Final Performance Report

Seasonal Ice Zone Reconnaissance Surveys Coordination and Ocean Profiles

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LONG-TERM GOALS

This grant with extensions has been for the coordination of and participation in the Seasonal Ice Zone Reconnaissance Surveys (SIZRS) program from the latter half of 2019 through FY 2021 with extension into 2022 to cover organization and venue of the of the CLIVAR Circulation of the Arctic Ocean and Sub-Arctic Seas Workshop. Some activities in 2019-2021 are also covered in the final technical report for the preceding grant, N00014-15-1-2295. SIZRS is a multi-investigator program of repeated ocean, ice, and atmospheric measurements. These measurements make use of U.S. Coast Guard flights across the Beaufort seasonal sea ice zone (SIZ), the region between maximum winter ice extent and minimum summer ice extent. The long-term goal of SIZRS is to track and understand the interplay among the ice, atmosphere, and ocean, contributing to the rapid decline in summer ice extent.

During this grant period our goals expanded to understanding the nature of near-surface circulation change over the whole Arctic Ocean and the implications for Arctic Ocean observing. This effort informed discussions at the CLIVAR Workshop and funds from this grant were put towards the venue for workshop held at the University of Washington.

Methodology

The fundamental SIZRS approach is to make monthly flights, June to October, with US Coast Guard Air Station Kodiak C-130s across the Beaufort Sea Seasonal Ice Zone (SIZ), e.g., along 150°W from 72°N to the maximum of 76°N or beyond the ice edge. We make oceanography stations every degree of latitude by dropping Aircraft Expendable CTDs (AXCTD) and Aircraft Expendable Current Profilers (AXCP) typically while traveling northbound (PI: J. Morison). On the return leg, we drop atmospheric dropsondes from 3000 meters altitude to measure atmospheric temperature, humidity, and winds (SIZRS PI: A. Schweiger). We also drop UpTempO drifting buoys that report time series of ocean temperature profiles (SIZRS PI: M.

Steele) and various meteorology and ice-tracking buoys of the International Arctic Buoy Program (IABP PI: I. Rigor).

In addition to overall coordination of SIZRS, this grant has covered the profile measurements of ocean temperature, salinity, velocity, and mixing across the SIZ that are core components of the SIZRS field campaigns. Our objective is to determine variations in ocean characteristics across the SIZ and how these relate to small- to mesoscale ice and ocean processes; to the larger-scale ocean processes of the Beaufort Sea; and ultimately to the variations in Arctic Ocean and atmospheric circulation.

Accomplishments

In over a total of 43 flights through 2019, more than 260 Aircraft eXpendable CTD (AXCTD) and Current Profiler (AXCP) profiles were recorded, with an estimated 95% instrument success rate. SIZRS has also deployed numerous meteorological buoys for the International Arctic Buoy Program (IABP). The 2012-2019 SIZRS data show a Beaufort Sea that warmed and freshened at the surface. Individual sections have shown freshening and warming associated with a receding ice edge, as well as a layer of Pacific inflow (50-80 m) similarly warming and freshening. The month-to-month variations are consistent in their connection to ice edge retreat [*Dewey et al.*, 2017]. As the ice edge retreats, it leaves a layer of freshened open water that is warmed by solar heating. The pattern at any one location was consistent with simulations using a Price-Weller-Pinkel 1-D mixing model [*Dewey et al.*, 2017] and became stronger likely due to recent increases in ice melt-back. These variations have been set within a changing Beaufort Gyre circulation. Model and observational evidence have indicated that over the last 15 years, the intensity of the Beaufort Gyre increased and stabilized [*Zhang et al.*, 2016]. We have found by including the ocean surface velocity derived from CryoSat-2 altimetry in the ice-ocean stress calculation, that under anticyclonic wind stress, the Beaufort Gyre spins up until ocean velocity exceeds ice velocity retarded by internal ice stress. This negative feedback is responsible for stabilizing the gyre spin up. The time scale of gyre energy dissipation due to this process is on the order of days to 1 or 2 months versus the 6-year scale of dissipation by eddy generation [*Manucharyan and Spall*, 2016].

Our SIZRS graduate student, Sarah Dewey, received her Ph.D., in August 2019. Also, as in 2017 and 2018, working with CAPT Dr. Shawn Gallaher (USNA), in 2019 we again had US Naval Academy midshipmen as summer interns, took them on SIZRS deployments, and sourced their senior projects [*Alleyne et al.*, 2018; *Cecchini et al.*, 2018; *Sweeney et al.*, 2020].

Recent Accomplishments

Field work in 2020 was severely impacted by the COVID-19 pandemic. The COVID-19 pandemic Alaska travel restrictions kept us from getting to Kodiak, but we were able to hire a Kodiak resident, Dave Knight, to go on a September 2020 flight with the Coast Guard during which the crew dropped ALAMO floats belonging to Steve Jayne for profiles at 76°N, 78°N, and 80°N, 150°W in place of our most northern AXCTD stations. We also provided four of our 2020 AXCTDs for the NOAA PMEL Arctic Heat project to drop at 71.6°N, 72°N, 72.5°N, and 73°N, 150°W. The SIZRS – Coast Guard – Arctic Heat collaboration yielded an oceanographic section across the SIZ at the time of the near record sea ice minimum.

In 2021, were able to resume Coast Guard flights with missions June 9 and July 21 with stations at 72°N to 76°N on 150°W. We were able to take one US Naval Academy midshipman as an intern on our June 9 flight. We performed a section on August 25 from 72°N to 77°N, and final 2021 section September 29 from 72°N to 78°N. We had planned a 2-day mission for the

August 24-25 period, with a section across the Makarov Basin on August 25, but an aircraft mechanical issue on August 24 forced the postponement of the planned section along 150°W to August 24 and the elimination of the flight to the Makarov Basin. However, the September 2021 and October 2021 flights proceeded as planned.

Field work in 2022 was covered under our present SIZRS grant (as will be 2023), However, owing to no cost extensions to the CLIVAR-related work, this grant contributed strongly to three publications we developed in 2020-2022 [*Guthrie and Morison*, 2021; *Morison et al.*, 2021; *Morison et al.*, 2022]. These cap years and even decades of research and motivate new foci our work. A fourth 2022 publication [*Hall et al.*, 2022] uses SIZRS salinity observations as ground truth for remotely sensed of sea surface salinity and ocean models of the Beaufort Sea.

The result of our internal wave modeling effort under ONR grant N000141612379 [*Guthrie and Morison*, 2021] addresses a key issue for the Stratified Ocean Dynamics of the Arctic (SODA) project, namely whether the historically low Arctic Ocean internal wave energies and background mixing would increase as sea ice diminishes and thus change the stratification. Our SIZRS AXCP data from ice-free conditions show no increase relative to ice-covered conditions. Clearly something besides the ice cover keeps Arctic Ocean internal wave energy and background mixing low. Our modeling result is that the low values of β (the variation of Coriolis parameter with latitude) characteristic of the Arctic, limit the amount of near inertial wave energy that propagates into the halocline and thus keeps internal wave energy and background mixing low even when no ice is present. This raises the question if background mixing is low, what controls stratification? We think the answer is shelf-basin interaction.

In trying to understand the connection between variations in the SIZ and interannual variability of the whole Arctic Ocean circulation, we have analyzed dynamic heights (DH) from Russian hydrography, 1950 to 1989, and SCICEX 1993 hydrography and dynamic ocean topography (DOT) from satellite altimetry, 2004 to 2019. Our work [*Morison et al.*, 2021] reveals that the dominant mode of variability in Arctic Ocean circulation, exemplified by the first EOF of sea surface height (Figure 1), is not the strength of the Beaufort Gyre, but a low in sea surface height with cyclonic circulation on the Russian side of the Arctic Ocean. When this mode of variation is in the positive (cyclonic) phase is superimposed on the mean surface height pattern characterized by the Beaufort Gyre, the result is a cyclonic mode circulation pattern expressed as an intensified but contracted Beaufort Gyre opposite a large trough with cyclonic circulation on the Eurasian side of Arctic Ocean. In *Morison et al*. [2021], we show that under the influence of an increased Arctic Oscillation (AO) index since 1989, the cyclonic mode has become more dominant, with associated losses of sea ice and freshwater and a weakening of the cold halocline layer that insulates sea ice from Atlantic Water heat.

Morison et al. [2022] combines the leading EOF result of *Morison et al.* [2021] with the records of drifting buoys tracked by the IABP from 2020 to 2022 to show (Figure 1) the Beaufort Sea sampling bias that has left the fundamental mode of circulation change with virtually no *in-situ* observations for the last two decades. Based the buoy records, the probability of finding a surface drifting buoy in the Makarov Basin at the heart of the principal EOF of DH and DOT change has been virtually zero, while the probability of finding a buoy in the Beaufort Gyre is around 60%. Part of this disparity is a natural consequence of the tendency for ice and buoys to diverge under cyclonic forcing and converge under anticyclonic forcing. A contributing factor is probably that it is much easier for ships to reach the Beaufort Sea than the Makarov Basin.

The CLIVAR The Observing, Modeling, and Understanding the Circulation of the Arctic Ocean and Sub-Arctic Seas Workshop

The CLIVAR workshop was held at the University of Washington Center for Urban Horticulture, June 2022. It brought together 75 scientists with a range of experience with the aim of understanding the changes in Arctic Ocean circulation and how to measure and model those changes. The organizing committee, which includes the PI on this grant as chair, Mary-Louise Timmermans from Yale University, Dmitry Dukhovskoy from the NOAA Center for Environmental Prediction, and Patrick Heimbach from the University of Texas, over a period of nine months developed the workshop report based on the presentations at the workshop and related publications. Seeing all these results together we were able to reconcile two prevailing visions of circulation changes that have developed over the last two or three decades and identify future priorities, challenges, and opportunities for research. The full report is extensive and is undergoing formatting and review by Mike Patterson and Sam Coakley at CLIVAR, but in view of ONR's important contribution to the workshop, the organizing committee has approved including the workshop report Executive Summary as a part of this grant's final report.

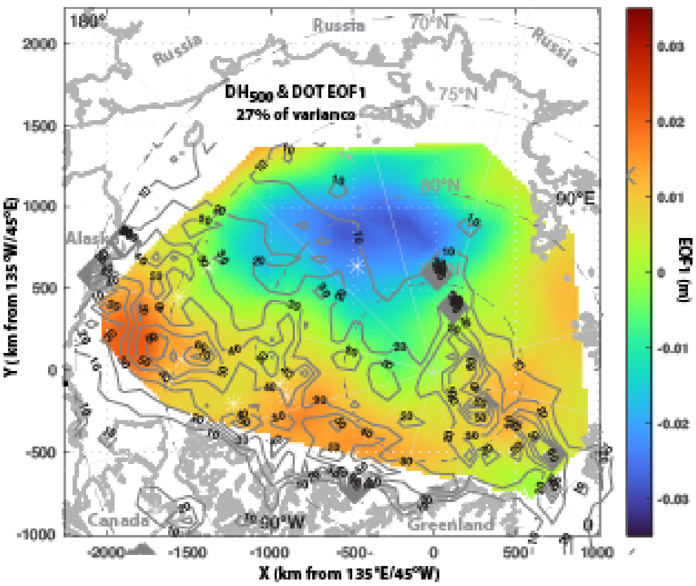

Figure 1 (CLIVAR workshop report Figure 6). Contours of the leading EOF of concatenated dynamic heights 1950-1989 and dynamic ocean topography 2004-2019 from *Morison et al.* [2021] with contours of the percent chance of finding an IABP buoy in a 250-km square based on buoy tracks from 2001 to 2021 [*Morison et al*.,2022; Rigor workshop presentation].

The CLIVAR Observing, Modeling, and Understanding the Circulation of the Arctic Ocean and Sub-Arctic Seas Workshop Report

James Morison, Mary-Louise Timmermans, Dmitry Dukhovskoy, and Patrick Heimbach

EXECUTIVE SUMMARY

The Observing, Modeling, and Understanding the Circulation of the Arctic Ocean and Sub-Arctic Seas Workshop has successfully reconciled two schools of thought on Arctic Ocean circulation changes and established the need for some new directions in observing and modeling those changes.

The Beaufort Gyre and Transpolar Drift have long been recognized as major features of the average surface circulation of the Arctic Ocean. In-situ hydrographic and buoy drift measurements over the last 20-30 years have revealed the anticyclonic or clockwise turning of the Beaufort Gyre has intensified. This has led to the sense that Arctic Ocean has become increasingly anticyclonic. However, satellite altimetry and gravimetry have shown major changes in circulation have emphasized a cyclonic or counterclockwise spin up on the Russian side of the Arctic Ocean, arguably associated with the cyclonic circulation in the atmosphere associated with the Arctic Oscillation (AO).

Recent comparisons of the satellite altimetry-measured sea surface height changes and sea surface height inferred from historical U.S. and Russian hydrographic records have shown that the average vorticity of the whole Arctic Ocean has become more cyclonic. They also indicate the dominant mode of variability has been the strength of a surface depression and cyclonic gyre centered over the Makarov Basin on the Russian side of the ocean, but with a halo of raised sea surface height and increased anticyclonic circulation on the Canadian side.

Thus, comparisons of results presented at the workshop indicate that the strengthening of anticyclonic circulation in the Beaufort Sea and strengthened cyclonic circulation in the Makarov Basin are two aspects of the same process. This concept of mutually reinforcing counterrotating gyres facing each other across the Transpolar Drift also resolves two seeming paradoxes: the Beaufort Gyre has intensified despite a weakening of the Beaufort High's anticyclonic atmospheric circulation, and at least on monthly time scales, the strength of the Beaufort Gyre has shown a positive correlation with the cyclonic Arctic Oscillation. One simple explanation is that basic kinematics require that while an atmospheric low-pressure pattern drives cyclonic surface stress curl, cyclonic ocean circulation, and divergence immediately under the low, there must be a peripheral halo of anticyclonic wind stress curl, anticyclonic ocean circulation and convergence. That the overall cyclonic mode pattern has strengthened and Arctic Ocean vorticity has increased are consistent with the one standard deviation elevation of the average AO since 1990, and the associated divergence of ice and ocean circulation is consistent with the basin-wide loss in sea ice over the same period.

The workshop showcased wide assortment of presentations on observations and modeling of the Arctic Oceans, and tremendous advances in both were apparent. Ship-based measurements continue to be critical for many measurements, but they are limited in how often and where they can be made. In-situ observations have benefited from tremendous advances in technology over the past 20 years that have improved the robustness, precision, and endurance of autonomous ocean measurement systems such as gliders (e.g., UW Seaglider), profiling floats (e.g., ALAMO Air-Launched Micro Observers), and autonomous vehicles (e.g., Saildrone). Ice-based measurement systems that drift with the sea ice and make measurements wherever the ice takes them have long been the mainstay of Arctic Ocean observing because they give real time measurement of atmospheric, ice, and water properties over long periods. Advances in ice-based profiling instruments like the ice-tethered profiler (ITP) provide measurements of temperature and salinity to depths up to 1,000 m and now include velocity measurements at high resolution. Expendable air-dropped probes such as the Aircraft eXpendable CTD (AXCTD) and Aircraft eXpendable Current Profiler (AXCP) allow oceanographic sections to be made from long-range aircraft.

Remote sensing measurements have long been important for estimating ice concentration and surface temperature. The new satellite altimeters ICESat, CryoSat-2, and now ICESat-2 have been critical in revealing ocean surface circulation over the whole Arctic Ocean, and with the GRACE and GRACE-FO satellite gravity measurements, yield estimates of freshwater content. The new SWOT satellite will bring fine resolution swath altimetry to part of the Arctic Ocean.

Modeling of the Arctic Ocean has improved dramatically. Particularly, model temporal and spatial resolution have improved to a degree not dreamed of 20 years ago. This is especially important for the Arctic because the reduced Rossby radius of deformation there requires fine resolution to get good model-to-model and model-to-observation comparisons. The wider use of improved data assimilation is critical to estimating ocean properties over time especially in under-sampled regions. Despite these improvements, modeling challenges remain for example in accurately modeling the salinity changes critical to Arctic Ocean density structure and freshwater content. Also, while model ice characteristics such as spatial distribution are realistic in winter, during summer simulated ice concentration and thickness are too low compared to satellite-based estimates. There is also that concern that the Arctic Ocean historical climatologies being assimilated into models may not represent present conditions leading to biased results. This is consistent with perhaps the most important finding of the workshop.

We urgently need to increase repeat *in-situ* observations of the Russian side of the Arctic Ocean. In spite of the east longitudes of the Arctic Ocean being the center of action of circulation change, the region has been very rarely sampled by any type of autonomous drifting platform over the last 20-years. The last hydrographic section across the Makarov Basin at the center of this region was the cruise of the *USS Pargo* 30 years ago. There are several reasons for this. The Makarov Basin is especially remote, so it is operationally hard to make sections and deploy buoys there. Further, especially in recent years, the region has been dominated by cyclonic surface circulation associated with wind-driven ice divergence, so that while drifting buoys tend to remain in the relatively well-sampled anticyclonic Beaufort Gyre, they tend to leave the cyclonic circulation of the Makarov Basin, rendering the most change sensitive region virtually unobserved except by remote sensing.

Increasing *in-situ* sampling on the Russian side of the Arctic Ocean to achieve a geographically balanced observing system is needed along with remote sensing to better-track the modes of surface circulation change and uniquely, to understand their consequences below the surface for example on freshwater content, freshwater pathways, shelf-basin interaction, the strength of the cold halocline, and Atlantic Water circulation. A key concern raised at the workshop was the currency of climatologies used in data assimilations. Conversely, model-based experimental design is problematic if it isn't based on current estimates of where variability is high. Thus, a more geographically balanced observing system goes hand in hand with improved data assimilation and modeling.

Expanding our observing system to include the Russian side of the Arctic Ocean will not be easy, especially given recent changes in our relations with Russia, but we have the instrumental and logistical capabilities to do it. The situation cries out for an interagency effort that will benefit the data and research needs of all the agencies and take advantage of each agency's operational resources. For example, the Coast Guard, DOD, NASA, and NOAA all have long-range aircraft that can reach the Makarov Basin to do various mixtures of aircraft remote sensing, buoy deployments, and hydrographic sampling with expendable probes. Coast Guard icebreakers could be making sections across the Makarov Basin that are comparable in terms of difficulty to cruises they make now to the North Pole. The SCICEX submarine science of opportunity cruises could be invigorated with an interagency plan to observe the east longitudes of the Arctic Ocean. An interagency effort could help harmonize the remote sensing efforts and in-situ observations to the great advantage of both. Sampling opportunities under such an interagency effort will potentially benefit all branches of Arctic oceanographic and atmospheric science.

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14. ABSTRACT
We proposed an extension and supplementation of the grant for the coordination of and participation in the Seasonal Ice Zone Reconnaissance Surveys (SIZRS) program through 7/31/2021 with anticipation of a new proposal to continue SIZRS operations at some level beyond 2021. In addition to covering the extension of SIZRS field activities and analysis, the supplemental support will cover a portion of the U.S. CLIVAR Workshop on Observing, Modeling, and Understanding the Circulation of the Arctic Ocean and Sub-Arctic Seas to be held in Seattle in the summer of 2020.

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