Toward reanalysis of the Arctic Climate System – sea ice and ocean reconstruction with data assimilation

Summary

The major goal of this project was to develop an integrated set of data assimilation procedures for the ice–ocean system that is able to provide gridded data sets that are physically consistent and constrained to the observations of sea ice and ocean parameters. The project uses modern four-dimensional variational (4D-Var, adjoint) data assimilation methods. Sea ice and ocean models with new data assimilation procedures were employed to maximize the integration of model results with observations and thus attempt to provide the arctic research community with complete and accurate data sets for 3 different climate regimes, namely: 1972-1978, 1989-1996, and 1997-2006. The reconstructed monthly mean water temperature, salinity and currents at standard for above mentioned climate regimes are provided in figures and in gridded digital form. Further information is posted at the project Web site:
http://www.whoi.edu/projects/AOREC

Citing These Data

Proshutinsky, Andrey. 2010. Toward reanalysis of the Arctic Climate System – sea ice and ocean reconstruction with data assimilation, Boulder, CO: National Center for Atmospheric Research, ARCSS Data Archive.

Overview Table

Category	Description
Data format	Data are in space-delimited ASCII format.
Spatial coverage and resolution	Data were simulated employing sea ice and ocean models with 4D-var data assimilation procedures covering the entire Arctic Ocean with a horizontal resolution of approximately 55 km at 18 standard ocean levels Southernmost latitude: 68° N Northernmost latitude: 90° N Westernmost latitude: 180° W Easternmost latitude: 180° E Standard levels: 5, 10,15,20,25,30,50,75,100,150,200,250,300,400,500,750,1000,1500 m
Temporal	Monthly mean data averaged for 1972-1978, 1989-1996, and 1997-2006

coverage	
File naming convention	Each file is named to identify the parameters and period of recontruction: Salinity files: salinity-1972-1978, salinity-1989-1996, salinity-1997-2006 Temperature files: temperature-1972-1978, temperature-1989-1996, temperature-1997-2006 Currents files: currents-1972-198, currents-1989-1996,currents1997-2006
File size	Files size range from 35 MB for salinity and temperature to 70 MB for currents. Total data volume is approximately 420 MB.
Parameter(s)	Depth, temperature, salinity, U and V components of velocity
Procedures for obtaining data	Data are available for ordering through NCAR.

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1. Contacts and Acknowledgments

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2. Detailed Data Description

Format

Data are in zip archives by time period, which when unzipped yield three data files in uncompressed, space-delimited ASCII format. Each file contains formatted information for 12 months at 18 standard levels.

File and Directory Structure

Data are contained in three directories: 1972-1978, 1989-1996 and 1997-2006

Each directory includes three data files containing monthly ocean parameters and a README file containing information about how to read data. Files include header rows identifying month and ocean level.

File Naming Convention

Each file is named to identify the parameter and reconstructed period:
parameter-YYY1-YYY2, where "parameter" is salinity, temperature or currents, YYY1 and YYY2 – years identifying climate period.

File Size

Files range in size from 35 MB to 70 MB. Total data volume is approximately 420 MB.

Spatial Coverage

Data covers the entire Arctic Ocean domain

Southernmost latitude: 68°N
Northernmost latitude: 90°N
Westernmost latitude: 180°W
Easternmost latitude: 180°E

Spatial Resolution

Data were reconstructed at horizontal resolution of between 30 to 40 km and vertical resolution with levels: 2.5, 7.5, 12.5, 17.5, 22.5, 27.5, 33.0, 39.5, 47.0, 55.5, 65.0, 75.715, 90.68, 113.665, 146.815, 192.645, 254.06, 334.31, 436.925, 565.705, 724.585, 917.485, 1148.085, 1419.7, 1737.065, 2108.895, 2542.395, 3041.73, 3613.145, 4262.90, 5000.00 meters. These data were interpolated to the grid with horizontal resolution of 55.5 km and standard vertical levels: 5.,10.,15.,20.,25.,30.,50.,75.,100.,150.,200.,250.,300., 400.,500.,750.,1000.,1500 meters. The interpolated results are presented here in the data files.

Temporal Coverage

Reconstructed data (monthly mean averaged for climate regime periods) covers 1972-1978, 1989-1996 and 1997-2006.

Parameter or Variable

Parameter Description

Depth/Level (m)
Temperature in situ (deg C)
Salinity
Currents (U and V components, cm/s)

Sample Data Record

Salinity file content:

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888.000  888.000  888.000  888.000  888.000
888.000  888.000  888.000  888.000  888.000
  888.000  888.000  888.000  888.000  888.000  888.000  888.000
888.000  888.000  888.000
  888.000  888.000  888.000  888.000  888.000  888.000  888.000
888.000  888.000  888.000
  888.000  888.000  888.000  888.000  888.000  888.000  888.000
888.000  888.000  888.000
   33.014   32.989   32.963   32.894   32.825   32.743   32.676
32.705   32.700   32.661
   32.658   32.676   32.682   32.680   32.697   32.747   32.784
32.803   32.836   32.969
   32.979   33.075   33.169   33.355   33.494   33.700   33.872
33.940   34.007   34.096
```

```
   34.170   34.188   34.188   34.180   34.156   34.179   34.183
34.163   34.132   34.105
  888.000   34.302   34.315   34.357  888.000  888.000  888.000
888.000  888.000  888.000
  888.000  888.000  888.000  888.000  888.000  888.000  888.000
888.000  888.000  888.000
  888.000  888.000  888.000  888.000  888.000  888.000  888.000
888.000  888.000  888.000
  888.000  888.000  888.000  888.000  888.000  888.000  888.000
888.000  888.000  888.000
  888.000  888.000  888.000  888.000  888.000  888.000  888.000
888.000  888.000  888.000
  888.000  888.000  888.000  888.000  888.000
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Error Sources

N/A

3. Data Access and Tools

Data Access

Data are available via FTP.

Volume

Total data volume is approximately 420 MB.

Related Data Collections

N/A

4. Data Acquisition and Processing

The Arctic Ocean is covered by sea-ice year round. Ideally, the data assimilation procedure should take into account ice-ocean interactions and the data assimilation algorithm should be designed for a sea-ice – ocean coupled model system. Development of a 4D-var data assimilation procedure for such coupled ice-ocean system is not straightforward. Strong non-linearity of the sea-ice dynamics complicates development of a stable adjoint model and results in low controllability of the sea-ice model. Effectively, dynamical complexity of these coupled ice-ocean system may limit applicability of 4D-var data assimilation methods for long time period integration intervals. Thus, to avoid such technical problems, we use a set of simplified sub-optimal data assimilation methods described below (see Figure 1).

Pan-Arctic Ice-Ocean Modeling and Assimilation System

The sea-ice data are assimilated by the Pan-Arctic Ice-Ocean Modeling and Assimilation System (PIOMAS) developed at the Polar Science Center, University of Washington (see *Zhang and Rothrock* [2001, 2003, 2005]). The PIOMAS is a coupled parallel ocean and sea-ice model with capabilities of assimilating sea ice concentration. It consists of the thickness and enthalpy distribution (TED) sea-ice model developed by *Zhang and Rothrock* [2001, 2003] and the Parallel Ocean Program (POP) developed at the Los Alamos National Laboratory. The TED sea-ice model is a dynamic thermodynamic model that also explicitly simulates sea-ice ridging. It has 12 categories each for ice thickness, ice enthalpy, and snow. The model employs a teardrop viscous-plastic ice rheology that determines the relationship between ice internal stress and ice deformation (see *Zhang and Rothrock* [2005]), a mechanical redistribution function that determines ice ridging (see *Thorndike et al.* [1975], *Rothrock* [1979], *Hibler,* [1980]) and an efficient numerical method to solve the ice motion equation [*Zhang and Hibler*,1997]). Assimilation of sea ice concentration data from satellites in PIOMAS is based on an assimilation procedure [*Lindsay and Zhang*, 2006] that "nudges" the model estimate of ice concentration toward the observed concentration in a manner that emphasizes the ice extent and minimizes the effect of observational errors in the interior of the ice pack. This is a relatively simple yet effective assimilation scheme that is computationally affordable for long-term integrations and experiments. In addition to improving the simulated ice edge, comparisons to observed ice thickness measurements in the Arctic indicate that the assimilation of ice data also improves the simulated ice motion and thickness.

Semi-implicit ocean model

Oceanographic observations are assimilated into Semi-Implicit Ocean Model (SIOM) data assimilation system. SIOM is a modification of the C-grid, z-coordinate OGCM (Ocean Global Circulation Model) developed in *Laboratoire d'Oceanographie Dynamique et de Climatologie* [*Madec et al*., 1999]. This model was designed specifically for the implementation of 4D-var methods into regional models controlled by fluxes at the open model boundaries and sea surface. The model is semi-implicit both for barotropic and baroclinic modes permitting simulations with relatively large time steps of approximately 0.1 day [*Nechaev et al*., 2005, *Panteleev et al*., 2006a,b]. The tangent linear model was obtained by direct differentiation of the forward model code. The adjoint code of the model was built analytically by transposition of the operator of the tangent linear model, linearized in the vicinity of the given solution of the forward model [*Wunsch*, 1996]. The details of the SIOM numerical scheme can be found in *Nechaev et al*. [2005].

Model configurations and assimilating system coupling

The PIOMAS is configured to cover the region north of 43°N with mean horizontal resolution of approximately 22 km (Figure 2). The model is one-way nested to a Global Ice-Ocean Modeling and Assimilation System which consists of similar sea ice and ocean models [*Zhang*, 2005]. The SIOM was configured for the domain shown in Figure 3. The SIOM's grid has a horizontal resolution of 75 km. The original version of SIOM does not have sea-ice model, but is able to assimilate the momentum, heat and salt fluxes between ice and ocean. We use this possibility in implementation of a two-step data assimilation algorithm to avoid problems associated with the strong non-linearity of sea-ice dynamics discussed above.

At the first step of the algorithm, we run PIOMAS for the entire Arctic Ocean domain and PIOMAS assimilates sea ice concentration data and simulates sea ice and water dynamics. At the 2^{nd} step, the SIOM assimilates external forcing provided by PIOMAS output over the SIOM domain (surface heat, salt and momentum fluxes) and all available hydrographic data (water temperature, salinity, velocity) employing a conventional 4D-var data assimilation procedure that ensures dynamical consistency of the ocean model solution ([*Nechaev et al*., 2005, *Panteleev et al*., 2006a,b). To reduce the number of "unknowns" in the 4-Dvar data assimilation procedure, the time variability of the SIOM forcing fields and the functions specifying the open boundary conditions is approximated by piece-wise linear continuous functions of time on 3-day intervals. The final product of the data assimilation system includes reconstructed patterns of circulation and water T&S fields stored at the end of every 10th day of the SIOM integration.

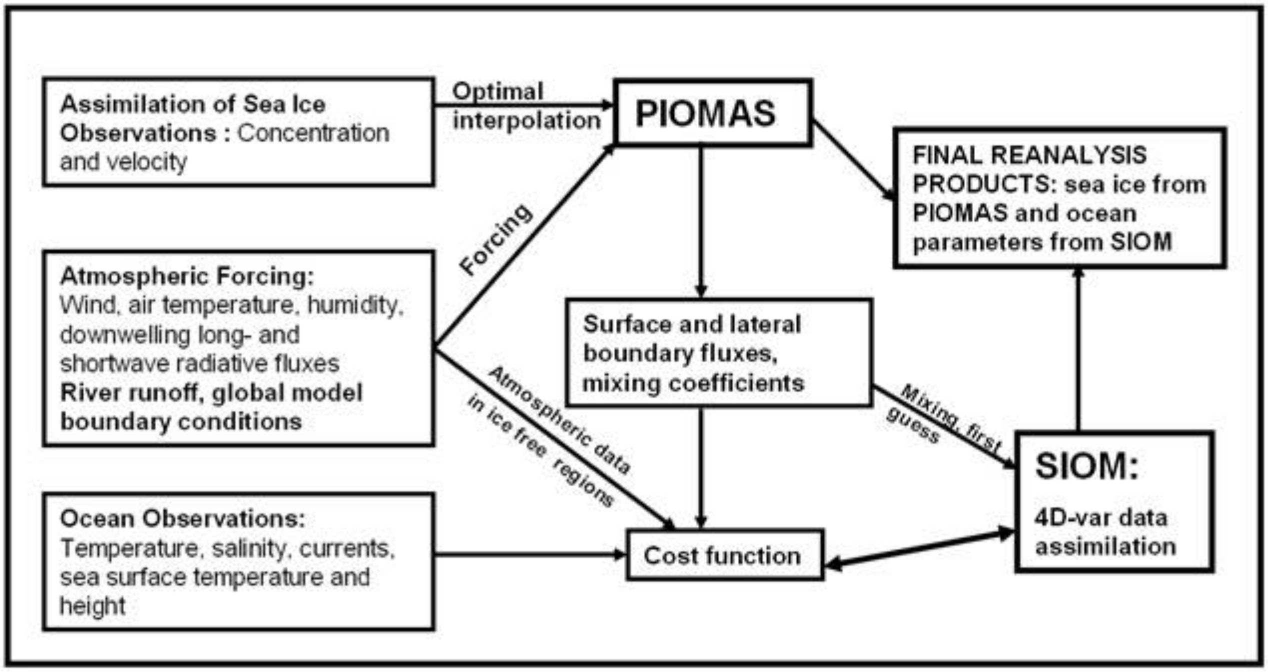

Figure 1. Data flow chart for the data assimilation procedure.

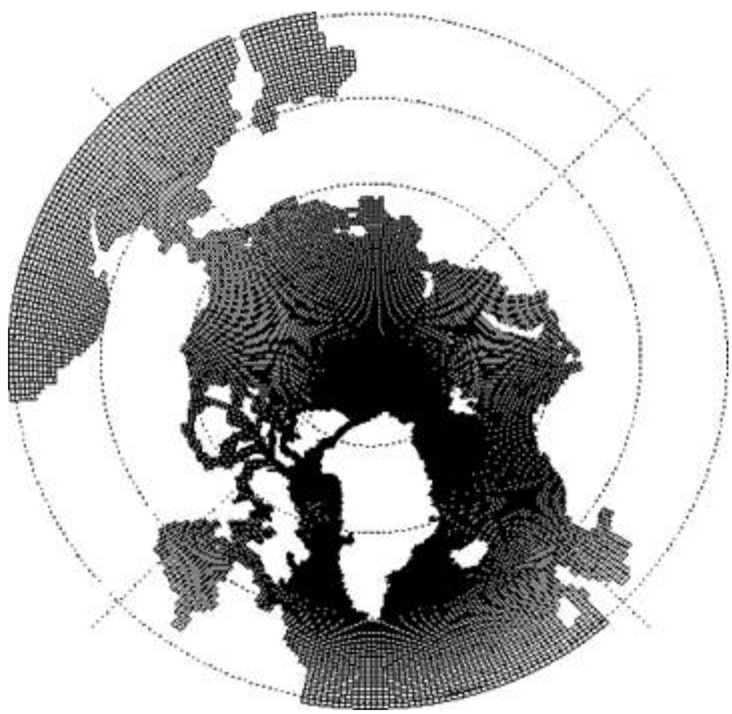

Figure 2. PIOMAS model domain

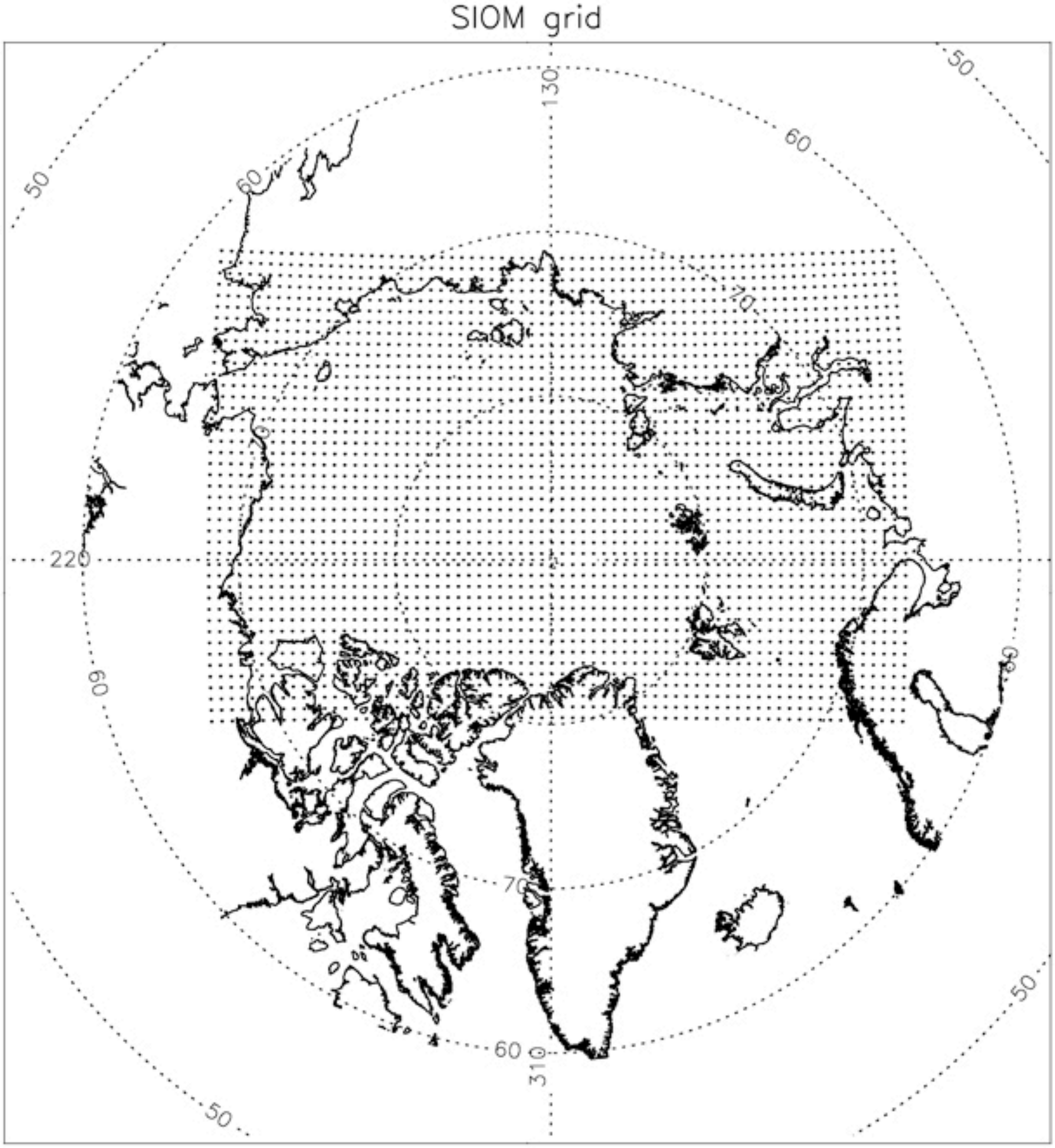

Figure 3. SIOM model domain

Data sources

PIOMAS is driven by atmospheric forcing applied to the ocean and ice surface and assimilates sea ice concentration and drift.

SIOM uses all available ocean hydrography and current data for assimilation and is forced by data from PIOMAS at the ocean-ice surface. The major sources of data needed for model forcing and assimilation are outlined below.

Atmospheric forcing data

Atmospheric forcing data is needed for both PIOMAS and SIOM. These data are taken from the ERA-40 Reanalysis through 2001 and the ECMWF operational analysis after that. The fields we need are daily averages of the 10-m wind vector, the 2-m air temperature and humidity, the sea level pressure, and the downwelling long- and shortwave radiative fluxes. The reason we select the ERA-40/ECMWF products over the NCEP reanalysis is that the downwelling radiative fluxes in the NCEP products are known to have large errors (Serreze *et al.*, 1998). Previous simulations often have used climatological cloud fractions and parameterized downwelling fluxes, but by using the ERA-40 fluxes we are able to include realistic interannual variability in the radiative fluxes. The ERA-40 downwelling fluxes compare very well to those measured during SHEBA (Liu *et al.*, 2005). Our analysis of the wind and temperatures of these products show there is no significant jump in their bias after 2001 when compared to NCEP products. Some inhomogeniety in the products may exist because of atmospheric model changes after 2001, but the changing mix of available observations during the entire reanalysis period also adds unavoidable inhomogeneities in the results.

Surface data

PIOMAS assimilates ice concentration (IC), ice velocity (IV), and wet-ocean sea-surface temperature (SST). The IC and SST data are obtained from the ERA-40/ECMWF data sets to insure that the air temperature, IC, and SST fields are mutually consistent. The source data from these fields are: 1) the monthly mean HadISST data set from the UKMO Hadley Centre for 1956-1981; and 2) the weekly NCEP 2D-VAR data for 1982-present (Reynolds *et al.*, 2002). Both data sets are based on satellite and conventional SST/IC observations. The principal reason for the higher quality of these source data sets is the use of a common consensus IC and a common IC-SST relationship in the sea ice margins. The most recent ECMWF SST fields are from new daily analyses made at NCEP. The IV are taken from the optimally interpolated ice velocity fields produced by Chuck Fowler and archived as a Polar Pathfinder dataset at NSIDC. They are derived from buoy, AVHRR, and passive microwave estimates of the ice velocity.

Ocean data

The adjoint data assimilation procedures of SIOM use a variety of ocean data including salinity, temperature, velocity, and sea surface height. The Arctic Ocean hydrographic data is sparse in temporal and spatial coverage. Recently, the climatology has expanded in two ways. First, historical hydrographic data have been declassified and released by both Russian and western sources in the form of smoothed, three-dimensionally gridded fields for summer and winter [Environmental Working Group Atlas, EWG, 1997, 1998]. This represents a significant advance but unfortunately, the data for these atlases were averaged for the decades of the 1950s, 1960s, 1970s and 1980s, irregardless of climatic regimes. Second, the arctic hydrography database has expanded recently due to an increase in the number of high-latitude cruises and the establishment of several long-term observational sites in key regions of the Arctic Ocean including major ocean boundaries (Bering Strait, Fram Strait, straits of the Canadian Archipelago, and in the central basin such as observations conducted in the vicinity of the North Pole (North Pole

Environmental Observatory, NPEO, http://psc.apl.washington.edu/northpole) and in the Western Arctic (Beaufort Gyre Observing System, BGOS, http://www.whoi.edu/beaufortgyre). In addition, there has been at least one major expedition by either icebreaker or submarine into the deep Arctic Ocean nearly every year between 1992 and 2005 (information about existing arctic hydrographic data is posted at the BGOS web site). Figure 4 shows distribution of hydrographic stations in space and time. These monthly gridded data with some spatial and temporal averaging are available at Digital hydrography data archive.

Other data include current velocity measured at moorings in the major Arctic Ocean straits and key regions of the deep basins. (Greg Holloway, personal communication).

Other sources include the Alfred Wegener Institute, the Polar Science Center, University of Washington, and Ohio State University). Significant amounts of data have already been incorporated into our data archives at WHOI. These data include climatologic information from the EWG atlas and specially selected and gridded T&S data provided by the scientists of the Arctic and Antarctic Research Institute, Russia, for different circulation regimes (http://www.whoi.edu/science/PO/arcticgroup/projects/andrey_project) and for particular years. Completely new data are available from the NPEO and BGOS observing systems. The mooring data from these observatories also includes an upward-looking ADCP at the top mooring float to measure ocean currents in the upper 50-m layer. For 2003/2004 we also collected T&S data in the upper 50-m ocean layer from four ocean buoys. Since 2004 the BGOS archive includes data from a new instrument, the Ice-Tethered Profiler (ITP), which repeatedly samples the properties in the upper 800 m of the ocean at high vertical resolution over long time periods. The instrument, its performance in the field, and examples of the data returned from the system are presented at http://www.whoi.edu/itp.

There also are numerous other sources of data containing water temperature and salinity fields; sea ice thickness, concentration, and drift; sea level; and ocean currents. These data are located in national data archives (NSIDC, ARCSS, NODC) and in local archives of different institutions of the project PIs. Most of the data archives are available publicly via the Internet. As part of this project we have collected and reprocessed all possible data from a variety of sources for the period 1950-2006 and prepared these data in a form suitable for assimilation procedures. The pre-processing procedures included: quality control and preliminary data analysis; data unification for data assimilation purposes including low-pass filtering and interpolation to model grids; estimation of typical spatial and temporal scales of variability; and obtaining physically meaningful estimates of the data error variance.

Reconstructed periods

We have reconstructed major oceanic parameters for three periods, namely: 1972-1978, 1989-1996, and 1997-2006. The periods for these circulation regimes were determined by Proshutinsky and Johnson [1997, updated, hereafter P&J]. The first period which we have reconstructed in this project is 1972-1978 was characterized by anticyclonic wind-driven forcing and circulation when the Arctic was relatively cold and there was a large quantity of hydrographic data available; the second is 1989-1996 (cyclonic circulation regime) when large changes begin in the Arctic Ocean circulation, in its hydrographic structure (freshwater release from the Arctic Ocean) and in sea ice conditions (thinning and reduction in concentration); and the third is 1997-2006 (also anticyclonic circulation regime) when substantial amounts of open water begin to appear in the late summer due to global warming and substantial changes in the Arctic climate have been detected in practically all environmental parameters and disciplines.

5. References and Related Publications

- http:/www.whoi.edu/projects/AOREC

Environmental Working Group, 1997, 1998. Joint U.S.-Russian Atlas of the Arctic Ocean (CD-ROM),Winter, Summer, National Snow and Ice Data Center, Boulder, Colorado, 1997 and 1998.

Hibler, W.D. III, 1980: Modeling a variable thickness sea ice cover. *Mon. Wea. Rev*., **108**, 1943-1973.

Lindsay, R. W. and J. Zhang, 2006a: Assimilation of ice concentration in an ice-ocean model. *J. Atmos. Ocean. Tech.*, **23**, 742-749.

Lindsay, R. W., and J. Zhang, 2006b: Arctic Ocean Ice Thickness: Modes of Variability and the Best Locations from Which to Monitor Them. Journal of Physical Oceanography, 36, 496-506.

Liu, J., J. A. Curry, W. B. Rossow, J. R. Key, X. Wang, 2005. Comparison of surface radiative flux data sets over the Arctic Ocean. *Journal of Geophysical Research*, Vol. 110,C02015,DOI: 10.1029/2004JC002381.

Madec, G., P. Delecluse, M. Imbard, C. Levy, 1999. OPA8.1 Ocean General Circulation Model. Reference Manual, Note du Pole modelisation, Institute Pierre-Simon Laplace (IPSL), France, 91pp.

Nechaev, D., G. Panteleev, M. Yaremchuk, 2005. Reconstruction of the circulation in the limited region with open boundaries: circulation in the Tsushima Strait. *Okeanologiya*, **45**(6), 805-828.

Panteleev, G., D. Nechaev, and M.Ikeda (2006a) Reconstruction of summer Barents Sea circulation from climatological data, Atmosphere-Ocean, 44(2), 111-132.

Panteleev, G. G., P. Stabeno, V. A. Luchin, D. A. Nechaev, and M. Ikeda (2006b), Summer transport estimates of the Kamchatka Current derived as a variational inverse of hydrophysical and surface drifter data, Geophys. Res. Lett., 33, L09609, doi:10.1029/2005GL024974.

Proshutinsky, A.Y. and M.A. Johnson. 1997. Two circulation regimes of the wind-driven Arctic Ocean. *J. Geophys. Res*. 102(C9 June 15): 12493–12514.

Reynolds, R. W., N. A. Rayner, T. M. Smith, D. C. Stokes, W. Wang, 2002. An Improved In Situ and Satellite SST Analysis for Climate*. J. Climate*, **15**, 1609-1625.

Rothrock, D.A., 1979. The energetics of the plastic deformation of pack ice by ridging. *J. Geophys. Res.*, **80**, 4514-4519.

Serreze, M.C., J. Box, and J. Key, 1998. A new monthly climatology of global radiation for the Arctic and comparisons with NCEP/NCAR reanalysis and ISCCP-C2 fields. *J. Climate*, **11**(2), 121-136.
Thorndike, A.S., D.A. Rothrock, G.A. Maykut and R. Colony, 1975. The thickness distribution of sea ice. *J. Geophys. Res.*, **80**, 4501-4513.

Wunsch, C., 1996. The Ocean Circulation Inverse Problem. *Cambridge University Press*, p. 442.

Zhang, J., and D. A. Rothrock, 2001. A thickness and enthalpy distribution sea-ice model. *J. Phys. Oceanogr.,* **31**, 2986–3001.

Zhang, J., and D. A. Rothrock, 2003. Modeling global sea ice with a thickness and enthalpy distribution model in generalized curvilinear coordinates. *Mon. Wea. Rev*., **131***(5)*, 681–697.

Zhang, J., and D. A. Rothrock, 2005. The effect of sea-ice rheology in numerical investigations of climate. *J. Geophys. Res.,* **110**, C08014, doi:10.1029/2004JC002599.

6. Document Information

Glossary and Acronyms

Please see the EOSDIS Glossary of Terms for a general list of terms.

List of Acronyms

The following acronyms are used in this document:

ARCSS: Arctic System Science
ASCII: American Standard Code for Information Interchange
CTD: Conductivity, Temperature, Depth
FSAO: Freshwater Switchyard of the Arctic Ocean
FTP: File Transfer Protocol
NPEO: North Pole Environmental Observatory
NSF: National Science Foundation
NCAR: National Center for Atmospheric Research
OPP: Office of Polar Programs
URL: Uniform Resource Locator

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