Toward optimization of observational arrays in the Arctic Ocean

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Purpose of the presentation

- To initiate discussion on *ADI Task Force Report goal (b)*: “Explore and evaluate promising methods to improve design and adaptation of observing system components through, e.g., observing system simulation experiments and other approaches”.
- To obtain a vision of *ADI Task Force* on role of the proposed research in AON Design and Implementation and to indicate possible directions of advancing for the proposed research

Overview of the presentation

- Proposed research
  - Motivation
  - Approach
  - Goals and Objectives
  - Method
- Preliminary results
- Discussion
Motivation of the proposed research

Ideally an observing system intended for monitoring the AO circulation should be guided by an objective strategy that optimizes the observing system coverage, design, and expenses of monitoring in the context of climate change.

A prerequisite for developing such a strategy is the ability to answer the following questions:

- What kind of data (including sample frequency, duration of observations, and geographic location) are optimal to obtain reliable estimates of Target Quantities (TQs) such as transport of Pacific water through particular sections, heat/salt content in certain basins, etc.?

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

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

This list of questions can be continued
Approach

Setting the problem of finding an optimal observational strategy requires:

- specification of the observational goals (definition of the TQs),
- detailed description of the procedure defining how observations are used to reach the observational goals (estimate TQs).

Estimation of TQs involves running models and/or assimilation of observations into a model (observations alone are incomplete and insufficient to compute TQs).

Optimization of observational strategy relies upon quantitative knowledge of :

- dynamics and variability of the circulation in the region (i.e. the background state and its error covariance),
- forcing mechanisms and their uncertainties,
- availability of prior (historical) observations and other critical factors.
Rigorous setting of the optimal observational strategy problem could be obtained in the framework of variational DA approach. Currently, there exist three well-established variational techniques for optimization of observations:

- Observing System Simulation Experiments (OSSEs) (e.g. Susskind et al., 1985; Zhu and Gelaro 2008; Gelaro and Zhu 2009);
- Adjoint Sensitivity (AS) approach (e.g. Kohl and Stammer, 2004; Panteleev et al., 2008) involving analysis of the dynamically-induced correlations between the TQs and observations;
- Variational Optimization of Data Arrays (VODA) (e.g. Berliner et al., 1999; Pokrovsky, 2000, Bergot, 2001; Daescu and Navon 2004) which can be considered as an extension of the AS technique. This method takes into account dynamically induced and statistical correlations between individual observations in the planned observational array and with other available observations.

These methods have been used successfully by NASA, NOAA, Meteo France, and the Met Office UK for planning and testing new observational systems in atmospheric science. There are also recent examples of their application for AO problems.
We propose to thoroughly explore and test these optimization methods for different types of observations under various dynamical conditions and with respect to different specification of the observational goals (TQs).

We plan:

- To conduct comprehensive statistical correlation and AS analysis of the available model solutions and perform OSSEs and VODA experiments in order to analyze the efficiency of the one of current observational programs in the AO, such as Shelf Basin Interaction (SBI), Nansen Amundsen Basins Observational Study (NABOS), Beaufort Gyre Exploration Project (BGEP), and North Pole Environmental Observatory (NPEO);
- To provide recommendations for designing of an effective AO observing system.
- To investigate how current and incoming observational projects can improve hindcasting and forecasting of climate changes throughout the entire AO.
All three approaches mentioned above are closely related and have a common feature limiting their wide application: implementation of these techniques requires development of the tangent linear and adjoint models.

Adjoint models:

- Are expensive to build and keep updated;
- Are unavailable for many community models;
- There are also well-known problems related to stability and applicability of the tangent linear and adjoint models for nonlinear dynamical systems in the presence of strong physical instabilities of the background state.

To resolve these difficulties we plan to develop and verify versions of the methods for optimization of the observational arrays based on low-dimensional ensemble approximations of the tangent linear and adjoint models.

Such an “adjointless” procedures can be used routinely for planning the field studies in the AO. Ideally such procedures should require minimal adjustment for optimization of the new sets of observations and should be able to operate with ensembles of model solutions generated by community OGCMs.
Goal and Objectives

**Major practical goal** of our work is

To provide observational Arctic community with an objective procedure for optimization of the observational strategy that can be used routinely and will deliver robust and efficient estimates of the optimal configuration of an observational array based on the information available from community AO OGCMs.

**Specific objectives** of the proposed research are:

- To verify and assess efficiency of the algorithms for optimization of observational arrays including the ensemble-based methods;
- To conduct comprehensive AS analysis of the available optimized model solutions and perform OSSEs and VODA experiments in order to analyze the efficiency of several current observational programs in the AO such as Shelf Basin Interaction (SBI), Nansen Amundsen Basins Observational Study (NABOS), Beaufort Gyre Exploration Project (BGEP), and North Pole Environmental Observatory (NPEO);
- To investigate how current and incoming observational projects can improve hindcasting and forecasting of climate changes in the AO;
- To provide recommendations for designing of an effective AO observing system.
Goal and Objectives (continued)

By accomplishing the proposed research we intend to answer the following scientific questions:

- What kind of data (including sample frequency, duration of observations, and geographic location) are optimal to obtain reliable estimates of transport and fate of Pacific water in the AO?
- How do observations in one region (e.g. velocity observations at particular sites in the Chukchi Sea) correlate with TQs in another region (e.g. with Bering Strait transport)?
- In what areas of the AO do we need improved coverage for robust monitoring of climate change indicators?
- What are the most climatologically important regions for CTD observations?
- Is it possible to propose a quasi-optimal set of hydrological sections (similar to the World Ocean Circulation Experiment) that, together with other observations, will provide a comprehensive view of the AO state?
Let
\[ y^1 = N(x^1) + f \]
be a solution of a well-posed data assimilation problem #1 (DA1) involving a set of observations \( d \) which represents both the background state and real data. Here \( N \) denotes a nonlinear physical model with input (control) parameters \( x^1 \) and forcing \( f \). The target quantity TQ is defined as a functional on the model solutions \( y \):
\[ v = V(y). \]

It is planned to perform additional observations \( q \) with prescribed error covariance \( R \) in a set of locations \( r \) to reduce uncertainties of the TQ.

Under these conditions, the problem of optimization of observations \( q \) can be formulated as follows:
Find locations \( r_{opt} \) minimizing a posteriori error variance of the TQ estimated from assimilation of both data sets \( d \) and \( q \) into the model (DA2).
The cost function of the DA2 can be written as:

\[ J(x,r) = (x-x^1)^\dagger B^{-1}(x-x^1) + (O(y) - q(r))^\dagger R^{-1}(O(y) - q(r)), \]

where \( B \) is a posteriori error covariance (inverse Hessian) of the solution of the DA1, \( y = N(x) + f, O \) is the observational operator of the data \( q \), and \( ^\dagger \) denotes transposition. For prescribed observational positions, solution of DA2 and estimation of a posteriori error variance of the TQ is known as Observing System Simulation Experiment.

Adjoint Sensitivity analysis and Variational Optimization of Observational Array are both based on the linearization of the DA2 in the vicinity of the solution \( y^1 \) which yields the following cost function:

\[ J'(x',r) = (x')^\dagger B^{-1}x' + (Hx' - q')^\dagger R^{-1}(Hx' - q'), \]  

written in terms of the perturbations \( x' = x - x^1 \) and \( q' = q - O(y^1) \). Here \( H \) denotes the product of the tangent linear physical and observational models.
Solution of the problem $J'\to \min(x')$ can be written as

$$x'_\text{opt} = K q',$$  \hspace{2cm} (2)

where $K$ is the Kalman Gain Matrix:

$$K = B H^\dagger (H B H^\dagger + R)^{-1}. \hspace{2cm} (3)$$

The *a posteriori* error covariance $P$ of $x'_{\text{opt}}$ is given by the expression

$$P = B - K HB = B - K (H B H^\dagger + R) K^\dagger = B - K P_q K^\dagger, \hspace{2cm} (4)$$

where the matrix $P_q = H B H^\dagger + R$ is known in Kalman Filter theory as an error covariance of the innovation vector.

Finally, perturbations $v'$ of the TQ can be assessed as $v' = V x'$ where $V$ is the product of the derivative $\delta V(y)/\delta y$ and the tangent linear physical model. We are interested in minimizing the posterior error variance $s$ of the values $v'$ by a proper choice of the positions of observations $r$:

$$s(r) = VPV^\dagger = VB V^\dagger - VK P_q K^\dagger V^\dagger = s_o - s_q(r),$$

$$s_q = (s_q^{\frac{1}{2}})^\dagger s_q^{\frac{1}{2}},$$

$$s_q^{\frac{1}{2}}(r) = V B H^\dagger P_q^{-\frac{1}{2}}(r). \hspace{2cm} (5)$$

AS and VODA methods find $r_{\text{opt}}$ maximizing $s_q(r)$ given by formula (5).
Methods: Problem setting (continued)

- **Optimization of a single observation: Adjoint Sensitivity analysis**

The problem of optimizing the position of a single observation can be solved by computing the gradient of $-s_q(r)$ with respect to $r$ and applying a descent procedure in the space of vectors $r$. Alternatively, we propose to restrict the optimization problem to a discrete set $R$ of observational locations corresponding to the subset of model grid nodes in a specified region of the model grid. The choice of optimal observational position is conducted by direct computation of $s_q(r)$ for every $r$ in $R$. Availability of the gridded values of $s_q(r)$ in our approach allows resolving possible problems related to the existence of multiple local extrema. The gridded values of $s_q(r)$ can be used for the analysis of the correlations between data and TQs or can be plotted for visual analysis.

If the number of vectors in the set $R$ is $N_r$, optimization of a single observation requires $N_r$ runs of the tangent linear and adjoint models and $N_r$ multiplications of the background error covariance matrix by a vector, which is a moderate amount of computations if $N_r$ is of the order of $10^2$. It is obvious that at approximately the cost of solving one optimization problem it is possible to assess reductions of the error variances for several TQs.
Variational Optimization of Data Arrays and time series of observations

For optimization of $K_q$ simultaneous observations of the same type in $K_q$ locations we propose to use an efficient simplified procedure that can be performed at the expense of the same number of runs of the adjoint and tangent linear models as the optimization of a single observation. This suboptimal procedure is a version of “coordinate descent” in the $2K_q$-dimensional space of observational locations.

Since the proposed procedure allows monitoring the TQ’s error reduction with each additional observation, it can provide an estimate of the optimal number of observations required to reduce the error variance to a specified threshold value, or to determine the number of observations when additional observations do not significantly improve the errors in TQs.
Methods: Problem setting (continued)

- **Ensemble Approximation of the Background data error covariance:**
  
  "adjoint-less" algorithms

  Inverse Hessian matrix $B$ (background error covariance) describing our *a priori* knowledge of the uncertainties in the background state of the ocean has a profound influence on the choice of optimal position of the observations.

  Given the large number of input parameters for the state-of-the-art numerical models (control vector dimensions $N_c$ exceeding $10^6$), computations of the full inverse Hessian matrix for the DA1 is not feasible. In the proposed research we will take into account valuable experience gained by the DA community in development of the ensemble-based DA methods (Ensemble Kalman Filters).

  We will develop a procedure for generating an ensemble of solutions of the full non-linear model to approximate propagations of the square root background error covariances ($HB^{1/2}$ and $VB^{1/2}$). We plan to conduct thorough tests and validation of the ensemble-based algorithm by comparing its results with adjoint-based algorithm.
Methods: Numerical Models

- **Semi-Implicit Ocean Model (SIOM)** was designed specifically for the implementation of 4dVar methods into regional models controlled by currents at the open boundaries and by surface fluxes. SIOM is a modification of the C-grid, z-coordinate Ocean General Circulation Model (OGCM) developed in Laboratoire d'Oceanographie Dynamique et de Climatologie (Madec et al., 1999).

  SIOM will be used to verify the approaches adjoint based AS and VODA against the OSSE method. Ensemble-based optimization algorithms will be first tested with SIOM model.

- **Arctic Cap Hybrid Coordinate Ocean Model (NRL)**: 1/12° resolution HYCOM/NCODA/CICE system was designed for nowcasting/forecasting of the Arctic Ocean state. The system is based on the HYbrid Coordinate Ocean Model (HYCOM) (Metzger et al., 2008) coupled via the Earth System Modeling Framework (ESMF) (Hill et al., 2004) to the Los Alamos Community Ice CodE (CICE) (Hunke and Lipscomb, 2008).

  This model will be used to assess the robustness of the “adjoint-less” optimization algorithms by extracting the ensemble of solutions for the same AO region as in SIOM experiments.
Methods: Interactive web server

To simplify access of the interested researchers to the developed algorithms we propose to set up an interactive web server that will provide the potential user with an opportunity to run pre-configured observation optimization algorithms on a remote computer and to obtain results within a reasonable time-frame via the internet. Such a web-service will allow the user to avoid installing/configuring optimization software and to proceed directly to specifying the input data. The web-based interface will also have a link to the most current version of the observation analysis software, if the user prefers to run the model on the local computer.

We will use an Apache HTTP server (http://httpd.apache.org/) to host the proposed web-based user interface. We will exploit the Google Maps JavaScript API (http://code.google.com/apis/maps/) to enable a user to specify input data in a point-and-click fashion and submit the entered data to the web-server software, i.e. the observation optimization programs. The backbone of the communication between the user and the server software is to be Common Gateway Interface (http://www.ietf.org/rfc/rfc3875) scripts, which allow (1) formatting the entered data according to the specifications of the optimization software, (2) running the optimization programs, (3) post-processing the numerical results, and (4) dynamically visualizing the results in Google Maps. The proposed computational paradigm was successfully implemented in developing the Alaska Tsunami On-line Mapping Interface (http://burn.giseis.alaska.edu/).
Optimization of the mooring observations in the Bering Strait: Adjoint Sensitivity analysis:

The adjoint sensitivity map of the Bering Strait transport to velocity observations reveals regions of high correlation between the velocity data and total transport through the Bering Strait.
Errors in reconstruction of the Northern Bering Sea circulation as a function of mooring locations. The least errors are obtained with moorings placed at the optimal locations revealed by the adjoint sensitivity analysis.

Optimization of the mooring observations in the Bering Strait.

OSSE (twin data experiment):

\[ \text{err}_{\text{bst}} = 0.014, \quad \text{err}_{\text{uv}} = 0.51 \]
\[ \text{err}_{\text{bst}} = 0.017, \quad \text{err}_{\text{uv}} = 0.17 \]
\[ \text{err}_{\text{bst}} = 0.05, \quad \text{err}_{\text{uv}} = 0.17 \]
Optimization of the mooring observations in the Bering Strait. Adjoint sensitivity analysis of the optimized circulation in 1990-1991
From 1990-1991 observations:

Correlation ( $V_{A3}$, BST ) = 0.88

Correlation ( $V_{A2}$, BST ) = 0.94
Optimization of the High-Frequency Radar observations

Schematic showing desired coastal HFR observations in the Bering Strait region (Calder et al., 2009)
Optimization of the HFR observations

Adjoint sensitivity analysis:

Adjoint sensitivity of the integral surface circulation with respect to HFR observations in the eastern Chukchi Sea.

The “score” is estimated as squared sensitivity of the surface velocity with respect to small changes in the “observed” surface velocity field.
Optimization of the HRF (radar) observations

OSSE approach:

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<th>Days from 10.10.90: 6</th>
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<td>SSH Err= 0.38</td>
<td>SSH Err= 0.76</td>
<td>SSH Err= 0.83</td>
</tr>
</tbody>
</table>
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Optimization of the HRF (radar) observations OSSE: OSSE approach:

```
“True”                   err 0.12

2 HFRs
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Optimization of velocity observations in the AO

Optimized mean surface velocities for 1900-2006 (result of reanalysis of the Arctic Ocean circulation)
Correlation between the integral circulation in the upper 300 m and transport observations at isolated moorings and a hydrophysical section

Control vector = initial conditions
Correlation between the integral circulation in the upper 300 m and transport observations at isolated moorings.

Control vector = boundary conditions
Preliminary adjoint sensitivity experiments indicate that:

- a number of locations of primary dynamical importance do exist in the Northern Bering Sea. These locations are optimal for mooring deployment in the sense of the reconstruction of the circulation and the Bering Strait transport.

- if the Bering Strait transport is monitored with only one mooring, the best placement is in the US EZ in the Strait.

- the preference location of an HF radar in the Kotsebu Bay is at Kivalina. Two HFRs (in Kivalina and Shishmaref) provide a considerable improvement of the circulation reconstruction.

- In the open AO, a North Pole mooring constrains transport through the Canadian Archipelago, whereas moorings in the Beaufort Gyre control the flow through both the Canadian and the Chuckchi Sea regions.
If proposed research is successfully accomplished. What is possible influence on optimization of AON design and implementation?

Do you see directions for future extension of the proposed research in the context of optimization of AON design and implementation?

What are limitations of the proposed approach that you would suggest to address in the future?

Is it feasible to formulate TQs during the planning stage of observational program?

Is it reasonable to evaluate the existing observational arrays using the proposed approach?

Is sensitivity analysis more applicable to the processes study than to optimization of observations?