

**Office of Naval Research (ONR), Arctic and Global Prediction Program  
Department Research Initiative (DRI),  
*Sea State and Boundary Layer Physics of the Emerging Arctic Ocean*  
Quantifying the Role of Atmospheric Forcing in Ice Edge Retreat and Advance  
Including Wind-Wave Coupling**

Peter S. Guest (NPS Technical Contact)  
Naval Postgraduate School  
589 Dyer Rd, Root Hall, Rm 254  
Monterey, CA 93943-5114  
831-595-8253, [pguest@nps.edu](mailto:pguest@nps.edu)

Christopher W. Fairall (NOAA Technical Contact)  
National Oceanic and Atmospheric Administration (NOAA)  
NOAA/ESRL, R/PSD3  
325 Broadway  
Boulder, CO 80303-3337  
303-497-6978, [chris.fairall@noaa.gov](mailto:chris.fairall@noaa.gov)

P. Ola G. Persson  
University of Colorado, Cooperative Institute for Research in Environmental Sciences (CIRES)  
NOAA/ESRL, R/PSD3  
325 Broadway  
Boulder, CO 80305-3337  
303-497-5078, [opersson@cires.colorado.edu](mailto:opersson@cires.colorado.edu)

Award Numbers: N0001413WX20830 (Guest)  
N0001413IP20046 (Fairall, Persson)  
[http://www.apl.washington.edu/project/project.php?id=arctic\\_sea\\_state](http://www.apl.washington.edu/project/project.php?id=arctic_sea_state)

## **LONG-TERM GOALS**

1. Representing surface fluxes and ocean waves in coupled models in the Beaufort and Chukchi Seas.
2. Understand the physics of heat and mass transfer from the ocean to the atmosphere.
3. Improve forecasting of waves on the open ocean and in the marginal ice zone.

## **OBJECTIVES**

We plan an integrated approach, in collaboration with other groups, to address the issue of representing surface fluxes and ocean waves in coupled models in the Beaufort and Chukchi Seas. The effort principally addresses the physics of heat and mass transfer from the ocean to the atmosphere, but our observations of turbulent stress, wave properties, and components of the momentum and energy flux

budgets will contribute to improvements in forecasting of waves on the open ocean and in the marginal ice zone.

1. Quantifying the open-ocean fluxes of momentum, sensible and latent heat, shortwave radiation, and longwave radiation in the Chukchi and Beaufort Seas.
2. Quantifying atmospheric and oceanic characteristics strongly linked to these fluxes, such as ocean wave characteristics and surface-layer temperature, atmospheric kinetic and thermodynamic profiles, atmospheric cloudiness and basic meteorological parameters.
3. Improving and verifying model parameterizations of turbulent momentum and heat fluxes, radiative fluxes, and wind-wave coupling in the Beaufort and Chukchi Seas.
4. Quantifying temporal and spatial variability in surface forcing as a function of fetch from ice edges.
5. Providing “ground truth” for remote sensing and other non-direct measurement techniques.

## APPROACH

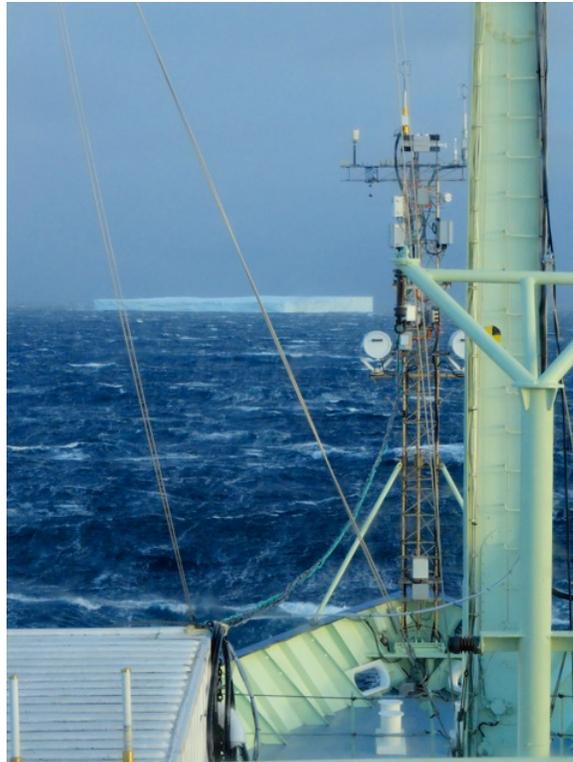
This research involves measurements from a ship platform. This will include direct covariance turbulent fluxes (including pressure-wave correlations), radiative fluxes, wave characteristics, and atmospheric boundary layer and troposphere profiles (see Table 1). These measurements are required to further our ability to predict sea state and oceanic boundary layer conditions in the future for these regions.

*Table 1. Shipboard Measurements*

| <i>Category – Parameters Measured</i>   | <b>Sensors</b>  |
|---|---|
| <i>Surface Meteorology – Wind Vector, Air Temperature, Air Humidity, Air Pressure, Precipitation</i>                  | <b>Propeller Anemometer, Aspirated and Shielded Thermistor/Humidity probes, Barometer, Tipping Bucket and Tympani Rain Sensor</b> |
| <i>Eddy Correlation Fluxes and Spectra – Wind Stress, Sensible + Latent (Moisture) Heat Flux, CO<sub>2</sub> Flux</i> | <b>Sonic Anemometer, Thermistor, LICOR (Humidity, CO<sub>2</sub>)</b>   |
| <i>Sky Radiation – Downwelling and Upwelling Solar and Longwave Radiation, Sky Temperature f(band)</i>                | <b>Pyranometer, pyrgeometer, narrow band IR radiometer, microwave radiometer,</b>   |
| <i>Surface Temperature – Ocean surface temperature, ice surface temperature</i>                                       | <b>IR Narrow Band Radiometer, Dragged Thermistor, Ship intake, Manual Bucket</b>  |
| <i>Tropospheric Profiles, 4/day – Pressure, Temperature, Humidity, Wind Vector</i>                                    | <b>Rawinsonde (Weather Balloon)</b>   |
| <i>Low-Level Profiles, Pressure, Temperature, Humidity</i>  | <b>Rawinsonde (Kite, Tethered Balloon and Miniature Quadrotor Unmanned Aerial Vehicle)</b>  |
| <i>Wave Characteristics, Wind wave and swell heights lengths, periods and surface wave 2-D spectra</i>                | <b>Multibeam laser altimeters, fast pressure sensors</b>  |
| <i>Cloud characteristics – cloud cover, cloud base height, water phase</i>  | <b>Ceilometer, W-band cloud radar</b>   |
| <i>Continuous wind vector profiles - low level wind field</i>   | <b>449 MHz wind profiler</b>  |
| <i>Observations, Upwind ice types and concentration, cloud type and coverage, sea state, visibility, weather</i>      | <b>Human eye, visible and IR photography, range finders</b>   |

## WORK COMPLETED

The field work for this project is planned for FY15, so the work completed so far has been primarily planning for the 2015 cruise, designing and ordering equipment, and testing sensors and sensors platforms in the lab and field, including three cruises of opportunity in the Arctic region described below. We have participated in the Sea State PI meetings, organized the future meeting in Monterey CA, and contributed to the Sea State Science Plan (Thomson et al., *Sea State and Boundary Layer Physics of the Emerging Arctic Ocean*). Other activities include designing a structure to mount instruments on the Sikuliaq bow mast and quantifying the accuracy of Unmanned Aerial Vehicle sensor platforms.



*Figure 1. View of the PSD flux mast aboard R/V Knorr in the Davis Strait during the HiWinGS cruise.*

## RESULTS

The FY14 cruises provide valuable data and are allowing us to test our observing technologies and methods in the harsh Arctic environment.

The HiWinGS (see Fig. 1) and ARCOSE14 cruises described below clearly showed deficiencies in conventional (unheated) T/RH systems and in the Gill (unheated) sonic anemometers we normally use. Heated sensors have been ordered for the Sea State deployment.

## IMPACT/APPLICATIONS

Since this project was started we have made progress refining our methods for performing measurements in harsh polar conditions which will impact the success of the 2015 Sea State DRI

cruise. More significant impacts on our understanding of sea state processes and the resulting implications are expected when the data are analyzed and presented after the cruise and in collaboration with the other participants.

## **RELATED PROJECTS**

We have participated in and contributed to the following cruises in polar regions which complemented and contributed to our the Sea State DRI planning and objectives.

**HiWinGS (High Wind GaS exchange study in the Labrador Sea, R/V Knorr).** This cruise was done in two legs 05 Sep – 04 Oct, Davis Strait and 10 Oct – 15 Nov 2013, Labrador Sea. PSD made air-sea flux and wave measurements. Other investigators made ocean turbulence and wave breaking observations.

**ARCOSE14 (Arctic Crossing 2014, R/V Mirai).** This cruise is conducted in the Bering and Chukcki Seas 1 Sep (Dutch Harbor) – 10 Oct 2014 (Japan). PSD is making air-sea flux measurements. There are a variety of observations by other groups from JAMSTEC.

**ACSE (2014 Swedish Arctic Clouds in Summer Experiment, R/V Oden).** This is a lengthy cruise on R/V Oden in the Arctic summer melt and freeze up seasons (03 Jul – 18 Aug and 20 Aug – 2 Oct 2014). PSD is making boundary layer and cloud observations. There are a variety of observations by other groups

Here are some details on the ACSE cruise which at the time of writing was currently underway.

During 2014, activities surrounding the Arctic Clouds in Summer Experiment (ACSE) had relevance to the Sea State project in several ways. ACSE was a 12-week "piggyback" atmospheric research program from July 5-Oct 4, 2014, on a cruise of the Swedish research ship Oden, whose primary scientific objectives were geologic and deep ocean in nature. The ACSE cruise spent approximately equal amounts of time in the open water of the Arctic Ocean and within the Arctic pack ice, with significant amounts of time spent in and crossing the marginal ice zone (MIZ). The first ACSE activity relevant to Sea State was an attempt by Sea State participants to acquire real-time SAR images during the Oden cruise to learn how to optimize the data acquisition and to communicate the time and place where the images are needed. The second aspect is that freeze-up conditions encountered and measurements made during ACSE can be used as a model for planning the Sea State field program. Thirdly, many measurements of the atmospheric boundary-layer, ocean and ice surface conditions, and upper ocean made during ACSE are similar to what will be attempted for Sea State, so their importance for Sea State can be evaluated. The meteorological instruments deployed during ACSE and meteorological data used are listed in Table 2.

**Table 2: Meteorological instrumentation deployed during ACSE on the Oden by the three main participants (Meteorological Institute at Stockholm University-MISU; University of Leeds, and CIRES/NOAA). Key ancillary weather and ocean data provided by other institutions are also listed.**

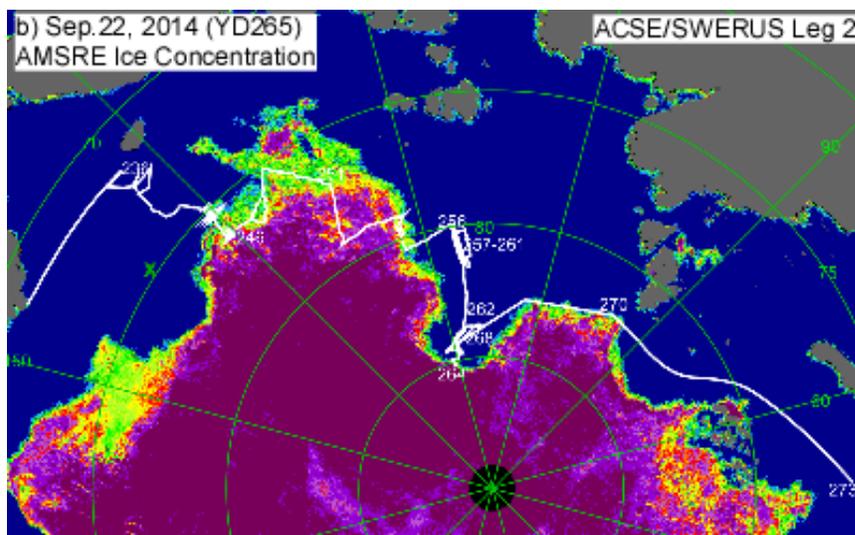
| <u>Instrument</u>                    | <u>Organization</u>              | <u>Measurement</u>                                   |
|--------------------------------------|----------------------------------|--|
| Stabilized W-band radar              | CIRES/NOAA                       | Cloud properties                                     |
| 449 MHz wind profiler                | CIRES/NOAA                       | hourly profiles of wind speed,/direction             |
| Sea snake                            | CIRES/NOAA                       | sea-surface temperature                              |
| 35-channel Radiometrics radiometer   | CIRES/NOAA                       | PWV, LWP, profiles of T, q                           |
| Ceilometer                           | CIRES/NOAA, MISU, Ship           | cloud base   |
| Flux tower with trims, motion sensor | Leeds, MISU                      | turbulent fluxes ( $H_s$ , $H_1$ , $\tau$ , $CO_2$ ) |
| CLASP                                | Leeds                            | aerosol size distribution                            |
| Stabilized, scanning Doppler Lidar   | Leeds                            | winds, cloud phase, turbulence                       |
| HATPRO, scanning, 12 ch radiometer   | Leeds                            | PWV, LWP, profiles of T, q                           |
| Rawinsondes - 4x daily               | MISU                             | profiles of T, RH, p & winds                         |
| IRT, up & down                       | MISU                             | surface and sky temperature                          |
| Broadband radiation                  | MISU                             | radiative fluxes                                     |
| Weather station                      | MISU                             | basic weather parameters, visibility                 |
| Webcams (3)                          | Leeds                            | local ice fraction, sea state                        |
| Waverider wave buoy                  | Leeds                            | directional wave-height spectra                      |
| Images of ship marine X-band radar   | Leeds, CIRES/NOAA                | local fetch, l precip structure, sea state           |
| Satellite (MODIS)                    | NOAA, NASA                       | large-scale weather, ice conditions                  |
| Satellite (SAR)                      | U Victoria, Bedford Inst. Ocean. | ice concentrations                                   |
| Ship data                            | Swedish Polar Inst.              | basic met, near-surface water T, salinity            |
| CTD/XBT casts                        | GU, SU/ Phys. Ocean.             | ocean temperature/salinity profiles                  |
| Surface forecasts                    | ECMWF, NOAA                      | 0-84 h sfc winds, slp, precip                        |

SAR images are typically needed to a) show the spatial ice distribution and ice-relative location of the point data being acquired; b) provide spatial distribution of derived parameters, such as wave state and winds, that can be related to the point measurements of these parameters, and c) for real-time use in navigation and short-term planning during the field program. The ACSE experience shows that the process of requesting and acquiring appropriate images is not trivial.

First of all, SAR images are needed to document the evolution of the ice, wave, and wind conditions, and different image types are needed for these, while only one type can be requested for each overpass. Hence, obtaining data/images from multiple satellites, such as both TerraSAR-X and Radarsat 2, is essential to obtain sufficient data for the various uses of these images in the post-analysis. Secondly, anticipating where the in-situ measurements will be made in order to place the SAR images over these sites depends strongly on the lead time required for the SAR requests and the other science priorities of the ship. For ACSE, the science priorities were not linked to the SAR images or the atmosphere/ocean/ice surface conditions, and hence the precise location of the ship at any time was dependent on what geologic or deep ocean features were being found just prior, with the atmospheric participants having no say in the movement of the ship. Combining this uncertainty with the 3-day lead time requirement for SAR requests made it practically impossible to locate the ship within the fine-scale stripmap or 4P images, which have footprints of a few tens of kilometers. This was only successfully done once. This difficulty will be better for Sea State, however, as a higher request priority is planned with only a one-day lead time, and some attempt will presumably be made to place the ship within a SAR image if that is needed. Nevertheless, very good communication between the ship and the people doing the SAR requests is needed. If the SAR images are to be used for navigation or science decision making on board the ship, the speed with which the acquired images are provided

to the requestors and the means by which the images can be transferred to the ship are both a concern. During ACSE, the images were frequently not available to the ship until 3 days later, or so, generally too late for either navigation or science decisions. This problem was exacerbated during weekends.

Furthermore, an additional complication in making the SAR requests is encountered if a prediction of wind conditions (e.g., on-ice/off-ice, strength) is a factor in the type and/or location of the SAR image. If this is a need, as it seemed to be as expressed in the June meeting, it is crucial that an experienced forecaster spends significant amounts of time talking with the scientists on the ship, the ship's crew, and the people doing the SAR requests. It is uncertain whether it is better to have this person on board the ship where the communication with the key people is easier and the current conditions are better known, or whether it is better to have him/her on land where the satellite and forecasting data is better. I found it perhaps a little bit easier being on board because of the better communication with the scientists and crew, but some basic forecasting products (e.g., onboard satellite receiver, tailored ECMWF and GFS forecast maps, direct verification) were essential as was my experience interpreting the recent observations and the forecast maps and satellite images.



***Figure 2: Track of the R/V Oden during Leg 2 of the ACSE cruise (white line) and the approximate location of the Mirai (green X) during its September deployment. Day of the year is indicated at intervals along the Oden track. The background map is the AMSRE ice concentration on Sep. 22, with purple indicating close to 100% concentration. Track positions after Sep. 24 are estimated***

During ACSE, two periods of freeze-up were encountered. One was fairly early during Leg 2 of the cruise, occurring the last few days of August into the first few days of September (YD239-YD245) during a time that the Oden was within the pack-ice environs (Fig. 2). This pack-ice region had an ice concentration of about 30-50%, with extensive open water regions within the ice. During this time, strong northerly winds accompanied by temperatures of  $-4$  C, thick clouds, and cold atmospheric temperatures at cloud level all likely contributed to reduce the net surface energy flux, depleting the upper ocean of its excess heat. Towards the end of this period during Sep 1 and 2, grease ice was seen to form on the open water areas as the sea water temperature reached its freezing point as determined

by the salinity. The ice regions already showed indications that surface melt had ended, with surface temperatures below freezing and frequently near  $-4$  C. Furthermore, melt ponds on the floes had frozen over and snow covered the floes and many meltponds, increasing the albedo and certainly contributing significantly to a likely near-zero or negative surface energy flux. This observation is in agreement with previous SHEBA and ASCOS studies (e.g., Persson 2012; Sedlar et al 2011) showing that surface melt ends on multi-year sea ice during the latter half of August. Analysis of the extensive atmospheric boundary-layer, surface energy fluxes, and upper-ocean measurements will be done to quantify the roles of the various processes in apparently at least temporarily producing freeze-up conditions over large open-water areas within the sea ice. Both SAR data and waverider buoy data were also acquired during this time and will be used in the analysis.

The second period of freeze-up conditions encountered were towards the end of the ACSE cruise from Sep. 19-25 near 85N, 150 E, at the northern end of a "bay" that had melted far northwards during the summer (Fig. 2). The Oden made several transits through the forming first-year ice, including grease ice, frazil, and pancake ice, and into the multi-year ice. During the days in that area, wind conditions encountered had a wide range between 5-15 m/s for both on-ice and off-ice airflow. Wind waves were clearly rapidly damped by even grease ice, producing a surreal ocean surface with only long wavelengths. Swell continued to propagate through the newly formed ice until the pancake ice became consolidated near the edge of the multi-year ice (Fig. 3). The full suite of atmospheric and surface energy flux measurements, including extra radiosoundings, were obtained, as were some wave buoy measurements both within the pancake ice and in the upwind and downwind open water. Continuous upper-ocean temperature and salinity measurements were made, in addition to occasional CTDs done by the oceanographers (for deep ocean purposes). During the off-ice winds the last few days in this area, extensive areas of the open water "bay" froze over with grease ice and pancake ice. Measurements are continuing in this area as this is being written on Sep. 24. Analysis of data from this time period and the evolution of the conditions is clearly very relevant to Sea State.



***Figure 3: Consolidated pancake ice in moderate on-ice flow conditions at about 85.1N, 151 E on Sep. 20, looking towards open water to the south.***

Instrumentation lessons learned from ACSE relevant to SeaState is that very good measurements of the atmospheric energy fluxes and the upper ocean temperature and salinity conditions are crucial to understanding the freeze-up process. Obtaining good energy flux measurements on board a ship is often difficult and involves compromises, so calibrations and redundancy should be emphasized. Buoy measurements of waves in forming sea ice is possible, but the buoys must be left unattended and the ship needs to be careful to not disturb the ice conditions for the buoy. Collecting and repositioning buoys under the conditions likely to be encountered and desired (high winds, snow, darkness, fog, significant swell) will take time, and may on frequent occasions not be possible. Losing buoys should be anticipated with spare ones. Other activities requiring being on deck may also at times be limited. The freeze-up and wave conditions are strongly driven by atmospheric synoptic evolution, and hence good forecasting is essential, as is preparation for the science to be done under a variety of conditions (off-ice flow, on-ice flow, weak or strong winds, large or small negative heat budget). Also, the "coastline" of the ice edge is dynamic with an apparent time scale of a day or two, and hence needs to be monitored carefully with imagery such as SAR. Waves, temperature, and surface energy fluxes probably vary significantly due to these local coastline variations. It isn't likely that an idealized straight ice edge will be found. Furthermore, while AMSRE images are useful for defining the ice on a large scale, it isn't clear whether there is a capability for these images to discriminate between multi-year ice and the nearby developing first-year ice.

Turbulent surface flux measurements were also performed by NOAA/CIRES Sea State participants on board the R/V Mirai during most of the month of September 2014 at 74.75N, 168W in open water of the Arctic Ocean. These fluxes will be part of an energy budget calculation describing the changes in the upper ocean heat content during this month as sea ice begins to form (Inoue-- personal communication). SSTs have decreased from 1.0 C to -0.5 C during the period, with the net surface energy budget becoming negative around Sep.15. Ocean turbulence measurements indicate an impact of winds on ocean mixing. As for ACSE, synoptic conditions determine the surface energy fluxes, and these synoptic conditions are well documented with 8 soundings per day.

## **PUBLICATIONS**

Andrey A. Grachev, Edgar L Andreas, Christopher W. Fairall, Peter S. Guest, P. Ola G. Persson, Similarity theory based on the Dougherty-Ozmidov length scale, Quarterly Journal of the Royal Meteorological Society, submitted April 2014, (minor revisions required)