Office of Naval Research (ONR)

Final project report

Canada Basin Experiment (CBEX) to Investigate Mechanisms of Sea Ice Thickness Variability and Freshwater Content Changes

Reporting period: 08/01/2015-07/31/2018

1. Long-term goals

The proposed CBEX goals and tasks listed below are divided in three categories, namely:

1. Core tasks and goals needed to conduct direct observations of the state and variability of sea ice thickness in the Canada Basin using ULS instruments;

2. Supporting tasks and goals to measure sea ice drift (using ADCP instruments) to determine sea ice motion for converting ice draft time series to spatial probability density distributions (as well as provide information about upper ocean currents); and

3. Additional tasks and goals for measuring bottom pressure (using BPR instruments) needed for better definition of the geoid which is a gravitational equipotential surface that most closely conforms to the mean sea surface. This information is needed to correctly

derive sea ice freeboard (*i.e.* thickness) from satellite altimetry data and improves satellite-based methods of sea ice thickness monitoring.

2. Objectives

2.1 Major

- *Provide* the CANAPE program with Eulerian sea ice thickness data at the mooring locations and over the region for the period of the experiment.

- *Coordinate* CBEX measurements with satellite and aircraft altimetry based sea ice observational programs. BGOS ULS data are already used to validate ice thickness (specifically freeboard) algorithms based on satellite altimetry

- *Investigate* relationships between sea ice volume changes in the Canada Basin and changes in the freshwater content for the entire region under investigation.

- *Examine* the mechanisms that drive variability of sea ice thicknesses for the purposes of adding to the predictability of sea ice conditions in the future.

2.2 Supporting

- *Measure* sea ice velocities (using ADCP instruments) to determine sea ice motion for converting ice draft time series to spatial probability density distributions.

- *Investigate* seasonal changes in the dynamics of the upper ocean mixed layer based on processed ADCP and ULS data, sea ice concentration from satellites, and atmospheric forcing data from NCAR/NCEP and Japanese reanalysis products (JRA-25 and latest versions).

2.3 Additional

- *Investigate* spatial and temporal variability of ocean bottom pressure based on observed and processed BPR data in the Canada Basin, paying specific attention to the analysis of bottom pressure variability at tidal, synoptic, non-seasonal (~ 1 month) and seasonal time scales.

3. Approach

We have expanded observations of sea ice thickness by instrumenting with Upward Looking Sonars (ULSs) an array of six (6) moorings that were deployed during the Canada Basin Acoustic Propagation Experiment (CANAPE) conducted by Scripps Institution of Oceanography (SIO, P.I. Peter Worcester) and Woods Hole Oceanographic Institution (WHOI, P.I. John Kemp) during 2016–2017. These observations were complimentary to the sea ice thickness observations at the 3 currently working moorings maintained by the Beaufort Gyre Observing System (BGOS) field program since 2003 (see Figure 1). The proposed locations of the 6 CANAPE moorings and 3 existing BGOS moorings with ULSs are shown in Figure 2. The combined number of sea ice measuring points was nine (9) and provide unprecedented coverage of the Canada Basin for quantifying spatial variability in all seasons at multiple scales.

In addition to the ULS instruments, we deployed Acoustic Doppler Current Profilers (ADCP) to each of the 6 CANAPE moorings in order to determine sea ice motion primarily for converting ice draft time series to spatial probability density distributions, but also for acquiring upper ocean velocities. Furthermore, one more option which increased the scientific value of the observational program was addition of Bottom Pressure Recorders (BPRs) on the 6 CANAPE mooring anchors in order to measure changes in bottom pressure of the water column (an equivalent of sea level) at tidal, synoptic and longer time scales.

4. Tasks completed

In 2015-2016 all instruments were purchased, calibrated and prepared for deployment. In autumn of 2016 instruments were deployed and in autumn of 2017 all instruments were recovered. In 2017-2016, all data from instruments were processed and distributed among project participants and a set of scientific papers was submitted for publications and presented at workshops, seminars and national meetings (see section results).

5. Results

The data from ADCP, ULSs and BRPs were analyzed and results presented and discussed with CANAPE and broader community at the:

5.1. Workshops and meetings

- Fall 2017 meeting of the Acoustical Society of America, New Orleans, 4-8 December, 2017.

- CANAPE workshop (April 24-25, 2018, Courtyard Marriot, Newark, University of Delaware, NJ; abstracts and presentations are included in the attached materials).
- CAATEX project meeting (May 2018) on the Norwegian 2014-2016 UNDER-ICE experiment in Fram Strait and our 2016-2017 CANAPE experiment in the Beaufort Sea, Bergen, Norway

- Fall 2018 meeting of the Acoustical Society of America, Victoria, 2018.

- 2018, 7th annual FAMOS (Forum for Arctic Modeling and Observational Synthesis), Bergen, Norway, October 2018.

- 2019 CANAPE workshop at Scripps Institution of Oceanography, April, 2019.

5.2 Presentations at workshops, published abstracts and published/submitted/in press papers based on project results

- John A. Colosi, Murat Kucukosmanoglu, Peter F. Worcester, MatthewDzieciuch, Andrey Y. Proshutinsky, Richard A. Krishfield, Jonathan D. Nash, J. Kemp (2018). An overview of Beaufort Sea eddies, internal waves, and spice from several recent field efforts and implications for acoustic propagation. *The Journal of the Acoustical Society of America*. 144 (3), . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = No ; DOI: 10.1121/1.5067423

- Kelly, S.J., A. Proshutinsky, E. K. Popova, Y. K. Aksenov and A. Yool (2019). On the origin of Water Masses in the Beaufort Gyre. *JGR*. . Status = ACCEPTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

- M. A. Dzieciuch, Worcester, P., J. Colosi, A. Proshutinsky, R. Krishfield, J. Nash, and J. Kemp (2018). Low–frequency acoustic transmissions under sea ice as measured in the Beaufort Sea. *The Journal of the Acoustical Society of America*. 144 (3), . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: doi.org/10.1121/1.5067422

- Proshutinsky A. , R. Krishfield and M-L. Timmermans (2019). Beaufort Gyre Phenomenon, Introduction for JGR-Oceans, special issue FAMOS: Beaufort Gyre Phenomenon. *JGR*. . Status = SUBMITTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

- Proshutinsky A. and R. Krishfield (2019). In a Spin: New Insights into the Beaufort Gyre. *Editors' Vox*. 100 . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = No ; DOI: 10.1029/2019EO119765

- Proshutinsky, Krishfield et al. (2019). Analysis of the Beaufort Gyre freshwater content in 2003-2018. *JGR*. . Status = SUBMITTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

- Worcester, P.F. M. A. Dzieciuch, A. Proshutinsky, R. Krishfield, J. D. Nash, J. Kemp (2018). The 2016–2017 deep-water Canada Basin Acoustic Propagation Experiment (CANAPE): A preliminary report. *The Journal of the Acoustical Society of America*. 144 (3), . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: doi.org/10.1121/1.5067422

6. Impact for science

6.1 Science: Our methods to examine the role of sea ice as an indicator of climate changes include joint analysis of our processed sea ice and ocean data with the results of AOMIP and

FAMOS coordinated experiments. Variability and trends of sea ice concentration, thickness and ice drift have been analyzed in conjunction with atmospheric and oceanic processes focusing on the conditions in 2003-2017. Based on these studies and analyses of sea ice concentration, thickness, and drift (from satellite and ADCP data) collected by ULS and ocean data collected by ITPs (WHOI), IMBs (CRREL), AOFBs (NPS), UpTempO (UW) and other surface buoys (IABP, UW), we have identified causes of the changes in processes operating in the Canada Basin related to sea ice conditions. The "modeling" activities have included analysis of AOMIP/FAMOS data available from wind-driven and thermo-driven freshwater experiments, partially described in *Proshutinsky et al.* [2011] where preliminary results of roles of different factors in the fresh water accumulation and release were described.

The conducted experiments have been focused on the studies to investigate seasonal changes of water stratification under different forcing at different time scales (tidal synoptic, non-seasonal from 10 to 30 days, and seasonal) and causes of these changes. The model's internal parameters were calibrated based on BGOS observations from 2003-2015 and on 2016-2017 joint CBEX-CANAPE-BGOS data. Based on these experiments, we have provided recommendations for the modeling community on how to improve the model parameters for reducing uncertainties in both oceanic and sea ice predictions (see FAMOS project results (famosarctic.com and https://web.whoi.edu/famos/, in particular, results of 2018 annual project meeting ttps://web.whoi.edu/famos/meeting-7-october-23-26-2018/)

6.2 Technology transfer: We have proposed to continue our experience in collaboration with acoustic community to accommodate ADCPs, ULSs and BPRs at 7 moorings crossing the Arctic Ocean from the Beaufort Sea to Spitsbergen in the Norwegian-USA Coordinated Arctic Acoustic Thermometry Experiment. Having all these instruments from our current CBEX project support we were able to continue these studies collaborating with other communities/projects at no cost for these instruments.

7. Relationship to Other Programs

This project has had the closest relation with NSF's long-term observational program Beaufort Gyre Observing System (BGOS) started in 2003 (see Figure 1 below and section 3 above).

8. Figures/Pictures

8.1 Figures for report text

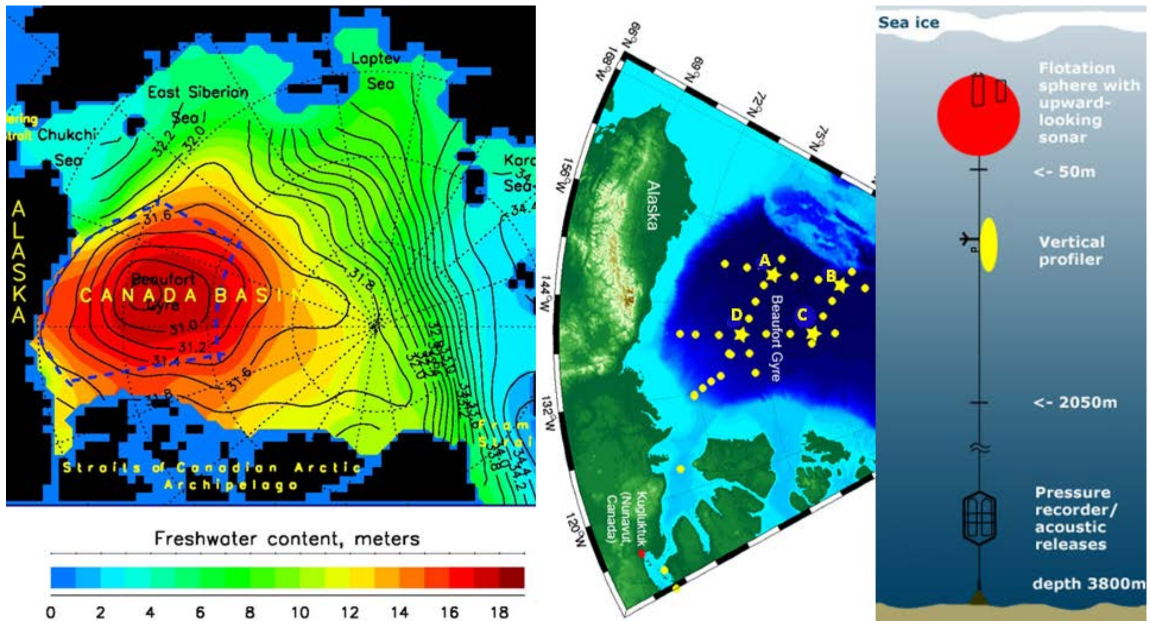


Figure 1 Beaufort Gyre Observing System (BGOS). ***Left:*** *Climatology of Arctic Ocean freshwater content (FWC, m, colors). Solid lines depict summer 1950–1980 mean salinity at 50 m. FWC is calculated relative to a salinity of 34.8. The Beaufort Gyre Region (BGR) is bounded by thick dashed blue lines;* ***Middle****: Beaufort Gyre Observing System (BGOS) field program with locations of A,B,C, and D moorings (stars) and sites of CTD casts (circles);* ***Right:*** *BGOS mooring diagram with: (a) floatation-mounted Upward Looking Sonar (ULS), and ADCP; (b) McLane Moored Profiler (MMP) measuring T, S and currents between 50 and 2050m, (d) anchor, (e) acoustic releases and (f) anchor-mounted Bottom Pressure Recorder (BPR).*

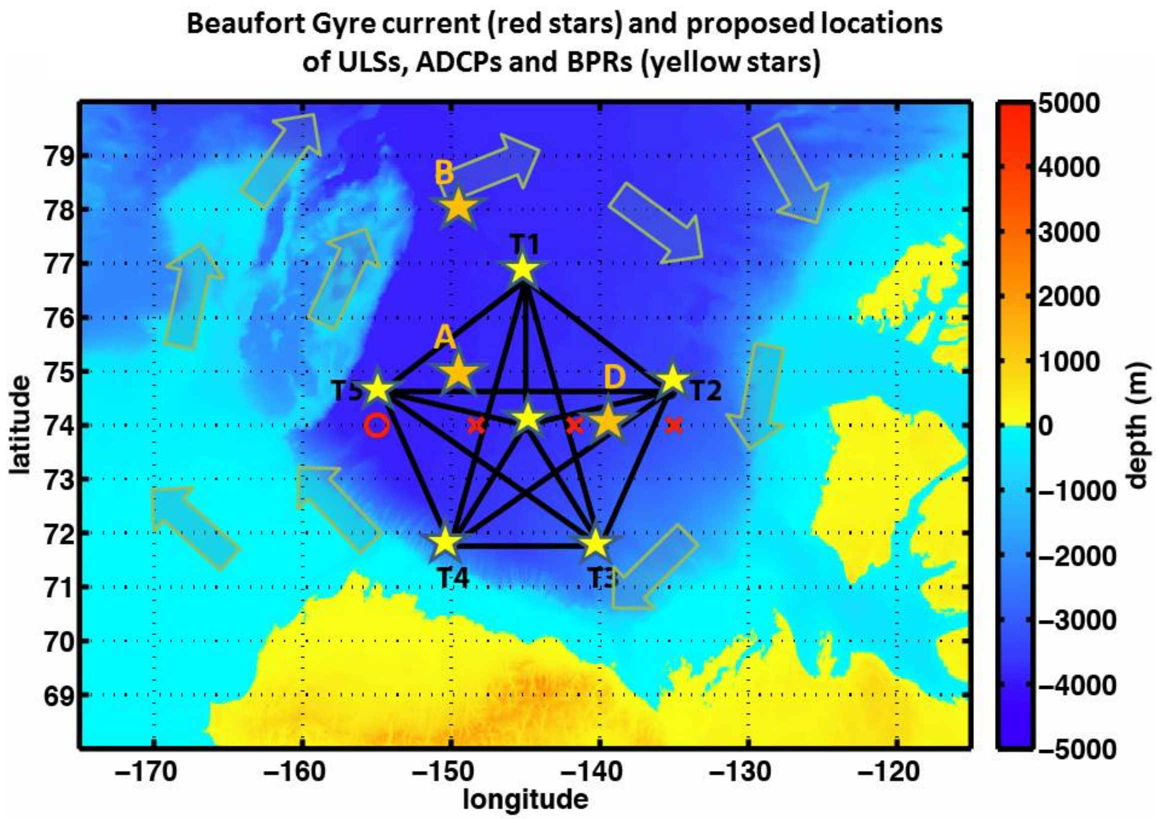
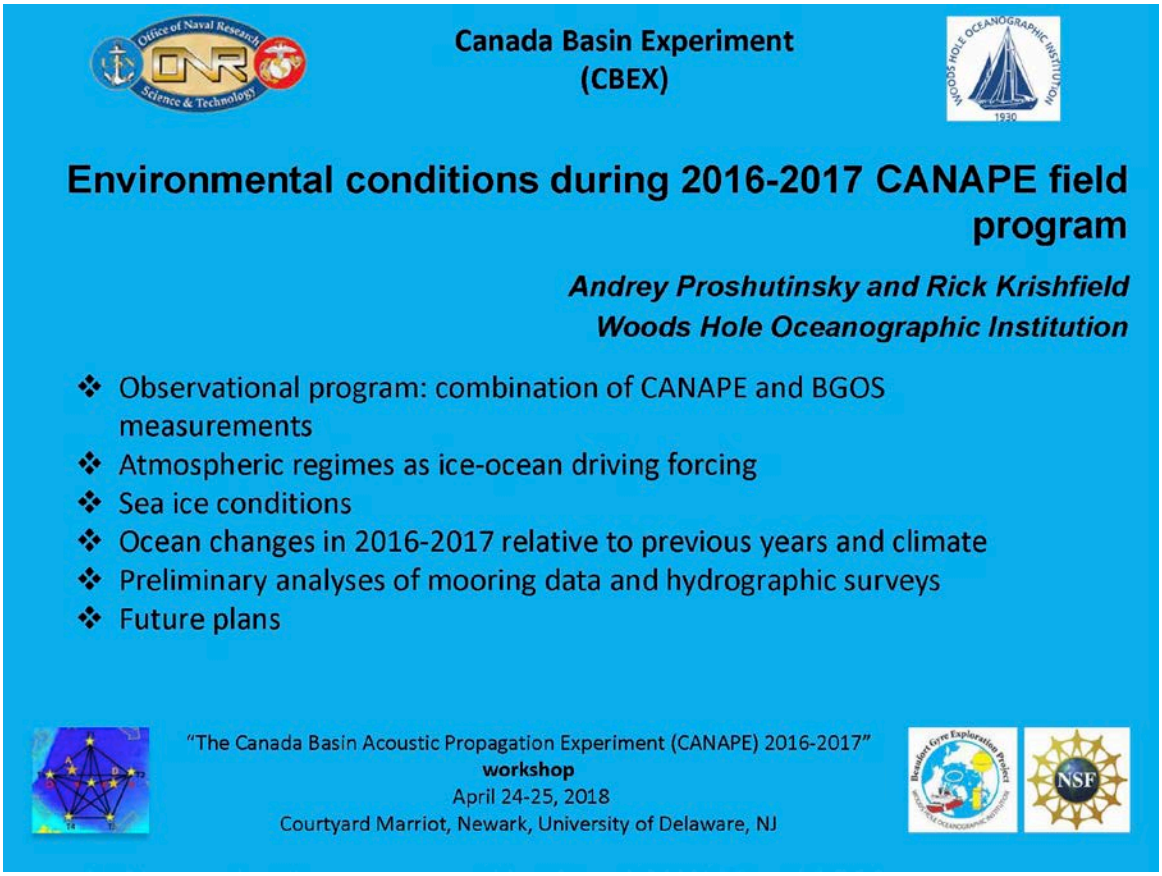
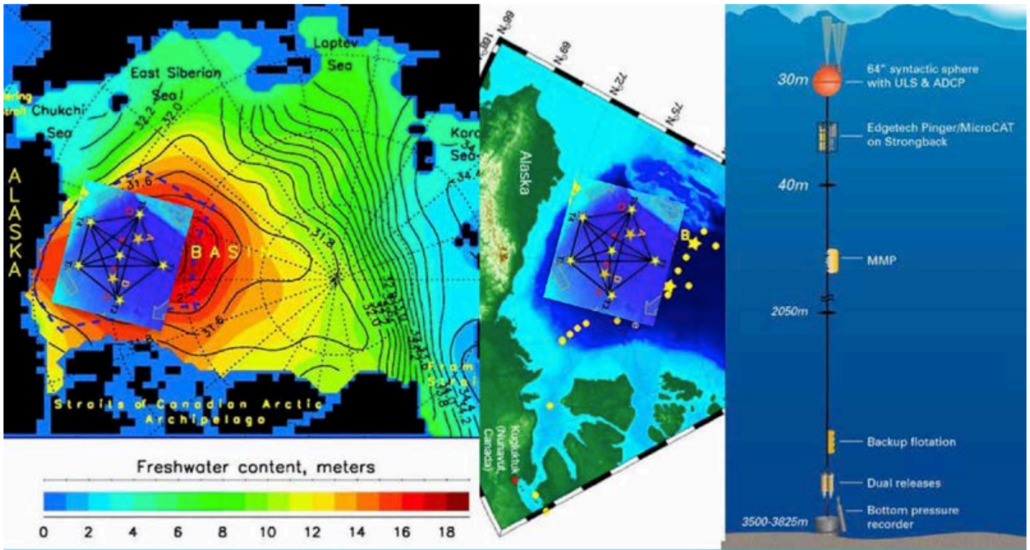


Figure 2 *Geometries of the 2015 CANAPE Pilot Experiment (red crosses) and the 2016–2017 CANAPE Experiment (black). The proposed ULSs and other instruments will be located at top of T1-T6 moorings 2016–2017 (yellow stars). Orange stars depict locations of "A", "B" and "D" BGOS moorings with ULS, ADCP and BPR instruments operational since 2003. Large arrows show climatologic ice drift.*

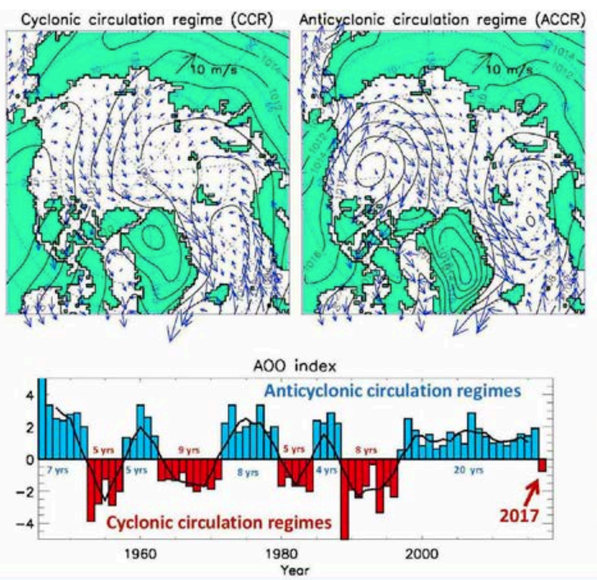
8.2 Power point presentations showing project results

8.2.1 Proshutinsky and Krishfield





Left: Climatology of Arctic FWC (m, colors). Black lines: 1950–1980 salinity at 50 m. Dashed blue line: BG region; **Middle:** BGOS moorings A,B,C, and D (stars) and CTD sites (circles); **Right:** Standard BGOS mooring diagram with: floatation-mounted Upward Looking Sonar (ULS), and ADCP; Pinger, MicroCAT, McLane Moored Profiler (MMP), backup flotation, acoustic releases, anchor and anchor-mounted Bottom Pressure Recorder (BPR).

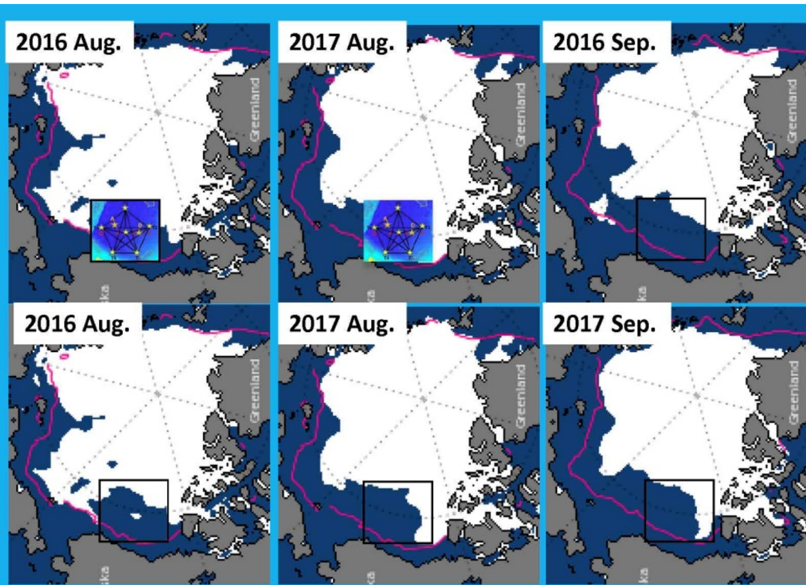


Time series of the AOO index from 1948-1996 indicate that ACCRs and CCRs alternate at approximately 5 to 7 year intervals with a period of quasi-oscillation of about 10 to 15 years.

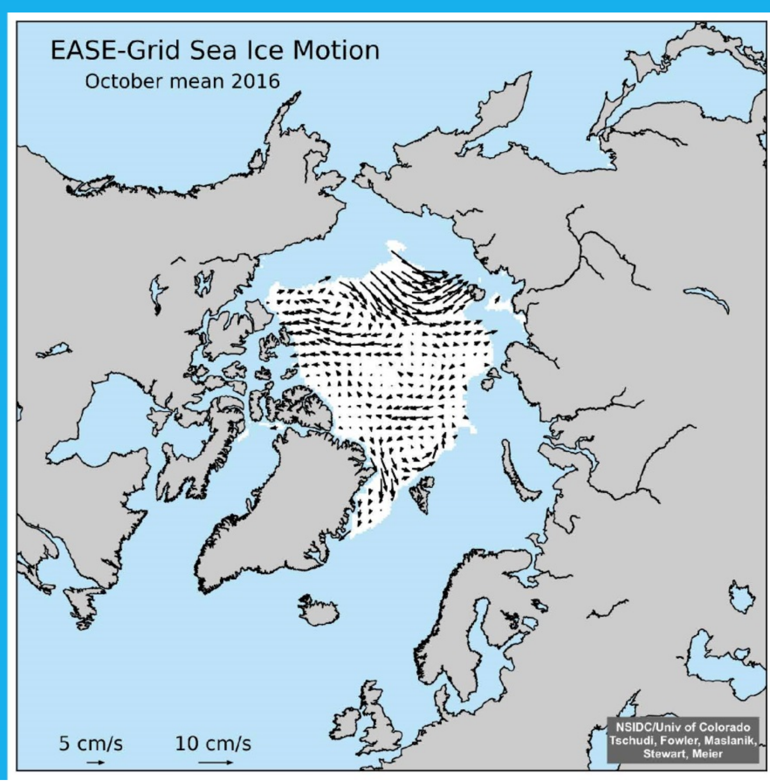
In a stark deviation from this pattern, the ACCR started in 1997 has dominated in the Arctic over the last 20 years.

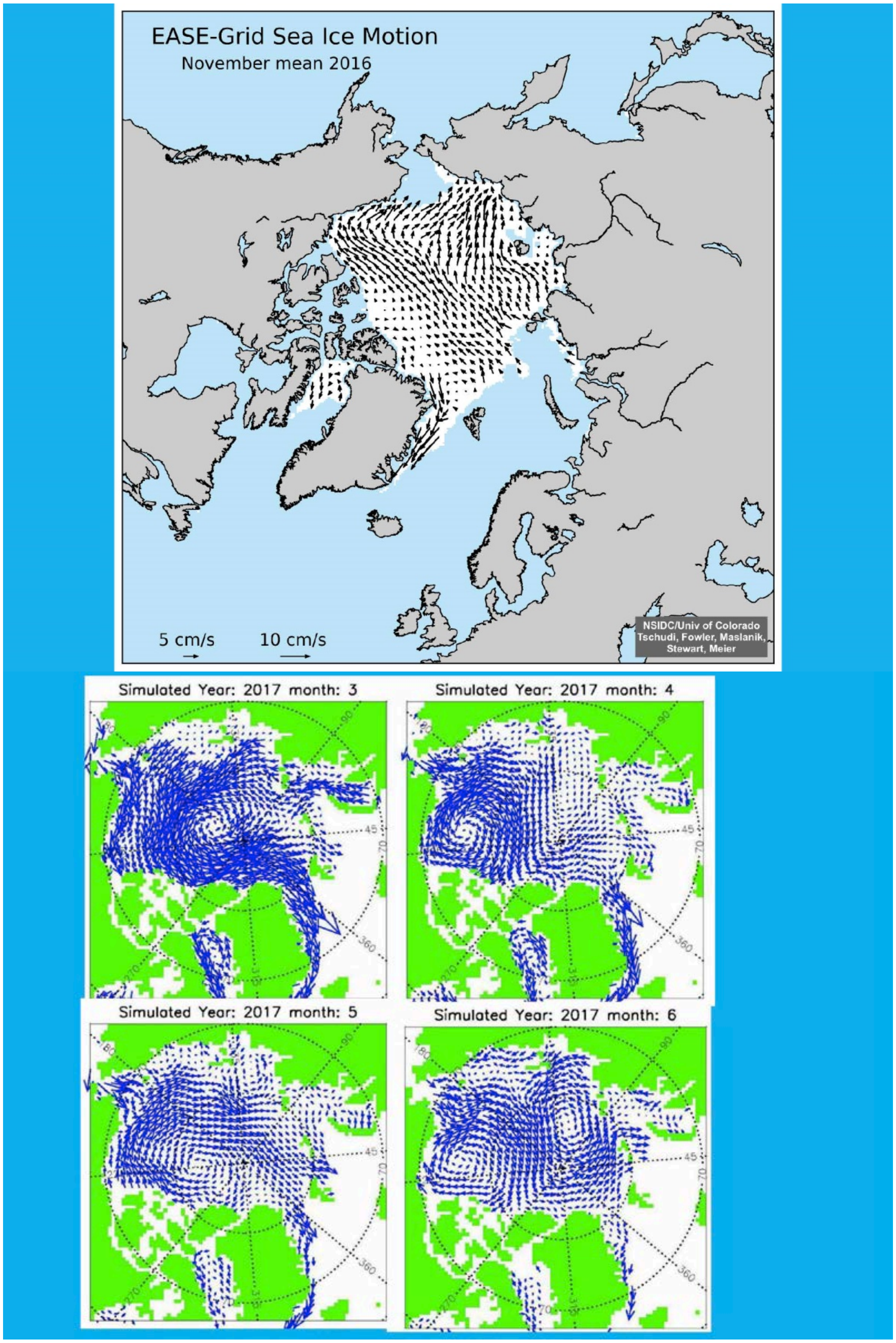
Proshutinsky et al. (2015) suggested that the well-pronounced decadal variability observed in 1948-1996 been replaced by a long-term ACCR due to Greenland ice sheet melt under the influence of global warming. This meltwater interrupted decadal variability.

Model results (Fig. 2) have shown that decadal variability could be replaced by 20-year ACCRs and 3-4 year CCRs.



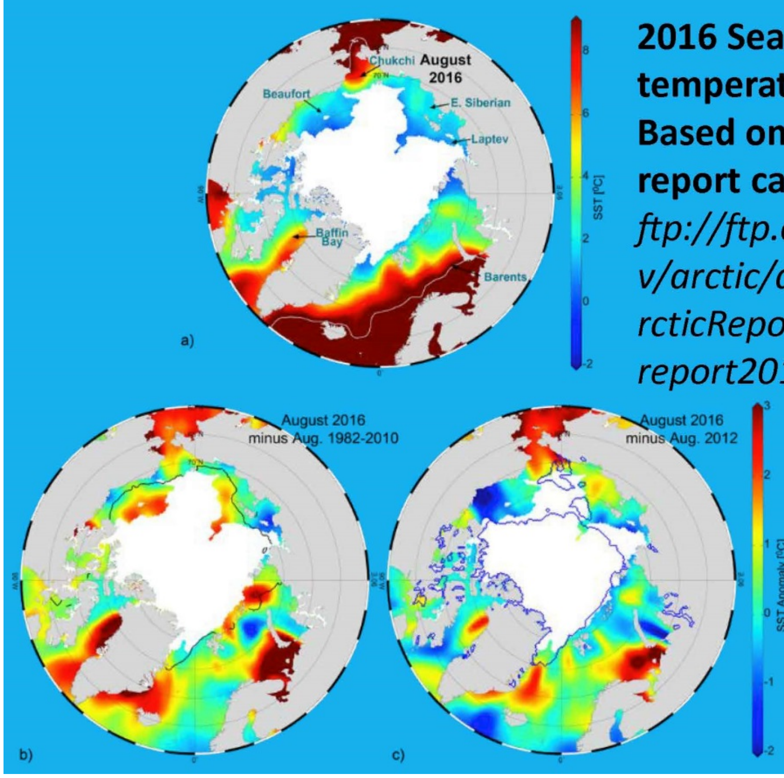
***Sea ice extent** in 2016 - 2017 during mooring deployment and recovery operations*




EASE-Grid Sea Ice Motion
November mean 2016
5 cm/s
10 cm/s
NSIDC/Univ of Colorado
Tschudi, Fowler, Maslanik,
Stewart, Meier
Simulated Year: 2017 month: 3
Simulated Year: 2017 month: 4
Simulated Year: 2017 month: 5
Simulated Year: 2017 month: 6

It is important that depending of circulation regime the ice ridging and ice thickness vary significantly.

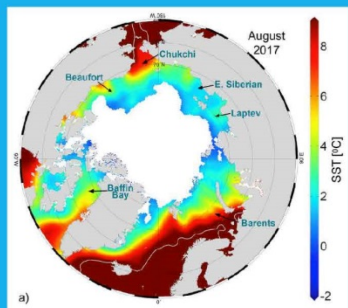
The ice ridging is increased during anticyclonic circulation regime (prevailing of ice convergence and increased internal ice stresses) and reduced during cyclonic ice motion (divergence and reduction of internal ice stresses)

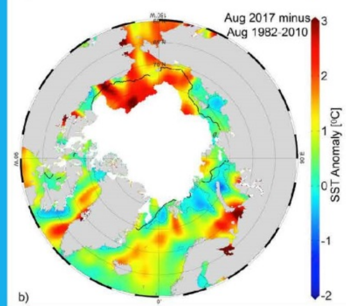


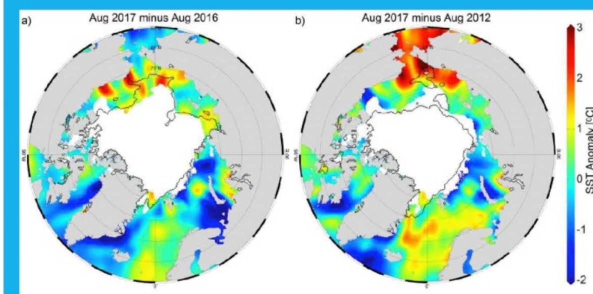
2016 Sea surface temperature (SST) Based on 2016 Arctic report card: *ftp://ftp.oar.noaa.gov/arctic/documents/ArcticReportCard_full_report2016.pdf*

2017 Sea surface temperature (SST), Based on 2016 Arctic report card:

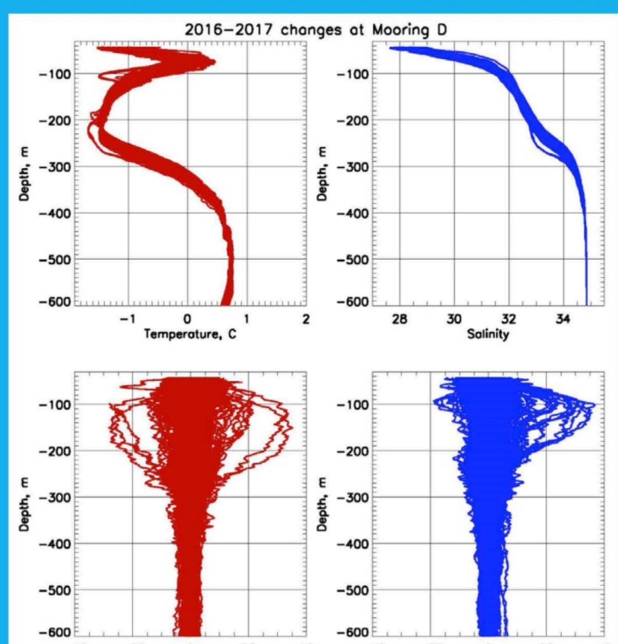
ftp://ftp.oar.noaa.gov/arctic/documents/ArcticReportCard

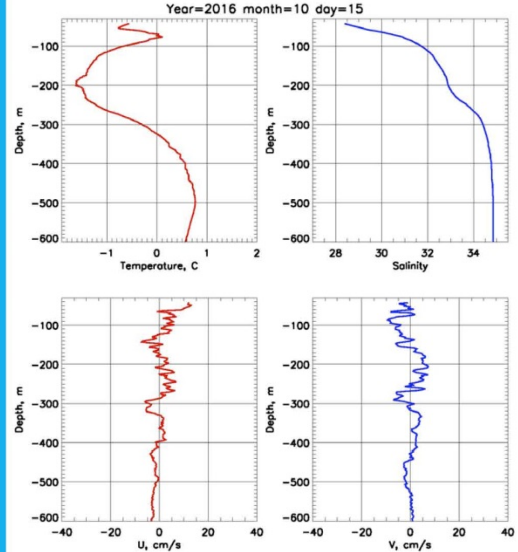


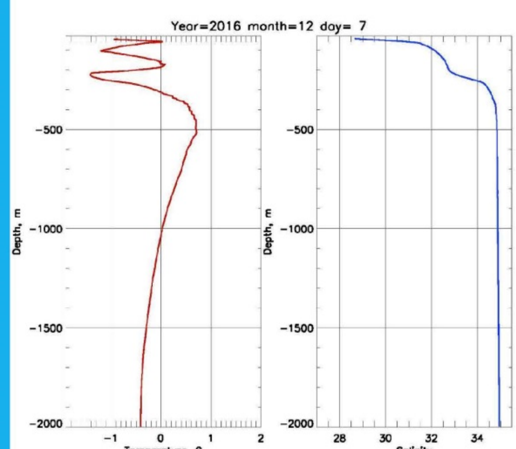


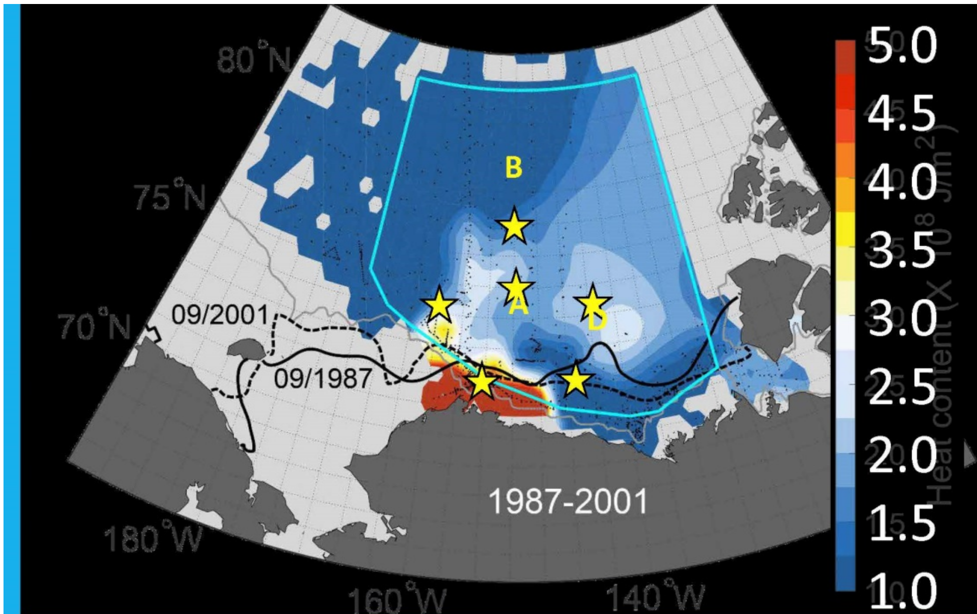


Vertical water structure based on MMP data

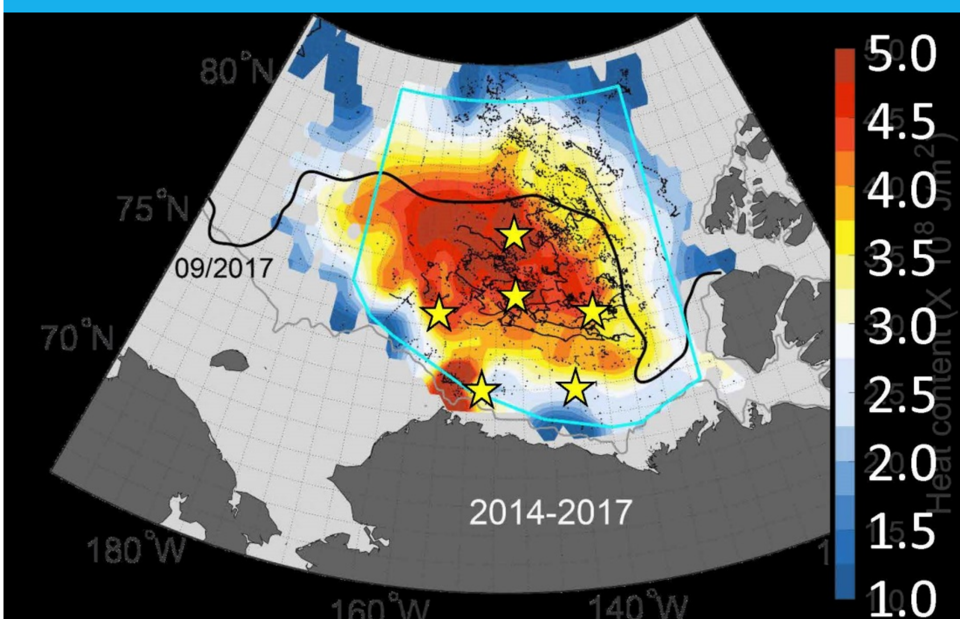



Year=2016 month=10 day=15
Depth, m
Temperature, C
Salinity
U, cm/s
V, cm/s

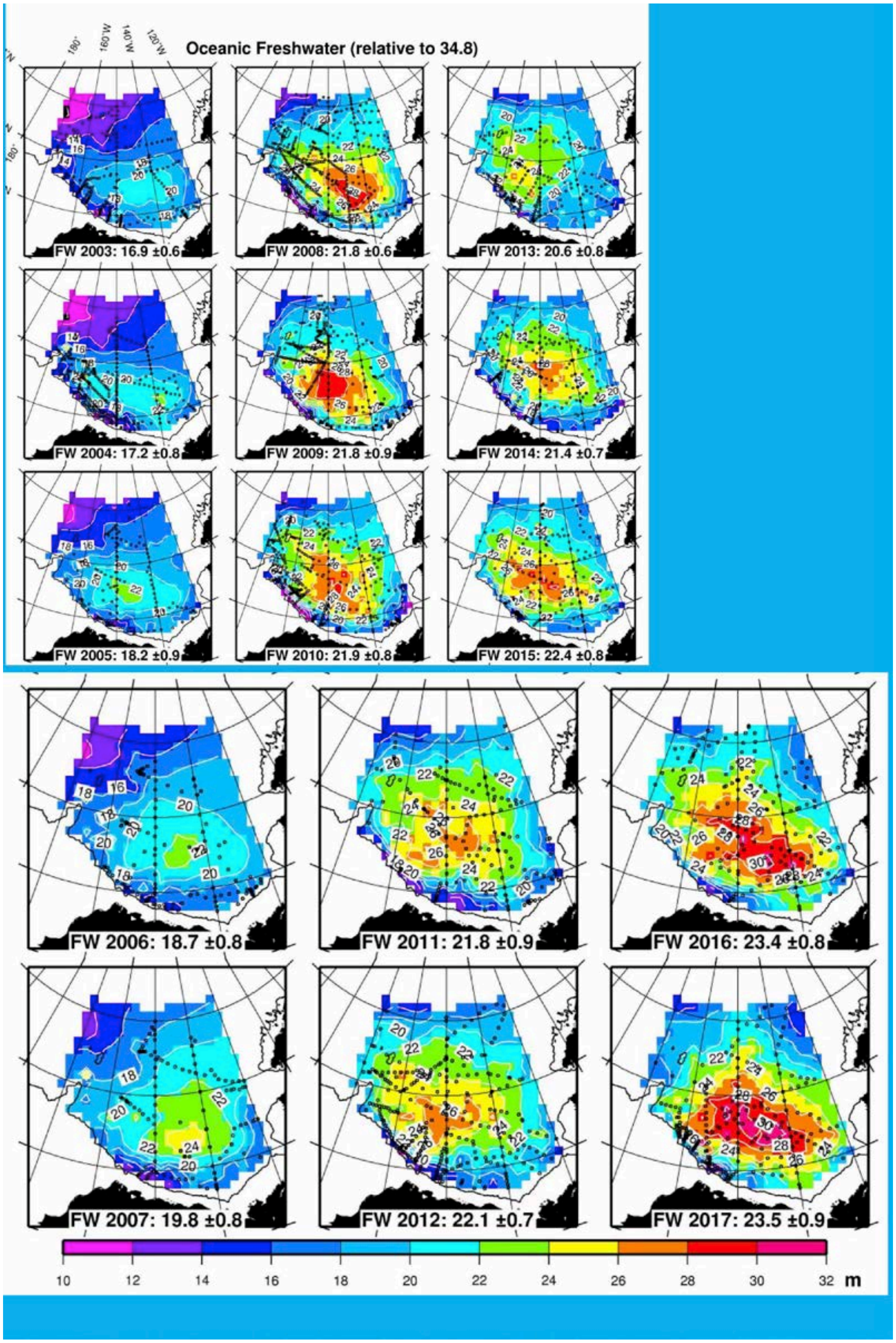

Year=2016 month=12 day= 7
Depth, m
Temperature, C
Salinity



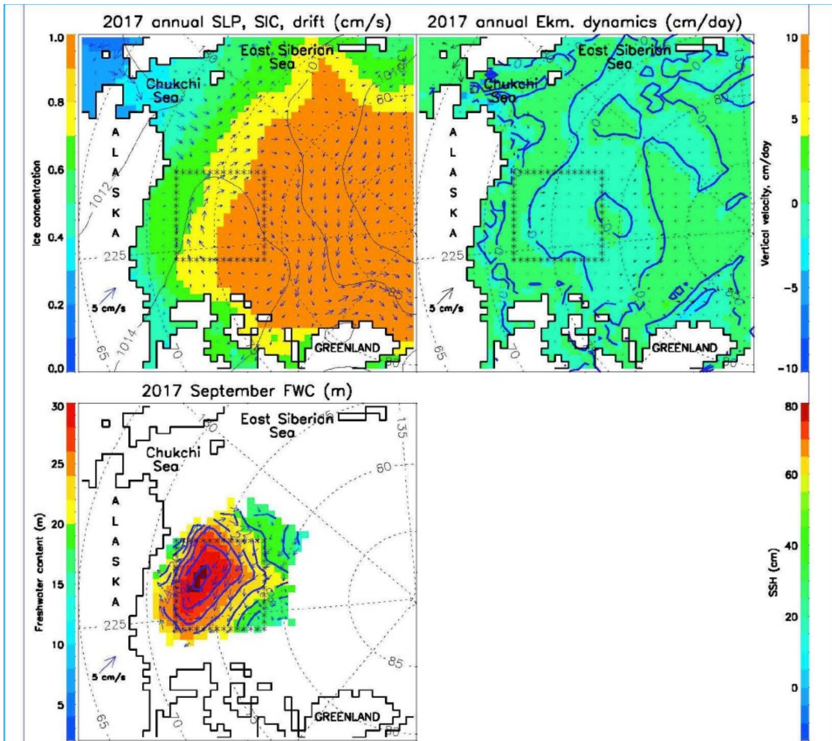
80°N
75°N
70°N
09/2001
09/1987
B
A
D
1987-2001
180°W
160°W
140°W
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0



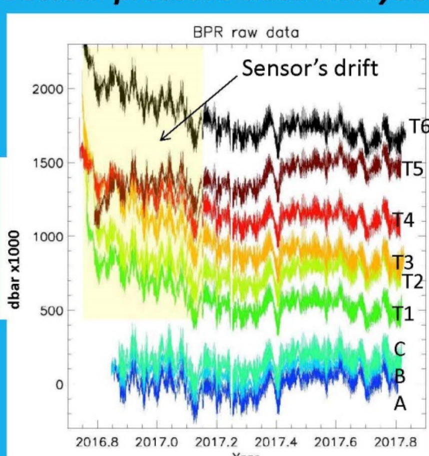
80°N
75°N
70°N
09/2017
2014-2017
180°W
160°W
140°W
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0

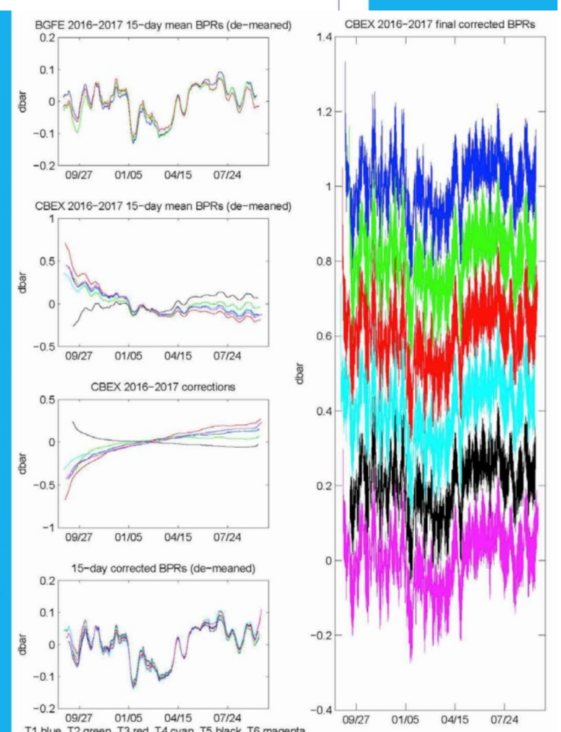


Oceanic Freshwater (relative to 34.8)
180°
160°W
140°W
120°W
FW 2003: 16.9 ±0.6
FW 2008: 21.8 ±0.6
FW 2013: 20.6 ±0.8
FW 2004: 17.2 ±0.8
FW 2009: 21.8 ±0.9
FW 2014: 21.4 ±0.7
FW 2005: 18.2 ±0.9
FW 2010: 21.9 ±0.8
FW 2015: 22.4 ±0.8
FW 2006: 18.7 ±0.8
FW 2011: 21.8 ±0.9
FW 2016: 23.4 ±0.8
FW 2007: 19.8 ±0.8
FW 2012: 22.1 ±0.7
FW 2017: 23.5 ±0.9
10 12 14 16 18 20 22 24 26 28 30 32 m



Bottom pressure data analysis





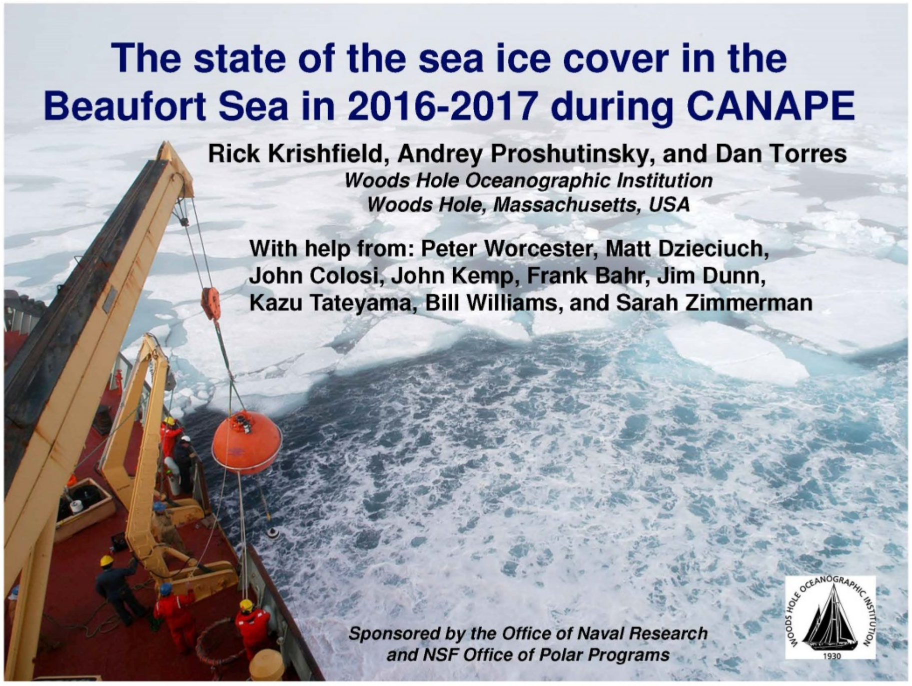
To remove BPR sensor's drift we processed T1-T6 data together with BPR data from moorings A-D (see results in right figure).

Bottom pressure data analysis: (an example for mooring A)

Major Tidal Constituents at mooring A

Name	Period	Magnitude	Phase
MSm	31.81 days	**1.07 cm**	153°
Mm	27.55 days	**1.65 cm**	263°
MSf	14.77 days	0.60 cm	80°
Mf	13.66 days	**2.39 cm**	250°
Q1	26.87 hours	0.75 cm	133°
O1	25.82 hours	**2.28 cm**	158°
K1	23.93 hours	**1.69 cm**	142°
N2	12.66 hours	0.71 cm	209°
M2	12.42 hours	**4.52 cm**	240°
S2	12.00 hours	**2.10 cm**	308°

8.2.1 Krishfield and Proshutinsky



The state of the sea ice cover in the Beaufort Sea in 2016-2017 during CANAPE

Rick Krishfield, Andrey Proshutinsky, and Dan Torres

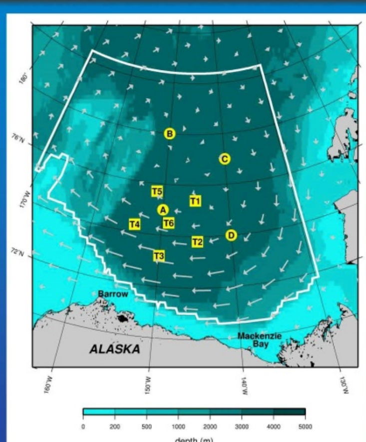
Woods Hole Oceanographic Institution

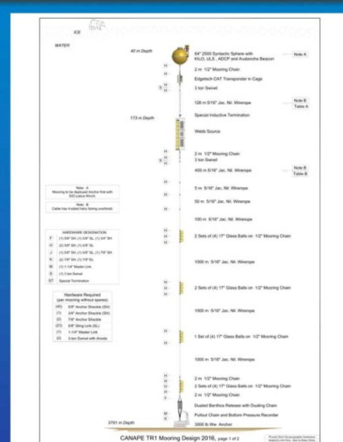
Woods Hole, Massachusetts, USA

With help from: Peter Worcester, Matt Dzieciuch, John Colosi, John Kemp, Frank Bahr, Jim Dunn, Kazu Tateyama, Bill Williams, and Sarah Zimmerman

Sponsored by the Office of Naval Research and NSF Office of Polar Programs

Mooring locations and T1 diagram





Six bottom-tethered moorings (T1-T6) were deployed from 2016-2017 during the CANAPE experiment as well as BGOS A, B, and D moorings which have been maintained since 2003 (BGOS C was removed in 2008). In addition to the acoustic sources on the CBEX moorings, all were outfit with ULSs for measuring ice draft, ADCPs for measuring ice and upper ocean currents, microcat CTD recorders and bottom-pressure recorders.

ULS and ADCP Instruments

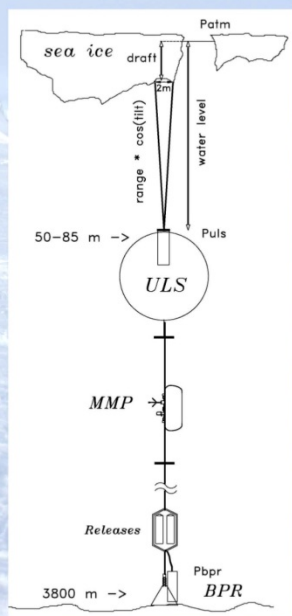
ULS: ASL IPS5 pings at 420 kHz every 1 second to determine ice drafts with a precision of better than +/- 10 cm after processing.

ADCP: RDI Sentinel 600 kHz averages 60 pings over a 2 minute period every hour over 25, 2 m vertical bins with estimated 0.97 cm/s accuracy.

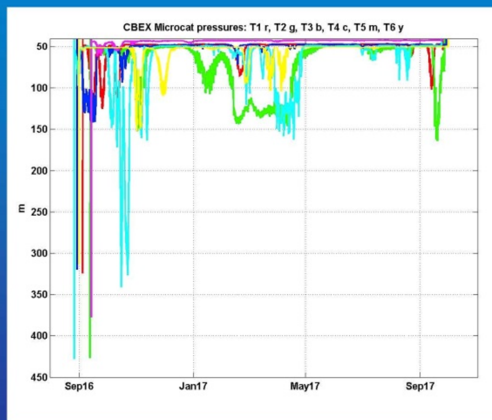
Ice draft measurements

Ice draft = water level – beta * range * cos(tilt)

- water level is determined from the pressure measurements corrected for atmospheric load.
- the beta correction incorporates changes in seawater T+S which vary sound speed.



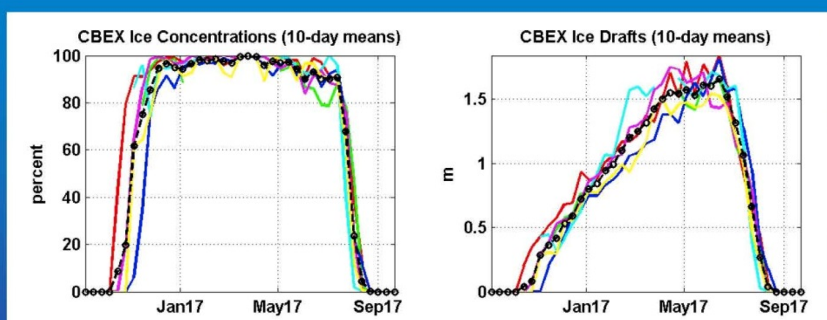
Mooring vertical deviations



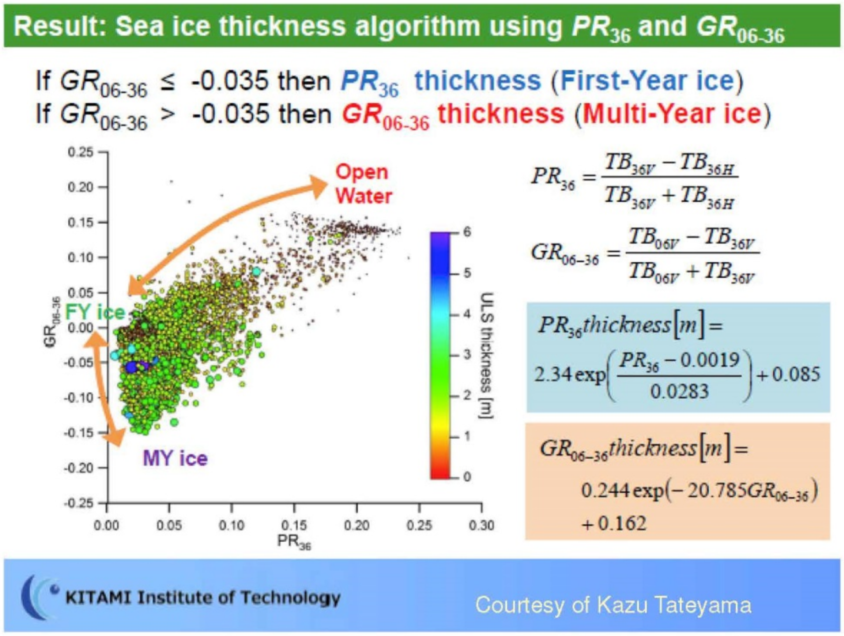
Pressure data from the microcat CTD recorders show that during the anchor last deployments, the top of the moorings sank to more than 300 m depths (exceeding the rating of and damaging the ULS pressure sensors), and that marginal floatation allowed the top of the moorings to be pushed deeper by strong currents throughout the year.

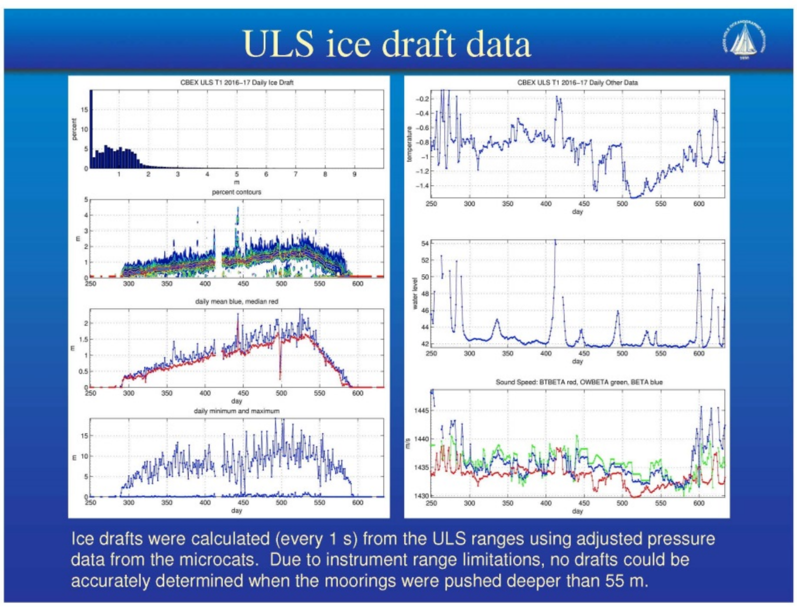
(Data courtesy of John Colosi)

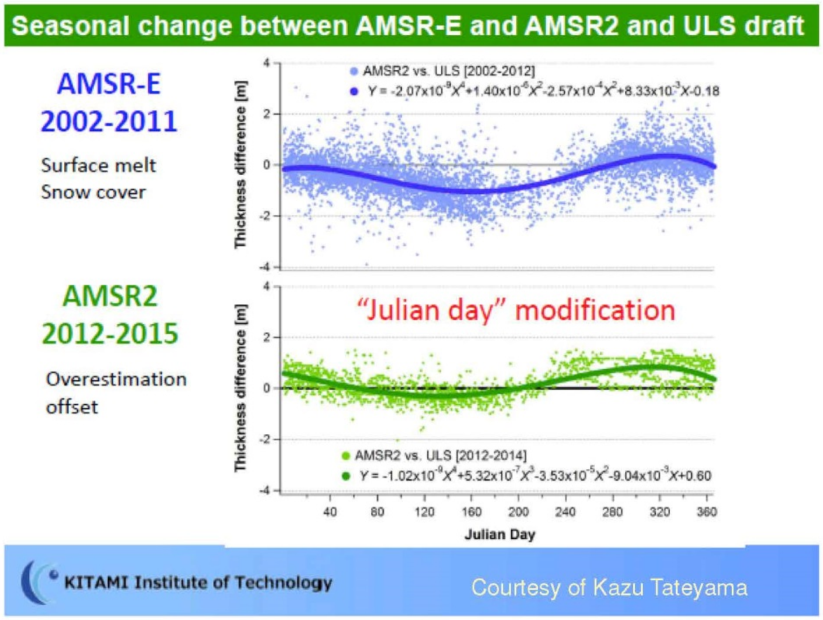
Time series of ULS ice data at CANAPE moorings

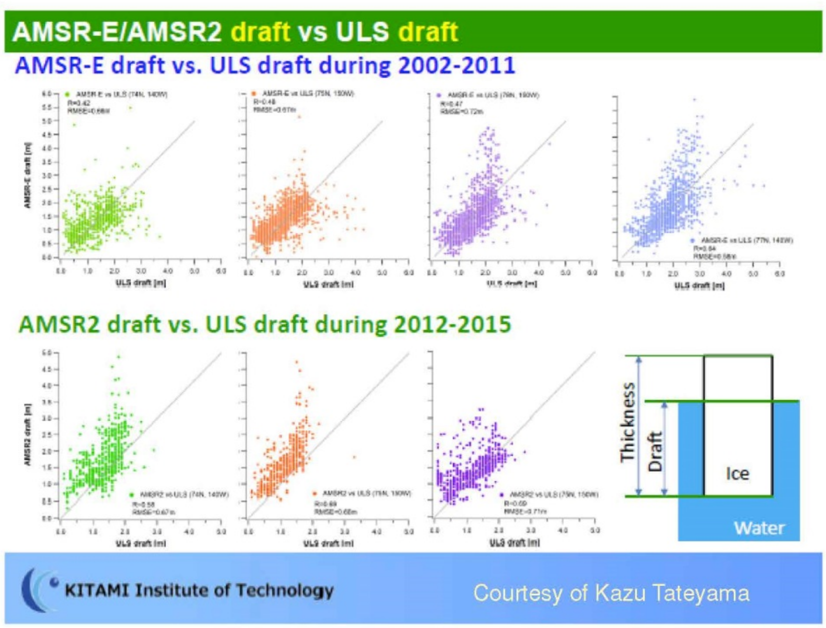


10-day mean ice concentrations (left) and ice drafts (right) from ULS data on all CANAPE moorings: T1 red, T2 green, T3 blue, T4 cyan, T5 magenta, T6 yellow, mean black o.

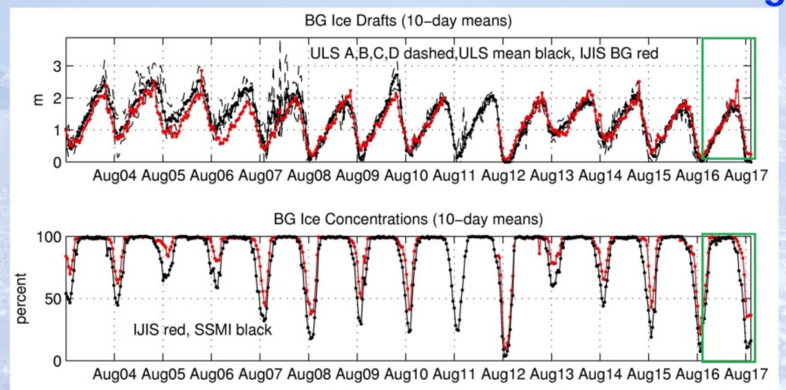

Result: Sea ice thickness algorithm using PR_{36} and $GR_{06\text{-}36}$
If $GR_{06\text{-}36} \le -0.035$ then PR_{36} thickness (First-Year ice)
If $GR_{06\text{-}36} > -0.035$ then $GR_{06\text{-}36}$ thickness (Multi-Year ice)
Open Water
FY ice
MY ice
$GR_{06\text{-}36}$
PR_{36}
ULS thickness [m]
$PR_{36} = \frac{TB_{36V} - TB_{36H}}{TB_{36V} + TB_{36H}}$
$GR_{06-36} = \frac{TB_{06V} - TB_{36V}}{TB_{06V} + TB_{36V}}$
$PR_{36} thickness[m] = 2.34 \exp\left(\frac{PR_{36} - 0.0019}{0.0283}\right) + 0.085$
$GR_{06-36} thickness[m] = 0.244 \exp(-20.785 GR_{06-36}) + 0.162$
KITAMI Institute of Technology
Courtesy of Kazu Tateyama


ULS ice draft data
CBEX ULS T1 2016–17 Daily Ice Draft
percent contours
daily mean blue, median red
daily minimum and maximum
CBEX ULS T1 2016–17 Daily Other Data
Sound Speed: BTBETA red, OWBETA green, BETA blue
Ice drafts were calculated (every 1 s) from the ULS ranges using adjusted pressure data from the microcats. Due to instrument range limitations, no drafts could be accurately determined when the moorings were pushed deeper than 55 m.


Seasonal change between AMSR-E and AMSR2 and ULS draft
AMSR-E
2002-2011
Surface melt
Snow cover
AMSR2 vs. ULS [2002-2012]
Y = -2.07x10^-9X^4+1.40x10^-6X^3-2.57x10^-4X^2+8.33x10^-3X-0.18
Thickness difference [m]
AMSR2
2012-2015
Overestimation
offset
"Julian day" modification
AMSR2 vs. ULS [2012-2014]
Y = -1.02x10^-9X^4+5.32x10^-7X^3-3.53x10^-5X^2-9.04x10^-3X+0.60
Julian Day
KITAMI Institute of Technology
Courtesy of Kazu Tateyama


AMSR-E/AMSR2 draft vs ULS draft
AMSR-E draft vs. ULS draft during 2002-2011
ULS draft [m]
AMSR2 draft vs. ULS draft during 2012-2015
Thickness
Draft
Ice
Water
KITAMI Institute of Technology
Courtesy of Kazu Tateyama

Time series of ULS ice draft at BGOS moorings



Top: Ice draft observations at the mooring locations tune estimates from IJIS AMSR-E satellite data (using Tateyama algorithm) to produce regional ice thickness grids.

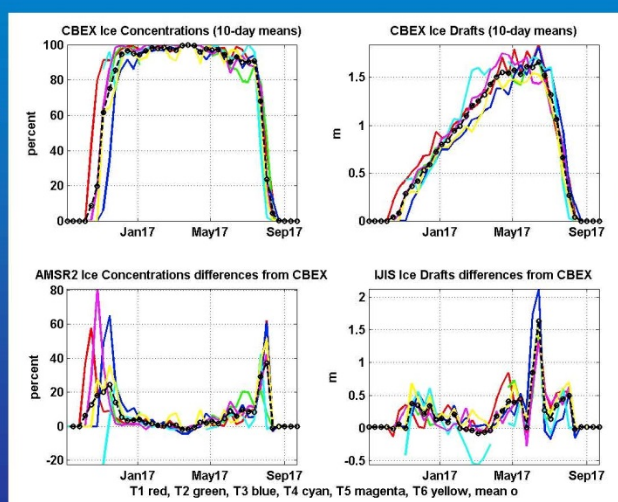
Bottom: IJIS-derived ice concentration are compared with SSMI Bootstrap ice concentrations (Comiso) for the BG region.

Krishfield et al. (2014), updated

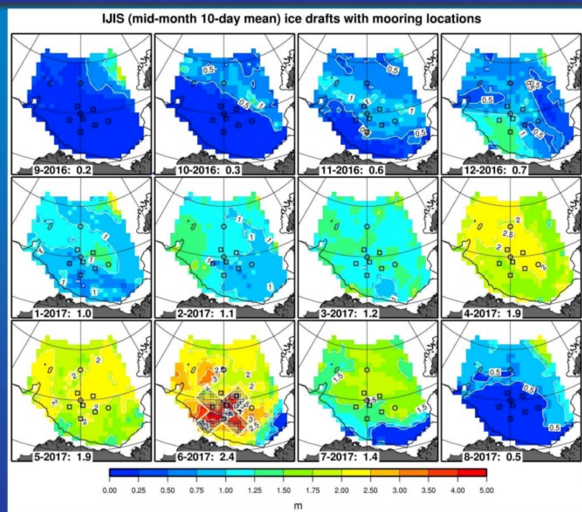
Time series of ULS ice data at CANAPE moorings

Top panels:
10-day mean ice concentrations and ice drafts from ULS data on all CANAPE moorings.

Bottom panels:
Differences of the mooring data from AMSR derived concentrations and IJIS estimated drafts (*Krishfield et al.*, 2014) at the mooring locations. Note large discrepancies between ULS and IJIS drafts in June 2017.



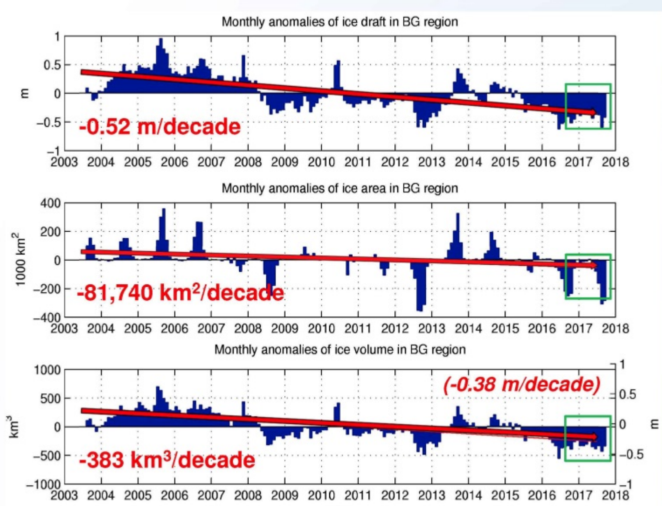
IJIS ice drafts in the BG 2016-17



Mid-month maps of ice drafts from IJIS AMSR2 parameterization for the Beaufort Gyre region. CANAPE moorings indicated by squares and BGOS moorings by circles. Thick ice (>2m) indicated in June 2017 does not match observed ULS data.

Trends in the BG ice cover 2003-2017

Computed from monthly anomalies after removing seasonal cycle

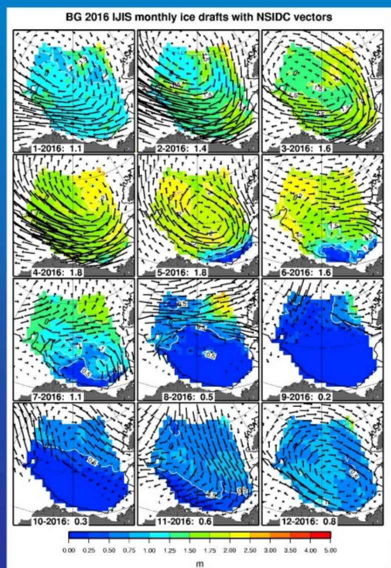


27% reduction
from max ice draft = 2.7 m

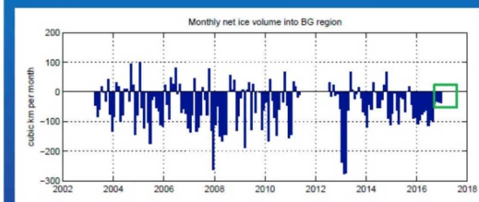
11% reduction
from max ice area = 1.022×10^6 km^2

23% reduction
from max ice volume = 2366 km^3

Ice volume advected into the BG



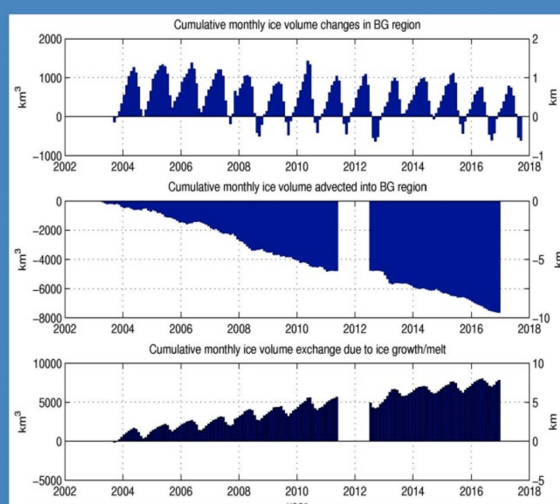
Left : Contour plots of monthly averages of ice draft (in m) estimates using the IJIS algorithm in the BGR over plotted with monthly-averaged NSIDC ice drift vectors (*Tschudi and Fowler*) for 2016. The numbers at the bottom of each panel are the regional ice draft means.



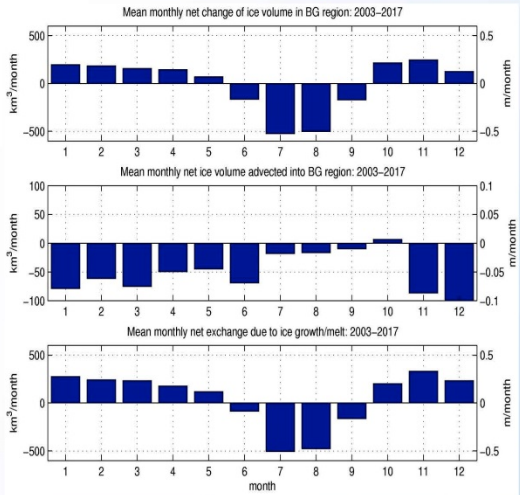
Above: Monthly values of ice advected into the BG are determined by combining the IJIS ice drafts, SSMI ice concentrations, and NSIDC ice velocities, and adding the fluxes along all edges of the region (positive inward).

Cumulative changes of ice storage, ice advection and ice melt in the BG region from 2003 to 2017

Over the nearly 14 year period from August 2003 to January 2017, nearly 8,000 km^3 of sea ice was advected out of the BG region than entered, and all but ~500 km^3 was replaced by ice growth.

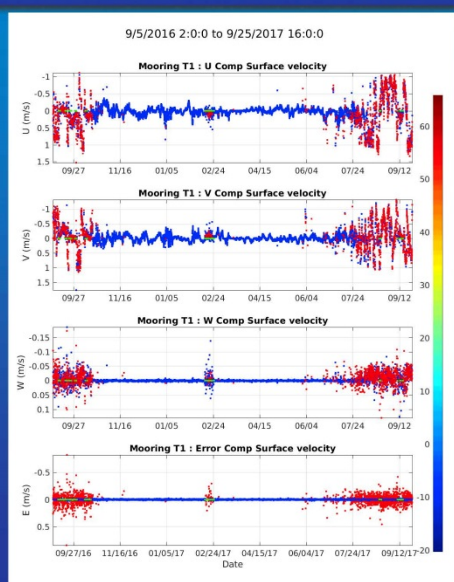


Seasonality of ice storage, ice advection, and ice growth/melt in BG



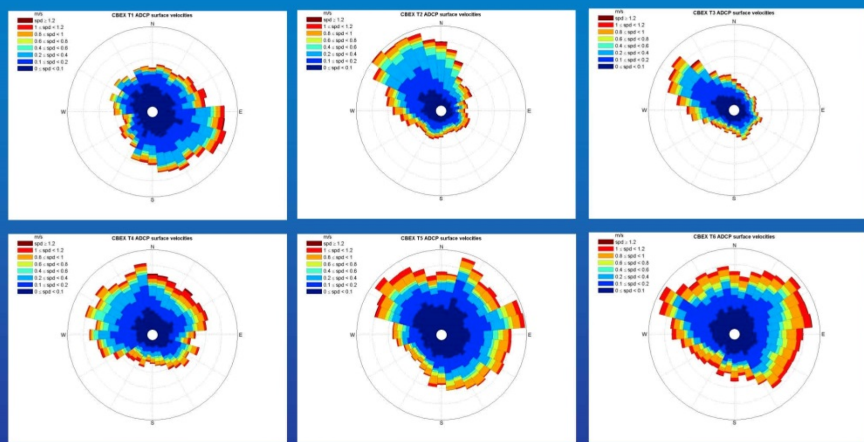
- Sea ice stored in BG is reduced rapidly between June and September and increases gradually the remainder of the year.
- On average, there is a net negative flux of sea ice out of the BG almost every month of the year.
- Net melting of sea ice occurs between June and September but overall there is a net increase (growth) for the year.

ADCP surface velocities at CANAPE moorings



- Hourly surface velocities were obtained from ADCPs on each CANAPE mooring using bottom tracking (time series from mooring T1 is shown).
- Ice drift is generally indicated where error velocities are less than 3 cm/s (blue dots), open water otherwise (red dots).
- Null data where the moorings were pushed deeper than the instrument range are indicated by green dots.

ADCP surface speeds at CANAPE moorings

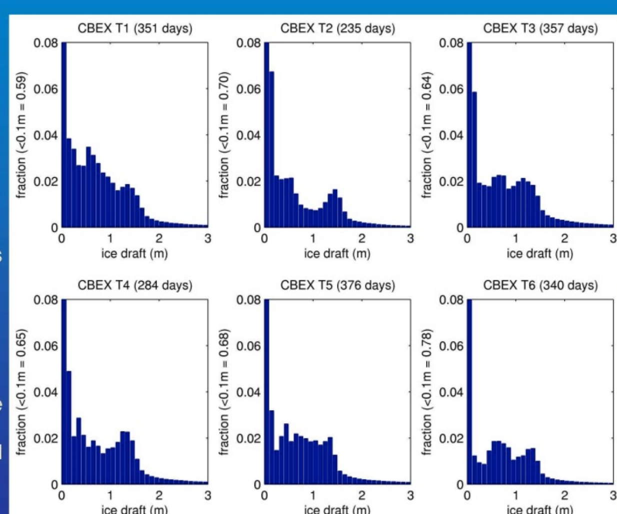


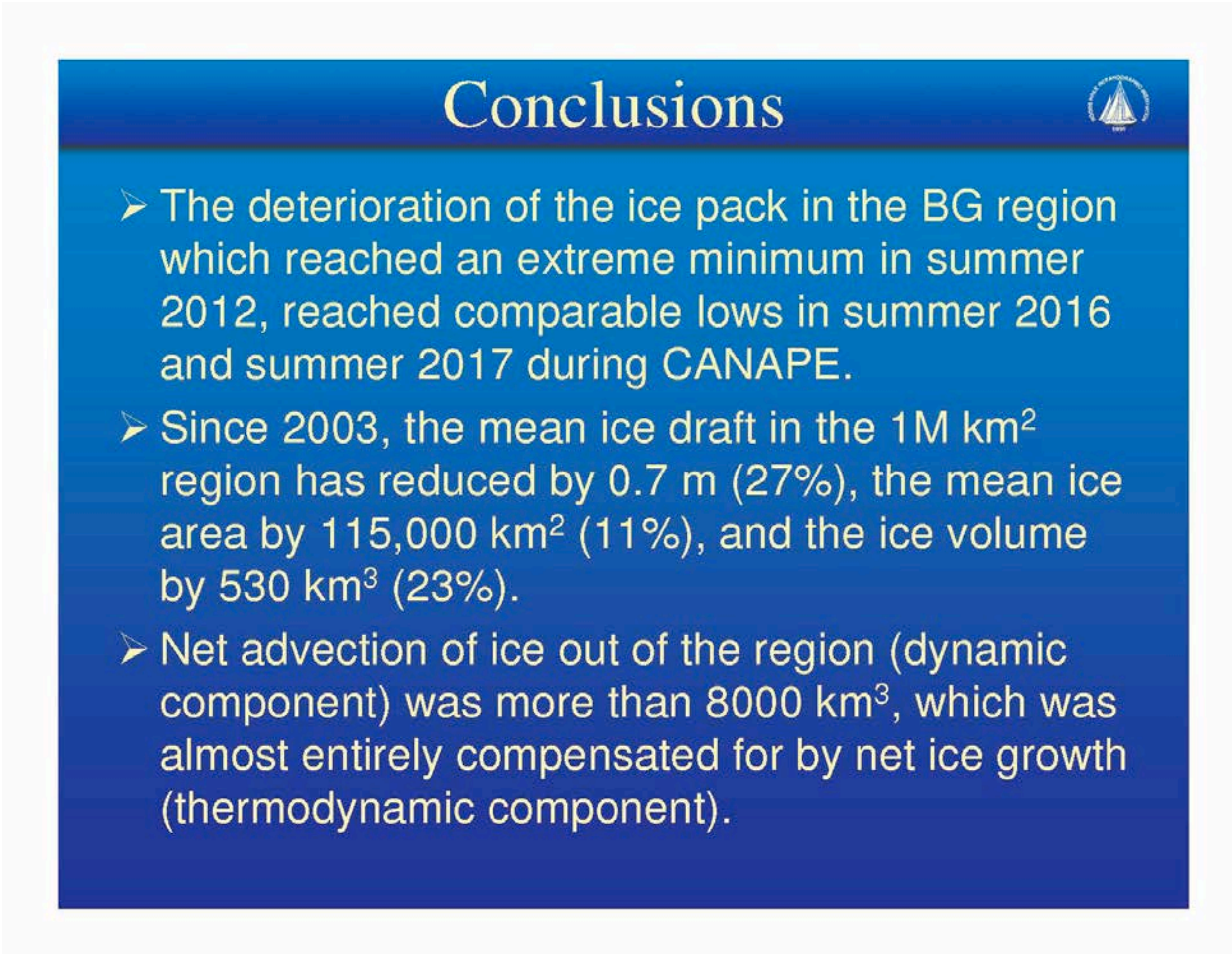
Rose plots of surface speeds (ice and open water) from the ADCP at each CANAPE mooring indicate the characteristics of flow at each site over the full year.

Ice draft PDFs at CANAPE moorings

Speeds from the ADCP data are used with the ice draft time series to produce spatial PDFs at each mooring site. During periods of open water, surface velocities are larger so that the non-ice (<10 cm) fraction is greater than ~60% at all moorings.

Note that the time period covered by each mooring differs due to gaps in the time series when the moorings were pushed deeper than the instrument ranges.





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