matches the satellite observations in the monthly averages qualitatively well (Figure 4, 2nd row), including the seasonal warming and cooling over the shelf,
 240 formation of the warm inner shelf front, and a tongue of relatively colder SST over the midshelf, over the location of the cold pool. On the shelf, fronts associated with mixing in the vicinity of the Pribilof Islands (on the southern Bering Sea shelf at approximately 170°W 56.5°N) persist throughout the summer despite the overall heating on the shelf.

Figure 5 shows monthly averaged temperature in a vertical section over the middle-
 245 and outer- shelf (see Fig.1 for section location). Whereas the inner shelf becomes largely well mixed and heats or cools uniformly with depth over the season, stratification on the middle- and outer- shelf intensifies through July and August. In September and October

increased winds and reduced insolation cause the surface boundary layer to entrain deeper colder water resulting in the signature of the underlying cold pool becoming more visible in the SST. Simultaneously bottom temperatures rise over the southern half of the Bering Sea shelf, with regions in the vicinity of the shelf islands (Pribilof, St. Matthew) warming more relative to the surrounding waters (i.e. Fig.4, bottom panel).

Low-pass filtered temperature time-series at moorings C55 and S55 emphasize the seasonal warming and cooling on the Bering Sea shelf (Figure 6). At each location, situated along the 55m isobath, temperature recordings are made at 10m, 22m and 51 m depth, providing information about stratification. At S55, observed surface layer (10m) and mid-depth (22 m) temperatures diverge over the month of June until the passage of a strong storm at the beginning of July causes the mixed layer to deepen below 22m. The upper water column restratifies through the end of August when surface cooling combined with wind-mixing events again cause temperatures at the two mooring depths to merge. At both the C55 and S55 moorings the water column becomes well mixed only in October.

The pointwise comparison between model temperature and S55 shows encouraging agreement (Figure 6, top). Near-surface, mid-depth and near-bottom temperatures all track the observed temperatures and the mixing events. The location of the inner-shelf tidal mixing front in the model is, for a significant portion of the simulation, coincident with the C55 mooring location. Model fields are more weakly stratified at this location than the observations indicate. However, if the model is sampled at a location 20 km to the west, the model comparison at C55 is much better (see Fig.6, bottom).

4. Advantages of high-resolution modeling in the eastern Bering Sea

4.1. Mixing fronts along the Aleutian Islands

One of the challenges with modeling the eastern Bering Sea is that the southern bound-
 270 ary is defined by an oceanic ridge of narrowly spaced island passes that range in depth
 from tens to hundreds of meters (Figure 7). To the south of the islands, the Alaskan
 Stream, a western boundary current, flows westward along the ridge. Driven by large
 scale winds in the subarctic gyre, the Alaskan Stream plays an important role in de-
 termining the low frequency transport through the passes. Higher frequency transport
 275 through the passes is driven by intense tidal flows that generate localized vertical mixing
 that helps perpetuate the density fronts both to the north and the south of the island
 chain, e.g., seen in the satellite and model SST on September 8th (Figure 7). The roughly
 10-km scale of many numerical models of the Bering Sea published to date (see Section
 1) preclude an accurate representation of the circulation through and in the vicinity of
 280 these passes. With the 2-km resolution in this model the main topographic features and
 three-dimensional structure of the flow in these regions can be captured.

Low-pass filtered (3.25 day) velocity (u , v), temperature (T), salinity (S) and eddy
 diffusivity (K_T) fields are shown along a North-South section through the center of Amukta
 Pass (at 171.8°W, Figure 8) on September 8th. These illustrate the complex structure of
 285 circulation in the vicinity of these passes. The strong tidal flow over the ridge leads to
 enhanced vertical mixing in different parts of the pass during different parts of the tidal
 cycle resulting in high time-averaged vertical eddy diffusivity K_T near the bottom, and
 higher than background levels at intermediate depths (Figure 8e). The mixing reduces
 stratification in the pass, leading to the formation of surface fronts of temperature and

290 salinity both to the north and south of the more well-mixed region. The along-island arc
flow both south and north of the pass is dynamically consistent with the density structure
this mixing establishes, southwestward on the Pacific side of the pass and northeastward
on the Bering Sea side. The strong northward surface flow within the pass (Figure 8b) is
associated with the front of warm Pacific water that is being drawn into the pass at this
295 time (as is apparent in the model results and satellite SST image on the same day, see
Figure 7). An intense eastward bottom flow is also present at this time in the low-pass
filtered fields along the northern side of the pass at 400 m depth. The north-south tidal
flow over the ridge results in steep isotherm and isohaline displacements particularly on
the northern flank, leading to localized mixing that sets up this bottom flow.

300 Observational evidence of the changes in stratification in the Amukta Pass frontal region
is found in Argo drifter data [*ARGO*, 2000-09-12]. Argo drifters that have been deployed
throughout the world generally sample ocean basin waters between 2000 m and the surface
by following park and profile missions. They are setup with a buoyancy designed to allow
them to drift at approximately 1000 m depth for roughly ten days, then descend to 2000 m
305 and rise to the surface within a single day to transmit profile data. Although this generally
precludes using them for obtaining profiles of temperature and salinity in coastal regions,
several Argo drifters were drawn within proximity of Amukta Pass during the summer
of 2009 (Figure 9). Figure 9a and b show the paths of the two drifters, one approaching
the pass from the north and the other from the south; circles indicate sampling locations.
310 Each temperature and salinity profile obtained by the drifters over the season is shown for
each set in Fig. 9 (c through f). The drifter profiles clearly indicate when the devices cross
strong temperature and/or salinity fronts as they approach the pass. Two profiles, shown

as thick lines, are selected as representative of conditions before and after each drifter moves from basin waters across the respective fronts into the strongly mixed region near the pass. The corresponding model profiles, displayed as thick dashed lines, are found to be largely in agreement with the observations. The front to the north of Amukta Pass, associated with the ANSC (Figure 9c and e), is characterized by a prominent horizontal temperature gradient at depths between 50 and 250 m below the surface. The water in the basin at depths greater than 40 m is colder and moderately fresher than the water in the pass region. The characteristics of the front to the south of the pass can again be inferred by comparing profiles from the Argo drifter that approaches the pass from the south. Figure 9d and f depict a front that is shallower, surface intensified, and associated with a stronger salinity gradient than the front to the north of the pass. The fresher surface waters to the south of the Aleutian Islands (also depicted in Figure 8) are likely associated with freshwater runoff which is largest in the early fall.

4.2. Aleutian Island Throughflows

The circulation through the passes is a complex sum of effects from direct forcing of several strong tidal constituents, rectified tidal flow effects, local and large scale weather patterns, and the influence of oceanic processes to both the north and the south (such as eddy variability in the Alaskan Stream in the North Pacific).

Variability in the SSH and transports around the eastern central portion of the Aleutian Islands (including the Amukta Pass region) is dominated by strong diurnal tides. The modeled SSH time series at the center of Amukta Pass is shown in Figure 10 (gray line). Periods of stronger and weaker diurnal tide are associated with the relative phases of the K_1 and O_1 constituents. The resulting spring-neap tidal cycle has a period of 13.7

335 days (compared to the M_2/S_2 spring-neap cycle with a 14.8 day period, that is predom-
 inant in many other parts of the world ocean). Although the M_2 is the third largest
 tidal constituent, it still contributes to the circulation by becoming the largest amplitude
 component of motion during neap periods where K_1 and O_1 constituents largely cancel.
 Tidal velocities can be over 2 m/s in the passes during spring tides but are weaker during
 340 neap periods. The transition from K_1 dominant to M_2 dominant frequency of oscillation
 leads to significant differences in the tidal excursions during times of peak (diurnal) spring
 compared to lowest (diurnal) neap resulting in complex variations in circulation through
 the passes.

Time series of area-integrated transports are computed for a number of the larger passes
 345 and low-pass filtered using a 3.25 day filter (Figure 10). The integrated subtidal transport
 through Amukta Pass (dark blue line) tends to be largest during periods of the spring
 diurnal tide, directed northward. Simultaneously it is largest and directed southward
 through the passes to the east of it, including Herbert and Samalga (red and green lines).
 Thus it is likely that some of the water fluxed into the Bering Sea through Amukta Pass
 350 circulates back out through one of the smaller passes to the east. Transport through
 Segum Pass (west of Amukta) is mostly northward and largest during (or closely fol-
 lowing) periods of smallest northward transport through Amukta Pass. Examination of
 SSH and velocity fields in this vicinity suggests that this is consistent with an anticyclonic
 flow that persists around Segum Island (located between Segum and Amukta passes)
 355 when diurnal tidal motions dominate but is disrupted when semi-diurnal (M_2) forcing is
 strongest.

A series of snapshots of sea surface salinity and surface velocities in the vicinity of the islands is shown in Figure 11(left) over a diurnal tidal cycle during a period of spring tides (July 31st - August 1st 2009). Fresher water to the south of the Aleutian Islands penetrates into the Bering Sea primarily through Amukta, Herbert and Samalga passes. This water is advected far enough during the flood phase of the tide such that in the case of water coming in through Herbert Pass it tends to recirculate on ebb through the next pass over (Samalga). Similar patterns of recirculation exist for each of these passes with the exception of Samalga which has no significant pass to the east. Tidal circulation during neap tides (Figure 11 right) on the other hand exhibit penetration of salty Bering Sea surface waters into the North Pacific at times. During this portion of the diurnal spring-neap cycle tidal excursions are reduced and rectified anticyclonic flow around most of the islands in this region diminished.

A complex interplay develops between the effects of vertical and lateral mixing associated with the tides and their spring neap variations. Periods of stronger flow through the passes can lead to more intense vertical mixing that reduces stability. At the same time intrusion of shallow fronts of Pacific or Bering Sea water into the passes may enhance vertical stratification. These processes determine the average hydrographic structure in the passes. To illustrate, meridional velocity and salinity are averaged separately for a number of intervals of spring and neap tides and shown in along pass sections (Figure 12).

To the south of the island chain, fresher water forms a shallow stratified westward flow. The strong northward (flood) tides during the spring portion of the two-week cycle advect this stratified water into Amukta Pass resulting in higher stratification and lower surface salinity on average during spring tides (Figure 13a) versus neap (Figure 13b). In

380 Yunaska, Herbert and Samalga passes, east of Amukta, the returning north-to-south flow is intensified during periods of spring tides resulting in relatively weaker stratification compared to periods of diurnal neap tides (see Figure 12 c,d,e and h,i,j). Surface salinity, particularly south of Herbert Pass, where southward flow during spring tide is strongest, is on average higher during these times compared to neap (Figure 13c).

385 Atmospheric effects can occasionally dominate over tidal forcing in the passes. In the model simulation, a period of peak northward transport through Amukta Pass during the first week of September 2009 does not match the pattern in the spring-neap cycle observed at other times. This is a neap tide period where the transport is most strongly northward through Amukta, Herbert and Samalga passes simultaneously unlike in the rest of the
390 record (where Amukta would be out of phase). This event coincides with the atypical occurrence of a cyclonic weather system passing to the south of the Aleutian Islands. It leads to several days of strong easterly winds along the Aleutians producing a downwelling circulation along the south side of the island arc.

The strong spring-neap modulation in the subtidal transport through Amukta Pass
395 is consistent with the conclusions drawn by *Stabeno et al.* [2005] from the analysis of multiyear records from four moorings located across Amukta Pass. The season-averaged transport estimated from our model is lower than the average or even the minimum monthly transports reported by *Stabeno et al.* [2005] and later *Ladd and Stabeno* [2009]. They estimate an average of over 4 Sv transport through Amukta Pass based on data from
400 May 2001 through September 2003. *Ladd and Stabeno* [2009] estimated 4.7 Sv extending that data set with intermittent data through September 2008. The seasonal (summer/fall 2009) estimate from the model calculation is approximately 1.6 Sv of northward transport

through Amukta Pass. Part of the explanation for the discrepancy may lie in the fact that the simulation period does not coincide with the periods of observation reported in the literature, and summer 2009 may have been a season of particularly low northward transport. However, the model is consistent with the climatological model average of *Clement-Kinney and Maslowski* [2012]. It is possible a portion of the discrepancy between the model and observations is due to the difference in spatial resolution of the 2 km model compared with the mooring data which was obtained from 4 upward looking ADCPs distributed across the roughly 70 km wide Amukta Pass. Model results show strong southward circulation very close to Segum Island on the western side of Amukta Pass where mooring data had to be extrapolated (see Figure 12 b). *Stabeno et al.* [2005] also note trouble collecting data consistently in the upper 60-90 m of the water column on the eastern side of Amukta Pass. The mean northward velocity through the pass that they estimated (Figure 11 in *Stabeno et al.* [2005]) shows values near the surface that are larger than the model velocities displayed in Figure 12. Additional observations resolving the near-surface layer are needed to verify accuracy of these estimates. Interestingly, except for in these two areas (near surface and near the western boundary of the pass), the average northward velocity field in our model matches quite well with the average northward velocity they obtained from observations.

Model estimates of transport fall below measured transports for the easternmost Bering Sea pass, Unimak Pass. *Stabeno et al.* [2002] estimate approximately 0.4 Sv transport through Unimak pass whereas the seasonally averaged model transport is 0.19 Sv. If the model is underestimating northward transport through the eastern Bering Sea passes, a

425 potential source is inaccuracy in the representation of the Alaskan Stream which intersects
the model southern and eastern domain boundaries in proximity to the area of interest.

4.3. Slope Currents over Bering Canyon

The Bering Slope Current develops as the ANSC is diverted northwestward where the Aleutian Ridge meets the Bering shelf slope in the vicinity of Bering Canyon. As a result of the combined influences of the ANSC, tides, canyon dynamics and proximity to Unimak
430 pass, the modeled circulation in this elbow exhibits the regular formation of Rossby-radius scale (30 km) eddies. Figure 14 illustrates the evolution of the low-pass filtered SSH in this region over a two week period. At some times the ANSC extends eastward of 166° W. But subsequently northward-extending meanders or 'bulges' in the eastward flowing current develop (close to Unalaska and Akutan Islands) that cause the eastward extension
435 of this current to pinch off into cyclonic eddies.

The pattern that is exhibited here occurs repeatedly in the model at approximately a two week interval. Figure 15 shows a time series of low-pass filtered SSH on a meridional transect extending to the north from Unalaska Island at 167°W. Dashed lines indicate the times of peak (diurnal) spring high tide locally. High values of SSH extend northward
440 from the coast into the basin with roughly a two week period, suggestive that spring-neap tidal variability may be driving this process. These eddies presumably capture, transport, and mix basin waters with the waters of the upper Bering Canyon and shelf and could potentially play a role in determining the productivity in this ecologically significant region.

4.4. Finescale variability in the Bering Sea shelf cold pool

The surface heating, tidal mixing, and intermittent currents on the Bering Sea shelf combine to determine the evolution of the layer of cold bottom water referred to as the 'cold pool'. The pool forms as a result of winter conditions on the Bering Sea shelf, tending to be larger in extent following cold winters and smaller in extent following warm ones. The development and evolution has been modeled successfully in several recent studies [Hu and Wang, 2010; Zhang et al., 2012], but the detailed structure of the pool as it erodes over the summer months has not been presented. In the model the edge of the cold pool develops complex spatial and temporal structure (Figure 16). For purposes here the cold pool is defined by the 3.5°C isotherm and its edge by where this isotherm intersects the shelf floor. In Figure 16 contours of different colors show the edge of the cold pool at different times between June through October. In general the rate of erosion of the cold pool varies over the season, showing a rapid retreat from the coast in response to storm events and a more gradual erosion under more calm conditions. Spatially, the front shows variability over a range of scales with sharp changes in direction and no clearly dominant wavelength. Whereas along some portions of the front displacements propagate persistently in an alongfront direction, along much of the front features tend to either decay with time or become fixed regions of enhanced erosion into the cold pool. In some places these patterns appear to be correlated with mild variations in the shelf bathymetry.

The hole in the cold pool formed around the Pribilof Islands is a result of the intense mixing that occurs around the edges of these islands consistent with observations [Staben et al., 2008]. As the season progresses the boundary of the cold pool is increasingly distant from the islands. Southeast of the Pribilof Islands the offshore edge of the cold pool is not

well delineated by the criteria specified above. This may indicate a region of enhanced exchange between the slope and shelf cold pool waters.

The fine scale structure that is visible in the evolution of the cold pool is a ubiquitous
 470 feature on the Bering Sea shelf throughout the summer season not only along the pool
 boundary but in some regions in surface fields as well. The two kilometer scale model
 resolves these structures down to approximately a 10km scale. However, it is expected that
 the actual spectrum of scales that constitutes the dynamically and biologically important
 variability along the mixing fronts extends to even lower scales. In particular, this can be
 475 found in high-resolution satellite imagery. Fig. 17a shows the calcite signature associated
 with an episodic bloom of coccolithophorids obtained by the SeaWiFS on October 8th,
 2009 (<http://oceancolor.gsfc.nasa.gov>) along with the corresponding SeaWiFS SST (Fig.
 17b). The bloom appears to fall along a strong gradient in SST. While variability of
 biological constituents along the bloom edge is expected to be associated with non-physical
 480 factors such as growth, predation and nutrient concentrations, the scale and positions of
 short wavelength ($O(1-10\text{km})$) structures in the the bloom tend to resemble those in the
 temperature field in these images. Although our model resolution is still too coarse to
 capture the dynamics and structure of these features, it appears to be capturing the
 location and the larger-scale variability in the temperature field well (Fig. 17c).

4.5. High-frequency current variability

Model surface velocities are filtered with a 3.25 day Hanning window to distinguish currents associated with the tides and high frequency weather variability from the more gradual variations in the system:

$$u = u_{lp} + u_{hp}, v = v_{lp} + v_{hp}.$$

The root mean square (RMS) speed of the high frequency velocity component averaged over the 5-month period (T) is calculated as

$$u_{hp}^{RMS} = \left[\frac{1}{T} \int_0^T (u_{hp}^2 + v_{hp}^2) dt \right]^{\frac{1}{2}}$$

and is plotted in Figure 18. Areas of intensified u_{hp}^{RMS} on the shallow inner shelf and at the eastern Aleutian Island throughflows are associated with barotropic tidal flows. In the basins, north and south of the Amukta Pass region of the Aleutian Islands, patterns (stripes) of intense high frequency variability are also found. These are likely associated with internal tides emanating from the island ridge [Cummins *et al.*, 2001]. Interestingly u_{hp}^{RMS} is also large on the stratified outer shelf (see zoom in Figure 18b). Bands of high-pass variability parallel to the shelf break contours are consistent with the internal tide pattern [Kurapov *et al.*, 2010, 2003]. The scale of the pattern matches reasonably with what would be expected for a first-mode M_2 -internal tide in this region. The dispersion relationship for internal waves can be rearranged to give an estimate of the horizontal scale of an internal tide as

$$L \approx 2H \left[\frac{N^2 - \omega^2}{\omega^2 - f^2} \right]^{\frac{1}{2}}$$

485 . Substituting in $N = 0.01 \text{ s}^{-1}$, $H = 100 \text{ m}$, $\omega = 1.46 \times 10^{-4} \text{ s}^{-1}$, $f = 1.2 \times 10^{-4} \text{ s}^{-1}$, gives $L \approx 24 \text{ km}$, which this 2-km resolution model resolves well. Additional studies are needed to determine whether the internal tidal motions are generated at the Bering shelf slope or propagate accross the basin from other regions and where the internal wave energy is dissipated.

5. Summary

490 A high resolution circulation model has been developed to provide a framework for investigating a variety of tidal to seasonal scale physical processes in the eastern Bering Sea in greater detail than has been previously possible. The model has been demonstrated to show good agreement with observations from multiple sources including moorings, satellite sea surface temperature and Argo drifters.

495 The cold pool and the shelf tidal fronts in general exhibit a complex evolving submesoscale frontal structure over the course of the summer and early fall. It is likely that while the 2 km scale model begins to resolve these dynamics the preferred scales of these processes are not well resolved. More focused exploration with higher resolution models or nested model domains will aid in determining the impact of these small scale mixing
500 processes on cross shelf and vertical fluxes.

The complex of eastern Aleutian Island passes constitute an important exchange between the Bering Sea and the North Pacific basins. They are closely spaced and bordered by steep bathymetry both to the north and south, which makes them difficult to model accurately with moderate resolution. Here the circulation and transport through the passes
505 is well resolved. Strong fronts are found both to the north and south of the island arc as a result of mixing in the passes and over the ridge. These mixing fronts likely enhance the eastward transport of the Aleutian North Slope Current and the westward transport of the Alaskan stream. Transport through the passes is found to exhibit a strong two-week variability with peak northward transport through Amukta Pass during the spring tide
510 for the diurnal components (when the diurnal K_1 and O_1 amplitudes are in phase). At the same time transport through the smaller passes to the east of Amukta Pass is most

strongly southward, suggesting a recirculation pattern. Variability in transports through the passes is modulated by the predominance of a diurnal tidal component during spring tide (K_1 - O_1) and a semidiurnal oscillation at neap (M_2).

515 Two-week variability is also exhibited to the northeast of these passes in the Bering Sea where the ANSC turns northward to become the BSC. Here the modeled current tends to oscillate between following the contours of the canyon bathymetry and pinching off the canyon forming 30 km-scale cyclonic eddies that impinge upon the Bering Sea shelf near Unimak Pass. If observational confirmation of this pattern is forthcoming it may
520 present an ecologically important mechanism for transporting pelagic species into this highly productive region.

Analysis of the RMS speed of the high-frequency currents suggests that internal tides over the shelf and slope may be yet another interesting avenue for future research using high-resolution modeling. In particular, it would be interesting to learn whether the
525 internal tides propagate over the cold pool and play a role in its breakdown.

The notable characteristic of the model developed in this study is that it allows one to explore the impact of high spatial and temporal resolution over an expansive and complex domain. The striking result is the ubiquitous interplay between scales. The mean currents north and south of the Aleutians are in part dictated by the tidal frequency mixing within
530 the narrow passes. The expansive Bering shelf cold pool erodes with a very complex meso- to sub-meso scale structure and potentially vertically entrains aided by locally and remotely generated internal tides. And the Aleutian Island circulations connect with the dynamics at the shelf edge hundreds of kilometers away through narrow currents. A number of the topics introduced here will be the focus of future studies. In addition,

the model developed here must be augmented with an ice model as undoubtedly the
winter-spring seasons exhibit comparably intriguing phenomena.

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Figure 1. A map of the eastern Bering Sea model domain and bathymetry. Also marked are two BEST-BSIERP mooring sites, an offset mooring site (for model data comparison) and a model transect used in the analysis.

Figure 2. Seasonal average surface velocity magnitude and vectors from June through October 2009. Velocities less than 0.05 m s^{-1} are de-emphasized using gray-scale. Black contour lines indicate bathymetry at -50, -100, -200, -500 and -1000 m. The major currents are displayed schematically with colored arrows, ANSC -Aleutian North Slope Current, BSC - Bering Slope Current, AS - Alaskan Stream, ACC - Alaska Coastal Current.

Figure 3. Comparison of (a) low-pass filtered northward velocity at the C55 mooring location with (b) model currents at the same location (c) northward and eastward wind stress components (from model forcing) and (d) the northward geostrophic velocity based on east-west sea surface slope from the model at the observation location.

Figure 4. Top panels display monthly averaged satellite-derived sea surface temperature for each month of the simulation. Middle row shows comparable model averaged fields. Lower set of panels shows potential temperatures at the lowest sigma level of the model domain.

Figure 5. Monthly average of potential temperature for a shelf transect starting at Zhemchug canyon (as marked in Figure 1)

Figure 6. Time series of temperature at 3 depths for two shelf moorings (thick lines), C55 and S55 (See Figure 1), compared to model fields (thin lines). The model position that is used for comparison at C55 is offset to the West relative to the observational mooring (as marked in Figure 1)

Figure 7. Sea surface temperature on September 8th 2009, (top) a multisatellite blended 0.1° resolution product (NOAA CoastWatch http://coastwatch.pfeg.noaa.gov/info/BA_ssta_las.html) (bottom) model. In the lower panel, gray contours indicate bathymetry (-50, -100, -250, -500, -1000, -2000 m) and the names of the passes are shown in black.

Figure 8. Low-pass filtered (3.25 day) Velocity components, temperature, salinity and vertical diffusivity coefficient for a section through the center of Amukta Pass on September 8th 2009. Vertical mixing coefficient is contoured on a $\log_{10}$ scale.

Figure 9. Positions and temperature and salinity profiles for two Argo drifters in the vicinity of Amukta Pass during the summer of 2009. In the top panels filled circles indicate drifter positions that match the thick-line profiles in the lower panels. Thin lines are used for temperature and salinity profiles at other times. Model profiles at the same times and positions (thick-dashed lines - again corresponding to filled circles in upper panels) are also displayed.

Figure 10. Model low-pass filtered northward transport through several of the Eastern Bering Sea passes along with the sea surface height in the center of Amukta Pass (gray line) as a function of time.

Figure 11. The evolution of the surface salinity and velocity over a K_1 -tidal cycle during a spring tide period and a neap tide period in the vicinity of Amukta Pass. **H** and **S** in the bottom right panel denote the locations of Herbert and Samalga passes respectively.

Figure 12. Sections of northward velocity (color contours) and salinity (contour lines) averaged over all spring (top panels) and all neap (lower panels) periods of the 5 month simulation.

Figure 13. Model surface salinity (SS) averaged over all spring (top panel) and all neap (middle panel) periods of the 5 month simulation. Lower panel displays the difference ($SS_{Spring} - SS_{Neap}$)

Figure 14. Low-pass filtered model SSH in the vicinity of Bering Canyon over a two week period from late July to early August 2009. Contour lines indicate the -1000 m, -500 m, -200 m and -100 m isobaths.

Figure 15. Low-pass filtered SSH along a North-South transect at 167°W, northward from Unalaska Island into the Bering Sea. Dashed lines indicate the times of peak spring high tide locally.

Figure 16. The time evolution of the cold pool boundary as defined by the position where the 3.5°C isotherm intersects the sea floor. Boundary lines are plotted every 6 days from July 2nd through September 4th, 2009.

Figure 17. a) Seawifs satellite derived calcite concentration (indicative of a coccolithophorid bloom), b) Seawifs satellite derived SST, and c) model sea surface temperature, on October 8th, 2009 . Light contour overlaid in panels a) and b) indicates the 0.008 mol m⁻³ calcite contour for comparing the two fields.

Figure 18. Surface RMS high-pass currents for the 5 month simulation. Bottom panel displays a zoom-in view over the shelf break in the region of Zhemchug and Pribilof canyons.