REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
04/01/2022

2. REPORT TYPE
Final Technical

3. DATES COVERED *(From - To)*
10/1/2016 - 12/31/2021

4. TITLE AND SUBTITLE
Atmospheric Profiles, Clouds, and the Evolution of Sea Ice Cover in the Beaufort Sea Atmospheric Observations and Modeling as Part of the Seasonal Ice Zone Reconnaissance Surveys

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-17-1-3162

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
875 North Randolph Street
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)
ONR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT:

Distribution Statement A: Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The goal of this project is to examine the role of sea-ice and atmospheric interactions in the retreat of the SIZ. As sea ice retreats further, changes in lower atmospheric temperature, humidity, winds, and clouds are likely to result from changed sea ice concentrations and ocean temperatures. These changes in turn will affect the evolution of the SIZ. An appropriate representation of this feedback loop in models is critical if we want to advance prediction skill in the SIZ. To do so, we will conduct a combination of targeted measurements and modeling experiments as part of the atmospheric component of the Seasonal Ice Zone Reconnaissance Survey project (SIZRS). Combined with oceanographic and sea ice components of the SIZRS project, this project provides a multi-year observational and modeling framework that advanced our understanding of the variability of the seasonal ice zone.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Axel Schweiger
Unclassified	Unclassified	Unclassified	UU		**19b. TELEPHONE NUMBER** *(include area code)* (206) 543-1300

Final Report for ONR Grant N00014-17-1-3162

Atmospheric Profiles, Clouds and The Evolution of Sea Ice Cover in the Beaufort Sea: Atmospheric Observations and Modeling as Part of the Seasonal Ice Zone Reconnaissance Surveys

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Distribution Statement

What were the major goals and objectives of the project?

Goals The goal of this project is to examine the role of sea-ice and atmospheric interactions in the retreat of the SIZ. As sea ice retreats further, changes in lower atmospheric temperature, humidity, winds, and clouds are likely to result from changed sea ice concentrations and ocean temperatures. These changes in turn will affect the evolution of the SIZ. An appropriate representation of this feedback loop in models is critical if we want to advance prediction skill in the SIZ. To do so, we will conduct a combination of targeted measurements and modeling experiments as part of the atmospheric component of the Seasonal Ice Zone Reconnaissance Survey project (SIZRS). Combined with oceanographic and sea ice components of the SIZRS project, this project provides a multi-year observational and modeling framework that will advance our understanding of the variability of the seasonal ice zone and which is needed to improve predictions from daily to climate time scales
Objectives: Assess the ability of global atmospheric reanalyses and forecast models to reflect the details of the seasonal evolution of atmosphere-ice-ocean interactions in the Beaufort Sea SIZ through the use coordinated multi- year atmospheric, ice, ocean measurements, •investigate how regional meso-scale models can improve the representation of atmosphere-ice interactions in the SIZ spring through fall, •determine how changes in sea ice and sea surface conditions in the SIZ affect changes in cloud properties and cover, •develop novel instrumentation including low cost, expendable, air-deployed micro-aircraft to obtain temperature and humidity profiles and cloud top and base heights •Integrate atmospheric, oceanographic, and sea ice measurements and models to advance our understanding of seasonal ice zone variability.

Accomplishments

Field Experiments

- We developed a strong relationship with the USCG KODIAK, acquired and modified the necessary equipment, and obtained the necessary certifications from the USCG Air Craft Control Board (ACCB).

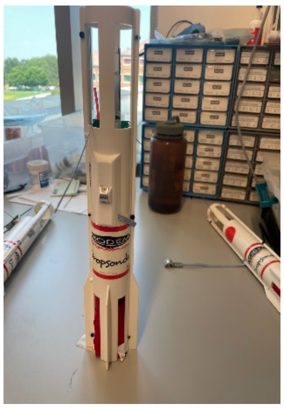
- From 2016-2021 we conducted 19 flights yielding 350 atmospheric profiles along the 150W and 140W longitude lines and across the ice edge with varying latitudinal ranges depending on the position of the ice edge from ~3000m altitude. The flight pattern across the ice edge was adjusted to a lower height (1700 m) to allow more dense sampling across the ice edge.Technology Development

Technology Development

Dropsonde System Evolution

We helped convert a commercial radiosonde (balloon system) into a dropsonde system. This adds another vendor to a very limited number of suppliers for dropsonde systems

IR Cloud Margin Drop Sonde



We designed and tested a dropsonde system that uses an IR sensor package to detect vertical cloud margins (cloud top/bottom) The IR cloud margin sensors on the GliderSonde have been refined through a design revision, and a large batch of the thermopile amplifier boards have been manufactured. These are ready for final assembly, and we plan to integrate them into conventional dropsondes as part of the routine deployments from the Coast Guard C-130 carried out by the SIZRS team. Modified dropsonde launches are planned for the SIZRS campaigns during 2019.

Glider Sonde

We experimented with designs for an expandable Glider Sonde with foldable wings that can be launched through a launch tube available on many military or research aircraft.The GliderSonde concept for deploying IR cloud margin sensors from a manned aircraft using a folding-wing glider is evolving in response to technical and regulatory challenges. A central issue has been obtaining permission to launch the GliderSonde. Although it is small and lightweight (about 1 lb.), it is classified as an unmanned aircraft system (UAS) by the FAA and is subject to stringent deconfliction measures in the National Airspace. An attempt was made to handle these concerns from the US Coast Guard (the original plan was to deploy GliderSonde from a USCG C-130) by launching in restricted airspace R-2204 near Oliktok Point, Alaska. Sandia National Laboratory manages this airspace, and we have worked with them extensively to fly ground-launched UAS in this location in the past. Although Aviation Safety Plans for GliderSonde use in R-2204 have been approved by Sandia, USCG approval was denied. As an alternative route for testing the design, we connected with the NOAA Arctic Heat to explore GliderSonde launches from the NOAA Twin Otter during the 2018 summer campaign north of Alaska. This change would have required significant design changes in the GliderSonde to accommodate a launch through the Twin-Otter launch tube. To ensure this path was viable, two “dummy” GliderSondes were sent to Alaska to conduct test drops from the Twin Otter sonobuoy tube. These drops were conducted in August, 2018, and performed well. Plans were then made to drop the GliderSonde in R-2204, and perhaps in the warning area W220 in the Beaufort Sea north of Oliktok, and the approval process was started at NOAA. Based on the prior approval from Sandia for R-2204, approval there was expected, but W220 was not in restricted airspace, and despite the ability to turn on the warning area as needed, it appeared that an FAA Certificate of Authorization would be needed there. This was problematic without some direct means of deconfliction (visual, radar, etc.).= Therefore an IOP request was submitted through Sandia to provide ground support for this effort in R-2204. During this time, University of Colorado DataHawk UAS were being used in R-2204 as part of the POPEYE campaign, and were experiencing unusual problems with Radio Frequency Interference (RFI) from the Air Force radar there, causing the DataHawk fleet to be grounded. Since the GliderSonde uses the same type of autopilot, this raised concerns that it could also be affected, effectively preventing GlilderSonde drops there until the problem could be diagnosed and mitigated. Thus, the efforts to deploy the GliderSonde have been unsuccessful to date.

Research and Results

Validation of Forecast and Reanalysis Models

We compared SIZRS profiles with Forecast models and Reanalysis data and dedicated regional atmospheric models. We found warm biases near the surface and a cold bias above. Changes in turbulent mixing schemes improve low level biases. Humidity biases are due to biases in global reanalysis/forecast fields **(Liu et al. 2015)**

Warm Air Advection and Melt Onset

We found that warm air advections from Alaska can play a significant role in melt onset and can affect surface type assignment in global forecast/reanalysis models (ECMWF). **(Liu and Schweiger, 2017)**

Sea Ice and Low Level Jets

We examined the role of sea ice on boundary layer profiles and the location of atmospheric Lower Level Jets (LLJ). We found that surface temperature contrasts affect wind speed at the level of LLJ. Sea ice strengthens the LLJ by pushing it northward over sea ice and increasing it by as much as 29%. Synoptic conditions are the primary reason for ice edge LLJs. A different mechanism for surface winds exists. Strong stratification over sea ice prohibits the transport of LLJ momentum down to the surface confining strong winds close to the ice edge **(Liu and Schweiger, 2019)**

Sea Ice Variability in the Last Ice Are

We examined the variability of sea ice in the so called Last Ice Area (LIA). An area of the Arctic that features thick sea ice. We found that the LIA is best separated into two regions (East/West). While both regions have been thinning, interannual variability can be out of sync **(Moore et al. 2019).**

High-Resolution Sea Ice Modeling

We investigated sea ice properties in high resolution sea ice models. Three Arctic sea ice-ocean models with varying high uniform horizontal resolutions of 6, 4, and 2 km for the whole Arctic Ocean were constructed. Sea ice thickness, concentration, velocity, deformation, and lead opening simulated by these high-resolution models over the period 2011-2018 were examined. Results from this investigation have been published in Journal of Geophysical Research **(Zhang, 2021)**.

Lead-Cloud Interactions

The conventional assumption of lead effects on clouds is that the heat and moisture fluxes from the leads will increase the amount of clouds due to the large surface contrast between open water and sea ice during the cold winter season. However, as the open lead freezes, the moisture flux is cut off drastically while the sensible heat flux is still large. This will heat and dry the atmospheric boundary layer and dissipate existing cloud cover. We combined the ICESat-2 sea ice height product (ATL07) and cloud product (ATL09) to examine the covariability of leads in the Arctic sea ice and cloud cover. The results show a clear signal of leads on cloud fraction. While large open leads tend to increase cloud cover, sensible heat flux from thin, refrozen leads tends to decrease cloud cover. This is potentially important feedback that is currently not accounted for in forecast and climate models. A paper describing this result is currently in review at Nature Communications **(Liu and Schweiger, in review)**.

Cloud Structure of Arctic Cyclone

Cloud structure of Arctic cyclones We implemented a Arctic cyclone (AC) tracking algorithm and established AC composites using the identified AC tracks from June 2006 to November 2017 using the ERA-interim reanalysis and cloud observations from CloudSat and CALIPSO (Fig. 2). Results show that mean AC composites are dominated by the axisymmetric equivalent baroctropic structure similar to the three long lasting summer ACs examined by Aizawa and Tanaka (2016). This agreement corroborates their argument that ACs, especially the long lasting ACs, are different from the mid-latitude cyclones in both structure and the role of TPV on their sustained development over the Arctic Ocean.

Sea Ice Model Improvement

The project contributed to the development of melt-pond and floe size parameterization schemes for PIOMAS. Satellite data were used to develop and validate parameterizations **(Zhang et al. 2016, 2018, Stern et al. 2018 a,b)**

Sea Ice Mass Budgets from Satellite and Models

We compared CryoSat derived sea ice mass budget (growth, advection) with two sea ice models. The results show that the ice growth feedback has been countering ice loss in some parts of the Arctic (Beaufort/Chukchi). An increased role of ocean heat flux associated with "Atlantification" has accelerated sea ice thinning on the Atlantic side of the Arctic **(Ricker et al. 2021)**

We contributed to a overview paper that inventories the contribution of sea ice loss to the global energy imbalance **(von Schuckman et al. 2020)**

Wandel Sea Polynyas

We examined two unusually large Polynyas that occurred in the Wandel Sea, an area of the LIA just north of Greenland, in February 2018 and in August of 2020. Unusually strong, offshore winds contributed to the formation of both Polynyas but while long term thinning contributed 20% to the summertime event **(Schweiger et al. 2020),** changing sea ice thickness appears to have played no role in the winter time event **(Moore et al. 2018)**. We also found that the thickness distribution, particularly the fraction of relatively thin ice was important in accelerating ice melt during the 2020 melt season in this region. This helped explain the formation of the Polynya in a year when initial sea ice thickness in spring was actually fairly normal for the recent period (Schweiger et al. 2020)

Sea Ice Variability and connections between the Beaufort Gyre and the Last Ice Area

The collapse of the climatological high pressure system over the Beaufort Sea and the associated reversal of the Gyre during winter of 2017 was attributed to thinning of sea ice which allowed storm system from the Atlantic side to penetrate further into the Arctic Basin **(Moore et al. 2018)**

We examined the role of sea ice transport within the Beaufort Gyre and between the Last Ice Area. Here we show that during the summers of 2020 and 2021, the Beaufort Sea hosted anomalously large concentrations of thick and old ice. We show that ice advection contributed to these anomalies, with 2020 dominated by eastward transport from the Chukchi Sea, and 2021 dominated by transport from the Last Ice Area to the north of Canada and Greenland. Since 2007 cool season (fall, winter, and spring) ice volume transport into the Beaufort Sea accounts for ~45% of the variability in early summer ice volume - a threefold increase from that associated with conditions prior to 2007 **(Moore et al, in review)**

SIDFEX Sea Ice Drift Forecast Experiment

The SIDFEX Experiment (Goessling et al. 2019), a multi-institutional international coordinated experiment to assess and improved sea ice drift forecasts, completed the 2021 season. The project contributed to the search for the Endurance. A paper summarizing the overall results is in preparation (Goessling et al. in prep)

SIPN Sea Ice Outlook

We completed a reforecast experiment that covers the period from 2000-2020. A derivative of the PIOMAS model is forced with NOAA CFSR/CSFv2 atmospheric forcing fields for a forecast period of 3 months. Forecasts are initialized monthly from June through September. Regional forecasts for subregions of the Arctic are completed. Results from the reforecast experiment are currently being analyzed as a group effort and a paper summarizing is in preparation (Bushuk et al. in prep).

What opportunities for training and professional development did the project provide?

The project provided field work and research opportunities for a a post-doctoral research associate (Zheng Liu). He is now and Senior Research Scientist with APL who has been developing his own research program.

How were the results disseminated to communities of interest?

The project yielded **15** peer reviewed papers and numerous presentations during workshops and conferences.

Products

Goessling, H. F., Tietsche, S., Reifenberg, S., & Schweiger, A. J. (2019). ECMWF joins Sea-Ice Drift Forecast Experiment. *ECMWF Newsletter, 158*.

Hunke, E., Allard, R., Blain, P., Blockley, E., Feltham, D., Fichefet, T., . . . Zhang, J. (2020). Should Sea-Ice Modeling Tools Designed for Climate Research Be Used for Short-Term Forecasting? *Current Climate Change Reports, 6*(4), 121-136. doi:10.1007/s40641-020-00162-y

Liu, Z., & Schweiger, A. (2017). Synoptic Conditions, Clouds, and Sea Ice Melt Onset in the Beaufort and Chukchi Seasonal Ice Zone. *Journal of Climate, 30*(17), 6999-7016. doi:10.1175/jcli-d-16-0887.1

Liu, Z., & Schweiger, A. (2019). Low-Level and Surface Wind Jets Near Sea Ice Edge in the Beaufort Sea in Late Autumn. *Journal of Geophysical Research: Atmospheres, 124*(13), 6873-6891. doi:10.1029/2018jd029770

Moore, G. W. K., Schweiger, A., Zhang, J., & Steele, M. (2018). Collapse of the 2017 Winter Beaufort High: A Response to Thinning Sea Ice? *Geophysical Research Letters, 0*(0). doi:doi:10.1002/2017GL076446

Moore, G. W. K., Schweiger, A., Zhang, J., & Steele, M. (2018). What Caused the Remarkable February 2018 North Greenland Polynya? *Geophysical Research Letters, 45*(24), 13342-13350. doi:10.1029/2018gl080902

Moore, G. W. K., Schweiger, A., Zhang, J., & Steele, M. (2019). Spatiotemporal Variability of Sea Ice in the Arctic's Last Ice Area. *Geophysical Research Letters, 46*(20), 11237-11243. doi:10.1029/2019gl083722

Moore, G.W.K, Steele, M., Schweiger, A., Zhang, J. (in review). Thin and thick ice in the Beaufort Sea: A new regime with enhanced mobility (in review at Nature Communications Earth and Environment)

Ricker, R., Kauker, F., Schweiger, A., Hendricks, S., Zhang, J., & Paul, S. (2021). Evidence for an increasing role of ocean heat in Arctic winter sea ice growth. *Journal of Climate*, 1-42. doi:10.1175/jcli-d-20-0848.

Schweiger, A. J., Steele, M., Zhang, J. L., Moore, G. W. K., & Laidre, K. L. (2021). Accelerated sea ice loss in the Wandel Sea points to a change in the Arctic's Last Ice Area. *Communications Earth & Environment, 2*(1). doi:10.1038/s43247-021-00197-5

Stern, H. L., Schweiger, A. J., Stark, M., Zhang, J. L., Steele, M., & Hwang, B. (2018). Seasonal evolution of the sea-ice floe size distribution in the Beaufort and Chukchi seas. *Elementa-Science of the Anthropocene, 6*. doi:10.1525/elementa.305

Stern, H. L., Schweiger, A. J., Zhang, J. L., & Steele, M. (2018). On reconciling disparate studies of the sea-ice floe size distribution. *Elementa-Science of the Anthropocene, 6*. doi:10.1525/elementa.304

von Schuckmann, K., Cheng, L., Palmer, M. D., Hansen, J., Tassone, C., Aich, V., . . . Wijffels, S. E. (2020). Heat stored in the Earth system: where does the energy go? *Earth Syst. Sci. Data, 12*(3), 2013-2041. doi:10.5194/essd-12-2013-2020

Zhang, J. L., Schweiger, A., Webster, M., Light, B., Steele, M., Ashjian, C., . . . Spitz, Y. (2018). Melt Pond Conditions on Declining Arctic Sea Ice Over 1979-2016: Model Development, Validation, and Results. *Journal of Geophysical Research-Oceans, 123*(11), 7983-8003. doi:10.1029/2018jc014298

Zhang, J. L., Schweiger, A., Webster, M., Light, B., Steele, M., Ashjian, C., . . . Spitz, Y. (2018). Melt Pond Conditions on Declining Arctic Sea Ice Over 1979-2016: Model Development, Validation, and Results. *Journal of Geophysical Research-Oceans, 123*(11), 7983-8003. doi:10.1029/2018jc014298

Zhang, J., Stern, H., Hwang, B., Schweiger, A., Steele, M., Stark, M., & Graber, H. C. (2016). Modeling the seasonal evolution of the Arctic sea ice floe size distribution. *Elementa: Science of the Anthropocene, 4*(1), 000126.

Zhang, J., Sea ice properties in high-resolution sea ice models. *Journal of Geophysical Research: Oceans*, *126*, e2020JC016686. https://doi. org/10.1029/2020JC016686, 2021.