Adjoint Sensitivity Analysis and Observing System Simulation Experiments as an tool to analyze and optimize observations in the Arctic Ocean

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Abstract Efficient Ocean Observational System in the Arctic Ocean is critical for understanding of the environmental changes in the Arctic where data acquisition is extremely complicated and expensive. Adjoint Sensitivity Analysis (ASA) and Observing System Simulation Experiments (OSSE) are the powerful tools that could be used for the optimization of the existing and incoming observational programs in the Arctic Ocean. We provide two examples how the ASA and OSSE can be used for optimizing the locations of the High Frequency Radars and passive tracer survey.

Introduction

With the diminishing of sea-ice during the past decades, we observe significant changes of the hydrophysical conditions in the Arctic Ocean. An incomplete list of observed changes includes: intensification of warm Pacific Water inflow through the Bering Strait (BS) (*Woodgate et al.,* 2012), changes in freshwater (FW) balance in the BS and in the Eurasian Basin, enhanced Arctic oscillation (AO) index "due to cyclonic shift in the ocean pathways of Eurasian runoff forced by strengthening of the west-to-east Northern Hemisphere atmospheric circulation" (*Morison et al.*, 2012), amplification of regional significant wave height by 35% (*Francis et al.*, 2010), and development of a new role for sea waves to further diminish Arctic sea-ice (*Simmonds and Rudeva*, 2012) and enhance vertical mixing *(Qiao et al.*, 2004). There is also a significant increase of human activity in the Arctic Ocean, which includes trans-Arctic transportation and shipping, mineral extraction, and oil/gas exploration in the Arctic shelf. These activities risk additional impacts on the fragile Arctic ecosystem.

Because of these changes and increased risk of accidents and technological disasters, there is a strong need for an efficient Observational Network (ON) that would: allow for reliable estimation of the observed changes; explain the most important factors responsible for the changes; forecast future changes in the Arctic Ocean hydrophysical, hydrochemical, and ecological states; and aid in responding to undesirable events. The need for better understanding has resulted in several observational initiatives such as Nansen/Amundsen Basin Observing System (NABOS), Beaufort Gyre Exploration Project (BGEP), East Siberian Shelf Study (ESSS), Distributed Biological Observatory (DBO), deployment of high frequency radar (HFR) systems along the Alaskan Coast, and other such programs.

Essential elements of modern observations in the Arctic Ocean include velocity observations from moorings and coastal High Frequency Radars (HFRs), and hydrographical observations from ships. Currently there are a significant number of moorings deployed in the Pacific side of the Arctic Ocean in the frame of the multinational efforts. However, such observational plans are usually based on qualitative understanding of the investigated processes and/or scientific intuition, both of which may be at least sub-optimal or subjective.

An ideal ON plan should be guided by an objective strategy that optimizes the expenses of monitoring coastal circulation in the context of existing activity and existing needs. A prerequisite for developing such a strategy is the ability to answer the following questions:

- How many observations do we need in order to obtain reliable estimates of various target quantities (TQs) (such as transports through certain sections, surface circulation) in these regions? Further: what is the relative impact of additional observations?

-What are optimal locations for glider-based scanning, mooring deployment, and HFR installation? What is optimal combination between these instruments?

-How do observations in one region (*e.g.* velocity observations at particular sites in the Chukchi Sea) correlate with observations in another region (*e.g.* with observation in the Bering Strait)?

- In what regions do we need improved coverage and what are the requirements for observational accuracy?

Given the high expense observational instrumentation and deployment logistics in the Arctic region, the first step in ON development should be preliminary analysis and optimization of future plans. For example, when located in appropriate sites along the Alaska coastline, HFRs can be effectively used to support local marine transportation and offshore operations, *i.e.* to provide benefit to local communities and businesses. Simultaneously, these data can contribute to numerous scientific projects of climatological importance, such as monitoring of the Bering Strait transport and the Alaska Coastal Currents.

Tools for objective planning of observation systems are well known and include the Adjoint Sensitivity Analysis (ASA) and Observing System Simulation Experiments (OSSEs). They are widely applied for analysis and planning of the observational grid in operational meteorology, where the corresponding volume of observations is critical for accurate weather forecast (Errico et al., 2013, Lahoz et al., 2005, Timmermans et al., 2015). Over the past decades, there have also been persistent efforts to introduce a similar approach for ocean observational programs. Despite these attempts, observational planning of oceanographic surveys and long-term monitoring still do not usually include quantitative estimates of the efficiency of the proposed observational plans.

In this paper, we describe the basic ideas behind the ASA and OSSEs techniques, and show how application of these tools may help to optimize the location of the HFRs, identify the gaps in existing observational programs. and increase the information content of the various passive-tracer observations collected during ship surveys.

2. Approaches

Currently, there exist two well-established techniques for optimizing ONs. Both of them make extensive use of link between numerical models and observations, and may be used in sequence.

First, one would perform Observing System Simulation Experiments (OSSEs) in order to identify optimal *in situ* observing site locations, the required measurement frequency, and acceptable levels of uncertainty. The idea underlying OSSEs is to simulate “data” using some reference model solution as a “true ocean state”, contaminate these data with noise (mimicking observational and modeling errors), and then reconstruct the “'true state”' from these “data.” The ancestor of the OSSE approach is the well-known twin-data experiment procedure, which is a basic method of testing data assimilation schemes developed during the last couple of decades.

Second, one analyzes the dynamically-induced correlations between the any TQs and observations through Adjoint Sensitivity Analysis (ASA) (*Köhl and Stammer,* 2004, *Panteleev et al.*, 2008). This approach requires the use of tangent linear and adjoint models (*Marchuk*, 1995; *Wunsch,* 1996), which may be problematic for some models and require time-consuming development if they are not already available.

3. Optimal location of HFR

The difference between these approaches is that ASA is usually applied to the states previously optimized with respect to available data, whereas the statistical analysis of OSSEs is usually applied to non-optimized model solutions, which may differ significantly from the true state of the ocean. The ASA is based on the strong relationship between observations and model state, which is the basic advantage of the 4-dimensional variational data assimilation approach based on the tangent linear and adjoint modeling. The technique allows one to analyze the impact of any additional observations on the optimized model state, and then project this to any TQ of interest. These steps are formally described as applications of linear operations on the model state and the reverse algorithm is also possible and usually less expensive.

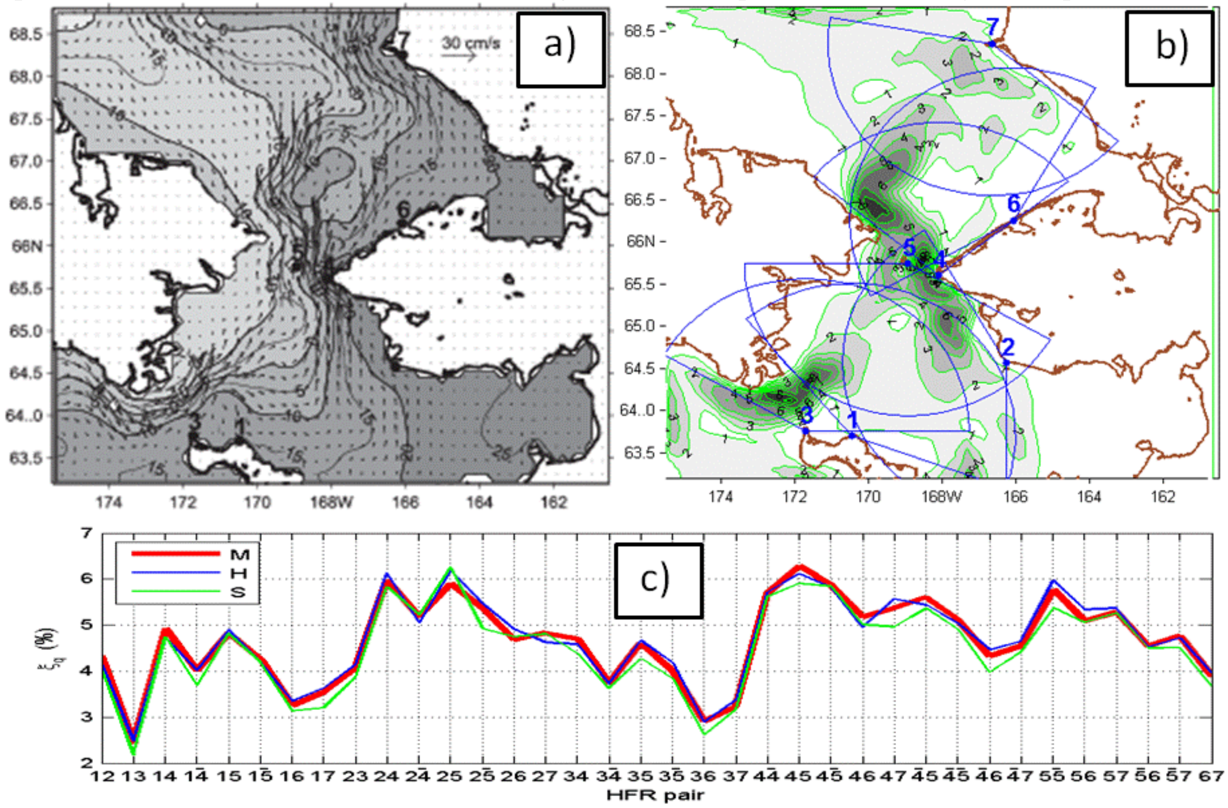

Figure 1. **a)** Surface current and SSH in the BS region. **b)** Time-averaged map of the mean BST sensitivity to surface velocity observations. Sensitivity values are normalized by their maximum at the Bering Strait. Number 1--7 designate the possible sites for HFR near villages along the Alaska coast: Savonga (1), Sinuk (2), Gambel (3), Wales (4), Diomede (5), Shishmaref (6) and Point Hope (7). **c)** Relative reduction of the errors in estimation of the momentum (M), heat (H), and salt (S) transports through the strait for various pairs of HFRs. Numbers labeling HFR pairs correspond to locations in Fig.1b. Bars over Wales (point 4) and Diomede (point 5) locations denote northward-looking antennas at those sites.

The key result of an ASA is an adjoint sensitivity map which establishes a formal relationship between the TQ and all elements of the model state. Figure 1b shows a time-averaged ASA map of the mean Bering Strait transport (BST) sensitivity to the surface velocity observations for the case of a slowly varied summer climatological circulation shown in Fig.1a (*Panteleev et al.*, 2015). Roughly speaking, the map in Fig.1b says that total flows through the Bering Strait are most strongly correlated with (observed) velocity values in the areas of maximum sensitivity, so that the HFR pair ‘45’ (Diomede and Wales, Fig. 1c) best measures the TQs of mass, heat, and salt (MHS) transport through the strait. An immediate conclusion is that if we have one mooring and want to measure the Bering Strait transport, it should be deployed in the American Part of the Bering Strait. Planning the deployment of multiple moorings would require a more complicated analysis taking into account adaptive sampling strategy (Bishop et al., 2001, Daescu and Navon, 2004), or conduct multiple OSSEs as in Panteleev *et al*. (2013a).

HFRs observe surface velocity on the rays which project radially outward from the antenna with radius of about 200--250km (Fig. 2b). Therefore, it is necessary to account for the more complicated “observational operator” corresponding to the HFR configuration. This operator takes into account the area covered by the HFR observations as well as spatial orientation of the rays along which the measurements occur. Further, it must account for the decreasing accuracy of HFR observations with distance from the antenna; observations near the HFR site are usually more accurate than those further away. Technical details for construction of the HFR observation operator and error covariance approximation can be found in Panteleev *et al.* (2015).

By applying simple algorithms that take into account the geographical location of different HFRs on the adjoint sensitivity map Fig.1b, we can easily estimate the reduction of the Bering Strait transport errors due to observation by any pairs of the HFR as well as estimate the efficiency of those pairs. In particular, Fig.2c shows that two HFR located in Diomede and Wales (pair '45') and looking south will provide the least estimation error of the Bering Strait transport. The other reasonable combinations are HFR installations in Sinuk and Wales (pair '24'), Sinuk and Diomede (pair '25'), and two HFR in Wales looking to the north and south. Taking into account that installation in Diomede is logistically complicated (T. Weingartner, *personal communication*), the HFR configurations at Sinuk-Wales and Wales-Wales are reasonable sub-optimal alternatives to the Diomede-Wales setup. Note, however, that deployment at Wales-Wales maybe significantly cheaper.

The economical constrains may be technically incorporated into the algorithm, so in practice, the Wales-Wales pair can be found as a "best" solution when logistical expenses of installation and maintenance are included in the optimization. Simultaneously considering both financial and scientific (Bering Strait transport) values requires a relative weighting of these factors. This introduces subjectivity into the process, and it is therefore reasonable to avoid the economic aspects when pursuing an objective analysis.

The outlined algorithm can be easily extended to optimize installation locations and analyze ON efficiency for more than two HFR. In addition, we can conduct the multiple OSSEs and validate the results inferred from the adjoint sensitivity maps and other by-products of the ASA technique (*e.g. Panteleev et al.*, 2008, 2015). A very high number of moorings and/possible sites for deployment requires running the many OSSEs, which can be computationally prohibitive.

4. Optimal passive tracer survey

The ASA technique is a sensitivity analysis, which is formally involves computation of the TQs' derivatives (such as the MHS transports above) with respect to observations. This requires differentiability of the observation operator, so the ASA appraoch can only apply to certain kinds of observation systems. In the case of a non-differentiable observational operators, OSSEs are probably the only way to optimize ONs. An important example giving rise to non-differentiable observational operators are passive tracer surveys, the method of observation typically used in the study of the Arctic Ocean ecosystem.

The list of the publication related to optimal hydrographic surveys has a long history (*e.g. Panteleev and Semenov*, 1988; *Beckers and Rixen* , 2003). Here we present a simple example how the OSSE technique may help to optimize observations of passive tracers in the Chukchi Sea, where intense and variable currents should be taken into account for planning the surveys. The approach is based on a four-dimensional variational (4Dvar) algorithm applied to an advection-diffusion differential equation describing the behavior of passive biological content (such as small larvae, fish eggs, *etc.*) in known velocity field. The approach was successfully used to reconstruct silicate, phosphate, and nitrates concentrations in the Bering Sea (*Panteleev et al.*, 2013b).

To illustrate the approach, we utilize synthetic data sets which idealize those obtained from biological surveys in the Chukchi Sea. The background velocity field is a realistic reconstruction for the same region during August-September, 2012 as obtained using 4Dvar data assimilation with 10 km resolution. The mean Sep 1--3, 2012 circulation and mean "true" distribution of the passive tracer are shown at Fig.2a,b. A conventional passive tracer survey in the southern Chukchi Sea lasts approximately 3 days, during which tracer observations occur along the ship path. There are multiple possible sample paths for the survey, a few of which are shown by blue traces in Fig.2b,c,d. Each path yields a different set of tracer observations since this TQ moves with the background velocity field. To analyze the efficiency of different surveys, we sample the "true" passive tracer along the proposed cruise tracks with a relative measurement error of 10%.

Using the 4Dvar data assimilation algorithm applied to the advection-diffusion tracer model, the passive tracer field is reconstructed from observations taken along the different survey paths. The root-mean-squared difference between reconstructed and "true" distributions of the passive tracer is used as a metric to evaluate the efficiency of different surveys. Fig.2c,d shows that the ship paths (which define the survey observational operators) have a strong impact on the tracer field reconstruction, and an appropriate path may decrease the RMS by 10--20% and thereby reconstruct the tracer more accurately. Fig.2e,f show reconstructions obtained from the same ship paths shown in Fig.2c,d using traditional linear interpolation methods which do not account for advection of passive tracers. This method is common in analysis of the hydrochemical and biological observations. Comparing Fig.2c,d with Fig.2e,f shows that use of the non-stationary 4Dvar assimilation method is more important than the survey path configuration, and typically decreases the reconstruction RMS error by 20--35% as compared to non-stationary interpolation algorithms.

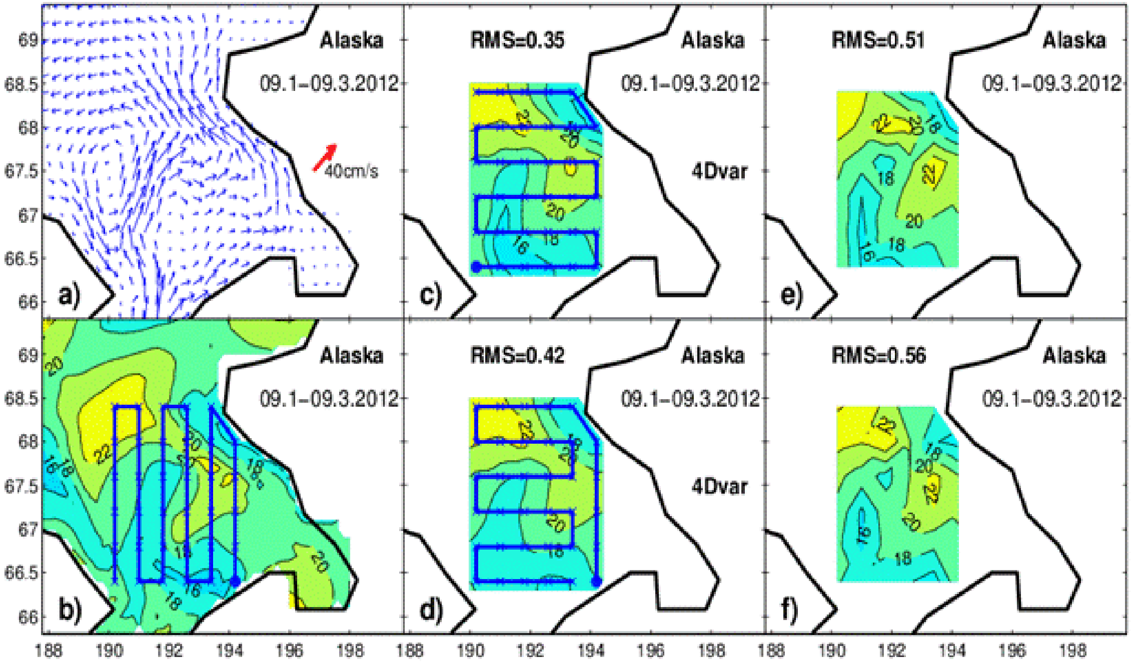

Figure 2. Mean circulation **(a)** and idealized passive tracer distribution **(b)** in the Southern Chukchi Sea during Sep 1--3, 2012. Blue lines designate the observation locations along the ship path. **c),d)** Results of the 4Dvar reconstruction of the passive tracer using observations from the overlain ship path. **e),f)** Results using the same paths but obtained using the linear interpolation algorithm.

4. Conclusions

The ASA and OSSE algorithms have been successfully used by agencies such as the National Aeronautics and Space Administration (NASA), NOAA, Meteo France, and the Met Office UK for planning and testing new observational systems in atmospheric science. Obviously they have a strong potential for the optimization of the observational programs in the in the Arctic Ocean. Currently, they can be easily applied for such planning using the existing (climatological or seasonal) circulations. Recently, we developed a prototype adjoint sensitivity web-server that can be used to optimize a set of user-specified HFR installations in the Southern Chukchi Sea (http://oregon.iarc.uaf.edu/hfr.html) using a non-stationary climatological summer circulation. We plan to develop a similar web-server for optimizing passive tracer surveys. However, these optimization systems and web-servers are designed for optimization with respect to regional *climatological* circulations. This is reasonable for long-term observation system planning (such as mooring deployment and HFR installation sites), but a practical survey optimization system would require an operational circulation model.

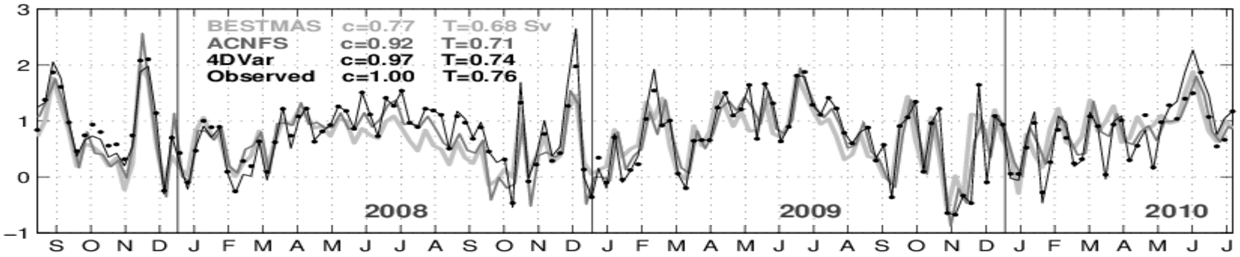

Figure 3. Weekly averaged Bering Strait transports (Sv) in the optimized solution (solid black line), and from the ACNFS (gray) and Bering Ecosystem Study ice-ocean Modeling and Assimilation System (BESTMAS) (light gray) output. Observed values are shown by solid dots. The time averaged values of the transport T and correlation coefficients c with observations are given.

Our analysis of the circulation from the Arctic Cap Forecast Nowcast System (ACFNS) developed in Naval Research Laboratory (http://www7320.nrlssc.navy.mil/hycomARC, *Posey et al.*, 2010) shows that ACFNS provides accurate estimates of the circulation in the southern Chukchi Sea. In particular, the Bering Strait transport from ACFNS has 0.92 correlation with observed volume transport (Fig.3). Flow though the Bering strait is the most influential forcing for the southern Chukchi Sea and thus, the velocity field from this system is recommended as a first guess state for different data assimilation algorithms, including the ones described above. Thus, access to operational output from the ACNFS would enable the development of online tools for operational survey optimization in the Chukchi Sea via OSSE and for post-processing of these observations using the simple advection-diffusion approach. Currently, we are pursuing the development of this kind of tool.

References:

Beckers, J.-M., and M. Rixen. 2003. "EOF Calculations and Data Filling from Incomplete Oceanographic Datasets." Journal of Atmospheric and Oceanic Technology 20.12

Bishop, G. et al., 2001."Adaptive Sampling with the Ensemble Transform Kalman Filter. Part I: Theoretical Aspects", 129,420-437 Montly Weather Review

Daescu D.N. and I.M. Navon, "Adaptive observations in the context of 4D-var data assimilation," Meteorology and Atmospheric Physics, vol. 85, no. 111, pp. 205–226, 2004.

Errico et al., 2013 Development and validation of observing-system simulation experiments at NASA's Global Modeling and Assimilation Office Quarterly Journal of the Royal Meteorological Society, 139-674, 1162–1178, Part A

Francis, O. et al. 2011. "Ocean wave conditions in the Chukchi Sea from satellite and in situ observations." Geophysical Research Letters 38.24

Köhl, A., Stammer, D., 2004. Optimal observations for variational data assimilation. J. Phys. Oceanogr. 34, 529

Lahoz et al. 2005. An observing system simulation experiment to evaluate the scientific merit of wind and ozone measurements from the future SWIFT instrument Q. J. R. Meteorol. Soc.,131, pp. 503–523 doi: 10.1256/qj.03.109

Marchuk, G., 1995. Adjoint Equations and Analysis of Complex Systems. Kluwer Academic Publishers.

Morison, J., et al. 2012. "Changing Arctic Ocean freshwater pathways." Nature 481.7379

Qiao, Fangli, et al. 2004. "Wave□induced mixing in the upper ocean: Distribution and application to a global ocean circulation model." Geophysical Research Letters 31.11

Panteleev, G., and E.V. Semenov. 1988. "On the strategy of hydrological array measurements." Oceanologia 6

Panteleev, G.G, M.Yaremchuk, D. Nechaev, 2008. “Optimization of mooring observations in Northern Bering Sea”, *Dynamics of Atmospheres and Oceans*, doi:10.1016/j.physletb.2003.10.071.

Panteleev, G., et al. 2010. "Reconstruction and analysis of the Chukchi Sea circulation in 1990–1991." Journal of Geophysical Research: Oceans 115.C8

Panteleev, G., et al., 2013a T.Kikuchi Configuring High Frequency Radar observations in the Southern Chukchi Sea, *Polar Science*, 7, 72-81, 2013.

Panteleev, G., et al. 2013b. "Seasonal climatologies of oxygen and phosphates in the Bering Sea reconstructed by variational data assimilation approach." Polar Science 7.3

Panteleev, G., et al. 2015. "Optimization of the high-frequency radar sites in the Bering Strait region." Journal of Atmospheric and Oceanic Technology 32.2

Posey, P., et al. 2010. "Validation of the 1/12 Arctic cap nowcast/forecast system (ACNFS)." EGU General Assembly Conference Abstracts. Vol. 12.

Simmonds, I., and I. Rudeva. 2012., The great Arctic cyclone of August 2012, Geophysical Research Letters 39

Timmermans et al., 2015. Observing System Simulation Experiments for air quality, Atmospheric Environment, 115, 199–213

Woodgate, R., et al. "Observed increases in Bering Strait oceanic fluxes from the Pacific to the Arctic from 2001 to 2011 and their impacts on the Arctic Ocean water column." Geophysical Research Letters 39.24 (2012).

Wunsch, C., 1996. The Ocean Circulation Inverse Problem. Cambridge University Press, Cambridge, UK