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Toward development of the 4Dvar data assimilation system in the Bering Sea: reconstruction of the mean dynamic ocean topography

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Abstract The Bering Sea circulation is derived as a variational inverse of hydrographic profiles (temperature and salinity), atmospheric climatologies and historical observation of ocean curents. The important result of this study is estimate of the mean climatological sea surface height (SSH) that can be used as a reference for satellite altimetry sea level anomaly data in the Bering Sea region. Numerical experiments reveal that, when combined with satellite altimetry, the obtained reference SSH effectively constrains a realistic reconstruction of the Amukta Pass circulation.

Key words Bering Sea, mean dynamic ocean topography, 4Dvar data assimilation system.

1 Introduction

Density and diversity of oceanographic observations in the Bering Sea (BSea) increased significantly during the last two decades (Figure 1). The observations comprise conventional temperature/salinity data, large number of high quality velocity time series from moorings[1], surface and subsurface (Argo) profiling floats [e. g., www. argo. ucsd. edu, www. pmel. noaa. gov/foci, www. aoml. noaa. gov/phod/dac/gdp. html]. Most of these data sets have been analyzed separately in a number of publications that outlined different aspects of the BSea dynamics. For example, Verhunov and Tkachenko (1994)[2], described major hydrophysical features of the Bering sea circulation and derived geostrophic estimate of the Kamchatka Strait transport. Woodgate *et al.* (2005)[1], analyzed velocity observations in the Bering Strait available since the beginning of 1990s and provided accurate estimates of the volume transport in the Strait. Extensive surface drifters program being performed by NOAA since the beginning of 1982, allowed to determine basic features of surface BSea circulation[3].

Since 1992, the satellite radar altimetry has become a conventional tool for remote monitoring of sea level variations and surface circulation in different regions of the ocean. Development of the instrumental technology and processing techniques and utilization of the multi-satellite datasets reduced errors of the satellite altimetry products to the order of 1 cm, sufficient to sense the SSH signal associated with the ocean currents and to resolve most upper ocean mesoscale eddies. Combined together, data from the TOPEX/Poseidon, Jason-1, Earth Resources Satellite (ERS)-1 and-2, Envisat, and Geosat Follow-On (GFO) missions span the time period from October 1992 to present.

While it is natural to monitor the SSH variations using satellite altimetry observations, extracting the absolute dynamic topography of the ocean surface from satellite altimetry data is a difficult task clue to the uncertainties in the geoid models. Although the recent Gravity Recovery and Climate Experiment (GRACE) mission [http://www. csr. utexas. edu/grace/] significantly improved the models of the Earth's gravity and geoid, they still remains too coarse (400 km at best) to be directly used in a study of mesoscale ocean currents. A number of research groups have developed methods to combine various data to downscale the Mean Dynamic Ocean Topography (MDOT). One of the most widely used MDOTs is provided by Rio *et al.* (2005)[4], (hereafter RIO05). This product utilized advanced statistical methods to synthesize the multi-scale MDOT from the *Collecte Localisation Satellite* (http://www. cls. fr) mean sea level, drifters, satellite altimetry, and wind observations combined with the dynamic topography derived from historical conductivity-temperature-depth (CTD) profiles.

In the BSea region RIO05 has several drawbacks. Firstly, it suggests the presence of artificial quasi-stationary vortices in the eastern part of the sea. Secondly, according to Figure 2, the transport of the Kamchatka current is too small, which contradicts to the recent estimates of this current transports and drifter observations[5]. Thirdly, the dynamical calculations of the Bering Strait current with the RIO05 used to set up the reference pressure level significantly underestimate the Bering Strait transports, compared to other geostrophic estimates (e. g. Chernyavski *et al.* 2005[6]). Obviously dynamics of BSea is too complex to be described with the statistical techniques applied by RIO05 to the global ocean. Another popular global product derived by Maximenko and Niiler (2005)[7] and available at apdrc. soest. hawaii. edu/projects/DOT has a large gap in the eastern BSea.

Generally, to take into account the dynamical information, the MDOT estimate can be contsructed as an average of the ensemble of different model solutions. However, in application to the BSea region, thus-derived MDOT may contain significant uncertainties due to errors in model forcing and open boundary conditions. For example, most of the Bering Sea models give 2-2.5 Sv transports through the Amukta Pass, instead of more than 4 Sv transport recently observed by *Stabeno et al.* (2005)[8]. Thus, the application of this approach may be not appropriate for the BSea region.

As an alternative, the four-dimensional variational (4Dvar) data assimilation technique (Le Dimet and Talagrand 1986)[9] provides a promising approach for reconstructing MDOT as a component of the mean climatological circulation through the synthesis of a variety of observations and model dynamics. The optimal solution obtained by the strong constrains 4Dvar data assimilation technique satisfies exactly the equations of the ocean model.

This method has proved to be extremely useful and efficient tool for the study of ocean circulation [10-13]. The 4Dvar approach fills the gap between studies relying heavily on statistical analysis of observations (such as dynamical method, water mass analysis and diagnostic modeling) and methods based upon dynamical constraints alone (such as model simulations). It also has significant advantages in comparison with the simplified *nudging-type* data assimilation methods, such as the optimal interpolation data assimilation approach. The nudging-type methods applied for the reconstruction of the quasi-steady state climatological circulations result in significant violation of the model physics on climatological time scales[12]. Optimal interpolation commonly relies on strong assumptions regarding the Gaussian statistics of the model fields and utilizes stationary and isotropic (and thus sub-optimal) covariance matrices in the assimilation procedure[14].

Recently, Panteleev *et al.* (2006a)[5], fulfilled variational analysis of the summer climatological circulation in the main part of the BSea. One of the results of this study was an estimate of the 24 Sv transport through the Kamchatka Strait (KS) that agreed well with the 20 Sv transport obtained by Hughes *et al.* (1974)[15] through dynamical calculations referenced to the surface velocities taken from surface drifters. The reconstructed climatological circulation was also found to be in a good agreement with the Argo drifters velocities parked at 1000 m[16].

This paper describes the results of reconstruction of the climatological circulation in the entire BSea via variational assimilation of temperature/salinity, drifter velocity and meteorological data into the ocean general circulation model [5,13,17]. Obtained climatological SSH is used as an estimate of MDOT for the BSea region. To assess the accuracy of the 4Dvar MDOT estimate additional experiments in the Amukta Pass region were conducted, in which the 4Dvar MDOT and RIO05 were used as references for the altimetry anomalies data and compare reconstructed circulations with available data. The paper is organized as follows. The data sets used in data assimilation,, data assimilation technique, and results of climatological reconstruction of the BSea circulation are presented in Section 2. Section 3 describes the experiments on reconstruction of the Amukta Pass circulation. Section 4 concludes the paper.

2 Reconstruction of climatological circulation in the Bering Sea

2.1 Data

In the presented research we utilize the following data sets.

a) 81,911 *temperature/salinity profiles collected in the Chukcha and Bering Seas.*

This database includes bottle data, mechanical bathythermograph data, high resolution CTD profiles, expendable bathythermograph and the PALACE Argo float data. The data were collected by the US, Japanese and Russian institutions during the period 1932-2004. The composite sources of this database outlined in Panteleev *et al.* (2006a)[5]. Figure 1 shows spatial distribution of temperature profiles. Climatological data and estimates of their standard deviation (STD), derived from these data, were used in data assimilation. Temperature and salinity STD varied within the ranges 0.5 °C-1.5 °C and 0.1-2.0 ppt near the surface of the ocean and decreased down to 0.1 °C and 0.03 ppt, respectively, in deeper layers (down to 1000 m).

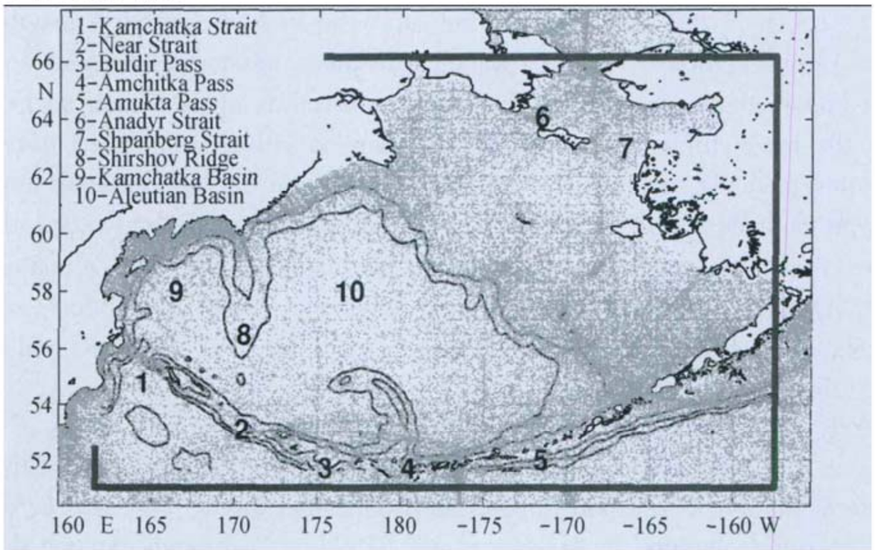

Fig. 1 Spatial distribution of historical temperature data in the Bering Sea. The model domain is shown by rectangle. Lines mark the coastline and 1000 m and 3000 m isobaths.

b) 500 *satellite-tracked drifter trajectories from the Fisheries Oceanography Coordinated Investigations* (*FOCI*) *data base and* 84 *drifter trajectories from the Global Drifter Program* (*CDP*) *data base.*

The FOCI surface drifters (www. pmel. noaa. gov/foci) had their drogues at approximately 40 m. The GDP drifters (www. aoml. noaa. gov/phod/dac/) had drogues at 15 m. Preliminary analysis of these data included: (i) temporal low-pass filtering of the trajectories with a 7 days cutoff period; (ii) spatial interpolation and smoothing of the filtered drifter velocity components onto the model grid with the correlation radius of 30 kin; (iii) estimation of the error variance of the gridded velocity components. Only gridded velocities obtained from the averaging of at least three different surface drifters were assimilated.

c) 57 *monthly mean velocity data from moorings.*

Most of these data came from the Alaska Ocean Observing System (AOOS) database. Preliminary analysis of the AOOS data (www. aoos. org) involved averaging of the velocity time series to obtain monthly mean values. Many of the AOOS velocity time series are only 2-4 months short and can not be a source for reliable estimates of climatological currents. To avoid the contamination of the solution with presumably strong "sub-seasonal" signal, the STDs of the monthly mean velocity data were prescribed as the largest of the following three values: 5 cm/s (an estimate of monthly variability of velocity amplitude), 20% of the monthly mean velocity amplitude, and the conventional STD estimate from the velocity time series.

d) *Estimates of the mean transport through the Bering Strait.*

Climatological estimates of the 0.9 ± 0.2 Sv transport were taken from Woodgate *et al.* 2005[1].

e) *NCEP/NCAR wind stress and surface heat/salt flux climatology.*

The NCEP/NCAR climatologies (www. cdc. noaa. gov/cdc/data. ncep. reanalysis. derived. html) were found unrealistically smooth. To allow for the adjustment of the spatial details in the model forcing fields, we used wind stress and surface heat/salt flux data with relatively high error variance equal to 40% of their spatial and temporal variability in the BSea. Significant errors in the NCEP/NCAR forcing were also noticed by Ladd and Bond (2002)[18].

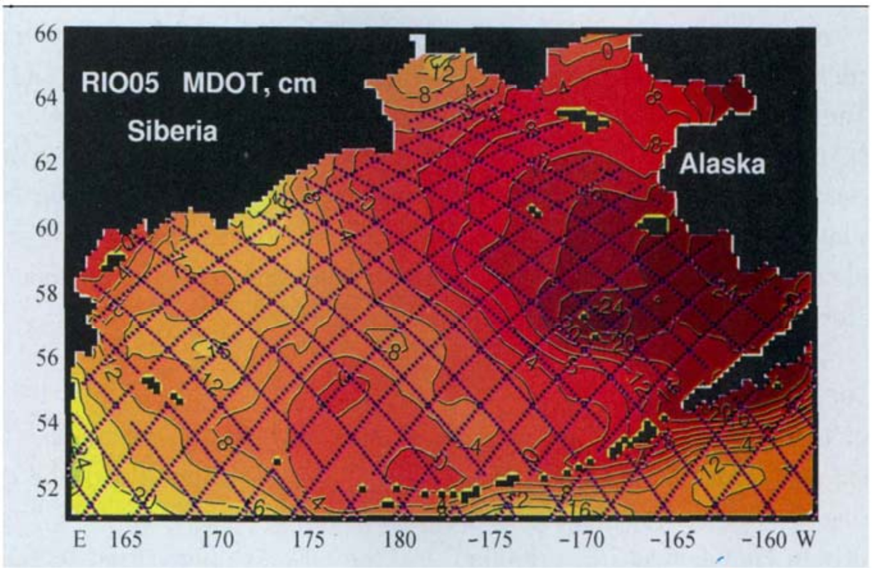

Fig. 2 MDOT in the Bering Sea according to Rio *et al.* (2005)[4] Dotted lines show tracks of the TOPEX/Poseidon and Jason-1 satellites (http://www.jason.oceanobs.com).

2.2 *Data assimilation technique*

To find the optimal model solution we applied strong constraints variational data assimilation approach that can be formulated as a traditional least squares problem [19-21][9]. The optimal solution of the model is found through constrained minimization of a quadratic cost function on the space of the model control vectors, where the cost function measures squared weighted distances between the model solution and data.

Application of the strong constraints 4D-var data assimilation approach involves (i) running the forward model starting with some prior estimate of the model control (socalled, first guess) to estimate the cost function and the model-data misfits; (ii) running the adjoint model backward in time to compute the gradient of the cost function with respect to control vector, and (iii) application of the descent algorithm to find the updated values of the control vector components. The procedure is repeated for the updated model control vector until specified convergence criterion is satisfied. Typically, the minimization of the cost function requires hundreds of forward and adjoint model runs.

The primitive equation model utilized in this study is the same as in Panteleev *et al.* (2006a)[5]. The model is a modification of the C-grid, z-coordinate OGCM designed by Madec *et al.* (1999) [22] (see Nechaev *et al.* 2005 for details[17]). The adjoint code of the model was built analytically by transposition of the operator of the tangent linear model, linearized in the vicinity of a given solution of the forward model[10,20]. Running the adjoint model for a nonlinear problem requires costly storing of the solution of the forward model on every time step. However, application of the implicit scheme with large time steps results in considerable reduction of storage requirements for variational data assimilation.

The tangent linear model was obtained by direct differentiation of the forward model code. Therefore the tangent linear and adjoint model were the exact analytical consequences of the forward model.

The model is configured in the domain shown in Figure 1 and is used in the "climatological"[23] non-eddy-resolving mode on a relatively coarse (≈18 km) regular z-coordinate grid. Meridional resolution of the grid is 0. 16°, zonal resolution is 0. 3°, and time step is 4 hours. The model grid resolves reasonably well the Kamchatka Strait, Near Strait, Amchitka and Amukta passes. Vertically, the grid has 34 levels with unequal spacing ranging from 5 m near the surface to 500 m in the deeper layers. The quasi-stationary variational data assimilation approach[23] has been applied. Climatological temperature/salinity distributions and corresponding geostrophic velocities were used to set up the boundary and initial conditions for the first guess solution of the model.

2. 2. 1 *Cost function*

Statistical interpretation of the variational data assimilation technique[21] considers cost function as an argument of the Gaussian probability distribution with the cost function weights being the inverse covariances of the corresponding data errors.

Similarly to Panteleev *et al.* (2006a)[5], the cost function, used in this work, includes data terms and regularization terms. The data terms measure weighted squares of the distance between the model solution and observations. The weights are inverse variances of corresponding data errors (see Section 2. 1). Errors for different observations are assumed uncorrelated.

The regularization terms penalize the grid-scale noise (squares of the second spatial derivatives of the model fields) and time evolution (squares of the difference between model solutions at initial and final times). Regularization terms allow to obtain the quasi-steady state optimal model solution [5,23] that can be viewed as an estimate of the mean climatological conditions in the BSea.

2. 3 *Climatological circulation*

The climatological surface circulation in the BSea obtained in the data assimilation experiment is shown in Figure 3a. Figure 3b presents the climatological velocity field at 1000 m. General circulation pattern reveals the intense (30-50 cm/s) Alaska Stream, somewhat weaker (10-20 cm/s) Aleutian North Slope Current flowing along the southern and northern flanks of the Aleutian Arc and cyclonic circulation in the deep part of the BSea that includes the relatively week (5-15 cm/s) Bering Slope Current and more pronounced (30-40 cm/s) Kamchatka Current along the eastern and western BSea shelfs respectively. According to Figures 3a and 3b, significant portion of the inflow through the Near Strait forms a cyclonic gyre in the south-western part of the BSea and then merges with the Kamchatka Current. The other portion of the Kamchatka Strait outflow comes from Bering Slope Current that originates from the inflow through other Aleutian passes.

The Alaska Stream is the most intense current in the region. It flows along the southern flank of the Aleutian Arc and feeds the throughflow in the Aleutian Passes [24]. The Bering Slope Current splits into two branches near the point 57°N, 180°E. This is similar to the flow pattern described by Stabeno and Reed (1994)[3]. The climatological circulation does not reveal clear splitting of the Kamchatka Current onto "coastal" and "off-shore" branches in the vicinity of the Shirshov Ridge as was shown in Panteleev *et al.* (2006a)[5]. Instead, a relatively broad westward current across the Kamchatka Basin is obtained. The difference from *Panteleev et al.* (2006a,b)[5,13] can be attributed to the seasonal non-stationarity of the "off-shore branch" of the Kamchatka Current.

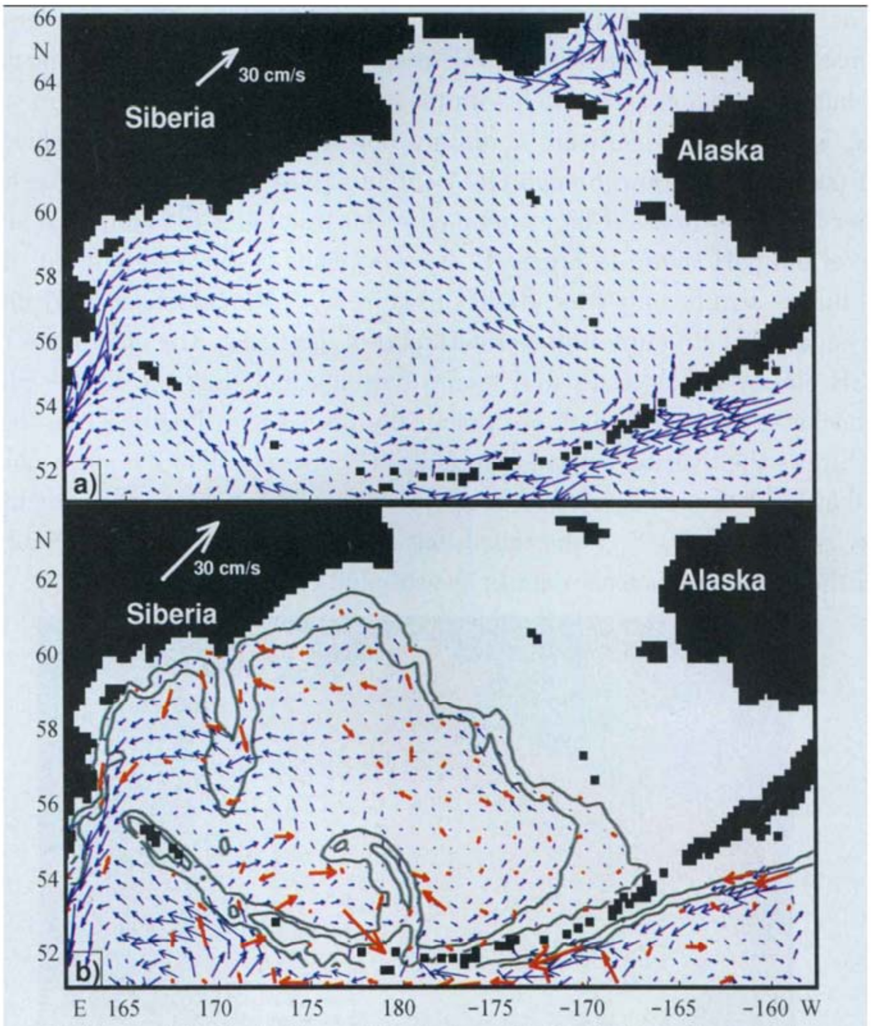

Fig. 3 Optimized velocities at 25 m (a) and 1000 m (b). Red arrows denote mean velocities at 1000 m estimated from Argo floats parked at 1000 m[16].

The mean relative mismatch between the reconstructed surface velocities (Figure 3a) and assimilated drifters velocities is 0.67. It is difficult to expect better agreement between the climatological velocity and highly variable surface currents derived from the drifter trajectories. Note that Panteleev *et al.* (2006a)[5] also obtained a similarly high model-surface drifter velocity misfits. Despite of this, the optimized surface velocities in the Kamchatka Current and Alaska Stream are found rather close to the observed currents indicating a good quality of the reconstructed pattern.

In order to validate our results, the optimized velocity field at 1000 m is compared with independent velocity data derived from the Argo float velocities (Figure 3b). Average speed of the Argo floats is 4.6 cm/sec and close to the mean optimized velocity amplitude of 3.7 cm/sec. We consider this fact as a good agreement with observations because significant fraction of ARGO drifters should be involved in eddies motion resulting in higher mean Lagrangian speed compared to the mean Eulerian speed estimates.

The optimized estimates of the mean volume transport through the major Aleutian Passes are found to be 2.5-7 times larger than the dynamical method estimates obtained by Stabeno *et al.* (1999)[25]. This discrepancy is likely due to significant underestimation of the barotropic velocity component in the Aleutian straits by the dynamical method calculations. The latter suggestion agrees well with the recent velocity observations in several Aleutian Passes, which reveal significant northward flow at 100-200 m depth indicating the importance of the barotropic flow through the Aleutian passes in the BSea volume balance[25].

Another important result of the variational reconstruction is the optimized climatological distribution of the SSH shown in Figure 4. It corresponds to the velocity field shown in Figure 3a and differs significantly from RIO05 (Figure 2). The optimized SSH does not have the non-physical eddy structure in the eastern part of the BSea. The map of the mean climatological SSH clearly indicates all well known currents including the Bering Slope Current and the Kamchatka Current, which are practically not seen in Figure 2. In the vicinity of the Bering Strait, the distribution of optimized SSH corresponds to the mean northward flow indicating that local dynamics is close to geostrophic. This agrees well with the results of Cherniavsky *et al.* (2005)[6], who found that the Bering Strait transport can be well estimated from the sea level anomaly data by geostrophic calculations.

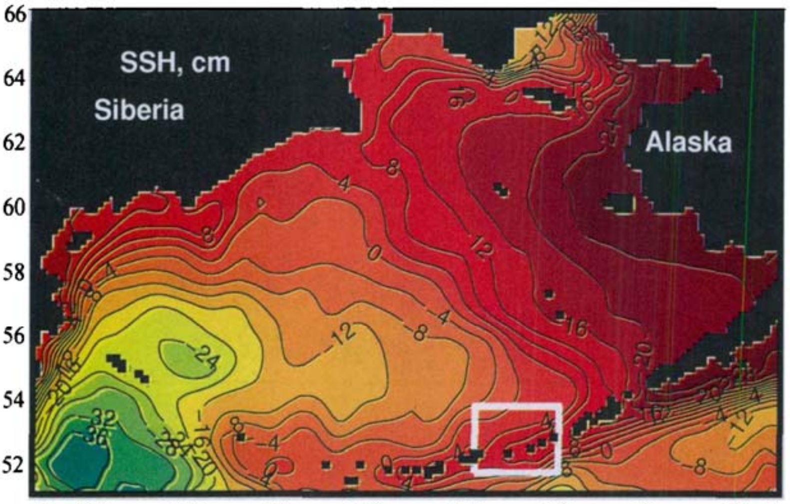

Fig. 4 Optimized climatological SSH. White rectangle shows the region of the Amukta-Seguam passes where hindcast experiments have been conducted.

The overall distribution of the mean climatological SSH looks more reasonable than RIO05. Importantly, the optimized SSH is dynamically balanced with the climatological temperature and salinity fields in the region. In the next section we utilize the reconstructed mean climatological SSH as a reference for satellite altimetry sea level anomaly data.

3 Hindcast of circulation in the Amukta Pass

In order to test the quality of the mean optimized climatological SSH we conducted two experiments and assimilated the gridded SSH anomaly data (www. aviso. oceanobs. com) combined with the absolute climatological SSH shown at Figure 4. The data assimilation model with the horizontal resolution of 6kin was configured for the domain shown in Figure 4. The gridded SSH data were linearly interpolated onto the model grid and assimilated through the 4Dvar data assimilation procedure that is similar to the method described in Section 2. Because in situ temperature/salinity observations are absent, climatological temperature/salinity distributions in the Amukta Strait were utilized. The reconstructed northward transport through the Amukta Pass was compared with recent estimates of the Amukta Pass transport derived by Stabeno *et al.* (2005)[24], from four bottom mounted ADCP moorings.

Circulation patterns obtained for January 10-20 and January 25 - February 5 are shown in Figures 5a and 5b. Very intense northward current on January 10-20 agrees well with the large positive anomaly (≈ 7 Sv) of the Amukta transport observed by Stabeno *et al.* (2005)[24]. The northward transports for these two periods were obtained to be 6. 1 Sv and 3. 5 Sv, respectively. This is approximately 0. 5-1Sv smaller than the transports calculated by Stabeno *et al.* (2005)[24]. Note that resolutions of gridded climatological SSH and AVISO sea level anomaly are not sufficient to resolve the complicated geometry of the Amukta Pass. Therefore, better agreement with observations may be expected, if a higher-resolution climatological SSH is used. Preliminary experiments also indicate that assimilation of the along-satellite-track sea level anomaly also improves the agreement between the reconstructed and measured transports through the Amukta Pass.

Figure 5c shows the Amukta Pass circulation derived by assimilating the AVISO sea level anomaly referenced to RIO05 (Figure 2). Very weak velocities in Figure 5c and transport of only 1. 6 Sv disagree with 4 Sv described by Stabeno *et al.* (2005)[24]. These experiments illustrate that RIO05 significantly underestimates the SSH slope in the region of the Aleutian passes. As mentioned above, one possible reason for this underestimation is that RIO05 provides general description of the global ocean dynamic, but does not pay enough attention to specifics of the BSea circulation.

Another possible weakness of RIO05 is that it was obtained under the implicit assumption of the level of no motion. The subsurface Argo floats indicate rather energetic circulation with velocities of 4-5 cm/s at 1000 m and 2000 m in the Bering Sea and in the Alaska Stream, respectively. The assumption of the level of no motion should lead to significant dynamical inconsistency between RIO05 and observed temperature, salinity and velocity fields. We speculate that this is the main reason why RIO05 (Figure 2) lacks the narrow Kamchatka Current along the Kamchatka Peninsula.

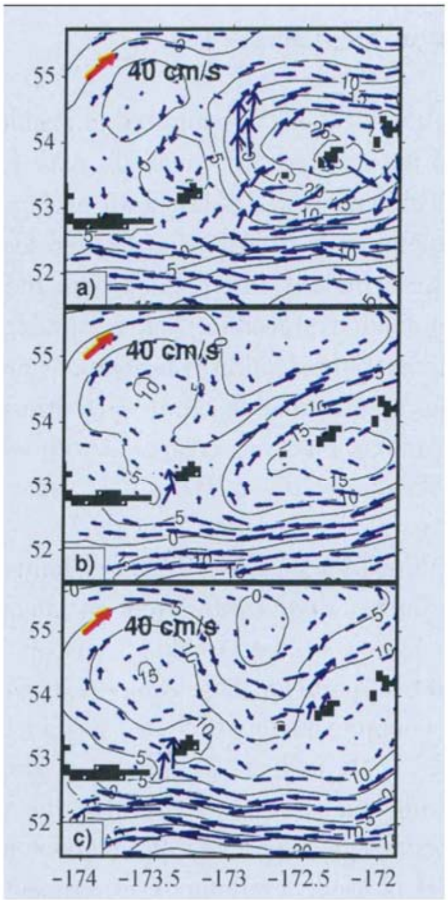

Fig. 5 Circulations in Amukta Pass on January 15 (panel a) and February 1 (panel b), 2002 derived by assimilating the AVISO sea level anomaly data referenced to the absolute SSH shown in Figure 4. Circulation in the Amukta Pass on February 1, 2002 (panel c) derived by assimilating the AVISO sea level anomaly referenced to RIO05.

4 Conclusions

Presented is a quantitative estimate of the mean climatological circulation and SSH in the BSea derived from all available hydrographic, velocity and meteorological observations. Optimized circulation is dynamically balanced within the framework of the model and is consistent with the utilized data. In statistical interpretation, the optimal solution is the most probable model state for the given data realization and prior error statistics [21]. The reconstructed circulation is in agreement with the conventional knowledge [3], and confirms the circulation features described by Panteleev *et al.* (2006a)[5].

The derived mean climatological SSH differs significantly from the MDOT proposed by RIOS. Several numerical experiments were conducted to assimilate the gridded AVISO sea level anomaly that proved that obtained mean climatological SSH can be successfully used as a reference for the BSea region, in which case it leads to more realistic 4Dvar hindcast of the the Amukta Pass circulation than RIO05.

Mooring velocity data are highly valuable for reconstructing the southern BSea circulation, but observations at only a few locations are not sufficient for reliable operational hindcast/forecast of the local circulation. Currently, satellite missions of Jason-1 and -2, Envisat, and GFO provide estimates of the sea level accross the entire BSea every 10-30 days. Unfortunately, because of the poorly known geoid and MDOT, use of the satellite altimetry data is not straightforward. Therefore, definition of reliable reference SSH is an extremely important step in the development of the data assimilation system for the BSea.

Simple examples of hindcast of circulation in the Amukta Pass are encouraging for the proposed approach. Meanwhile, there are several ways to achieve even better results. Several preliminary numerical experiments, which are not described in the paper, indicate that variational assimilation of the along-track satellite altimetry data gives better results than assimilation of gridded sea level anomaly fields provided by AVISO. We also speculate that a more sophisticated de-tiding procedure (e. g., Foreman *et al.* 2006[25]) based on the local data should further improve the result.

Currently, we are working on the development of the 4Dvar data assimilation system for the Aleutian Arc region. Such a system is important because the observed transports through the Amukta Pass (Stabeno *et al.* 2005)[26] and the Kamchatka Strait (Panteleev *et al.* 2006a[5]) are 2-3 times larger than the transports typically obtained in high resolution models (e. g. Maslowski and Lipscomb 2003[27]) indicating that present understanding of the BSea circulation and its variability is unsatisfactory. Improving the accuracy of quantification of the throughflow transports in the Aleutian passes is a necessary step to understand the drawbacks of the existing high resolution ocean basin scale model simulations. Recent long-term velocity observations in the Amukta, Tanaga, Seguam, and Akutan passes (Stabeno *et al.* 2005[26]) are extremely useful for monitoring the Aleutian pass transport. Assimilating these data using the 4Dvar system will allow to obtain reliable estimates of local circulation and will help to elucidate the relative importance of local tides and regional mesoscale and large-scale variability.

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