Arctic Ocean Storm Surges: origin, climatology, impacts, simulations and predictions

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Session 01: Driving factors and scales of storm surges

Storm Surges Congress 2010: *Risk and Management of current and future Storm Surges*, 13 – 17 September 2010, University of Hamburg, Germany

Outline/summary

- Critical environmental, socioeconomic, and defense issues have focused the people's attention on the coastal zone.

- This zone is particularly vulnerable in the Arctic, where unprecedented climate changes have already been observed in the context of high natural variability on a range of time scales.

- Key environmental issues affecting human activities on the Alaskan North Slope and Siberian coastal regions include:
  - coastal erosion,
  - recent decline in ice extent and thickness,
  - less stable and predictable shore-fast ice, gouging of shelves and coast by sea ice, pile-up of ice on shore,
  - rise in sea level, and storm hazards.

- One element of the observed climate change is the increased frequency and intensity of extreme events.

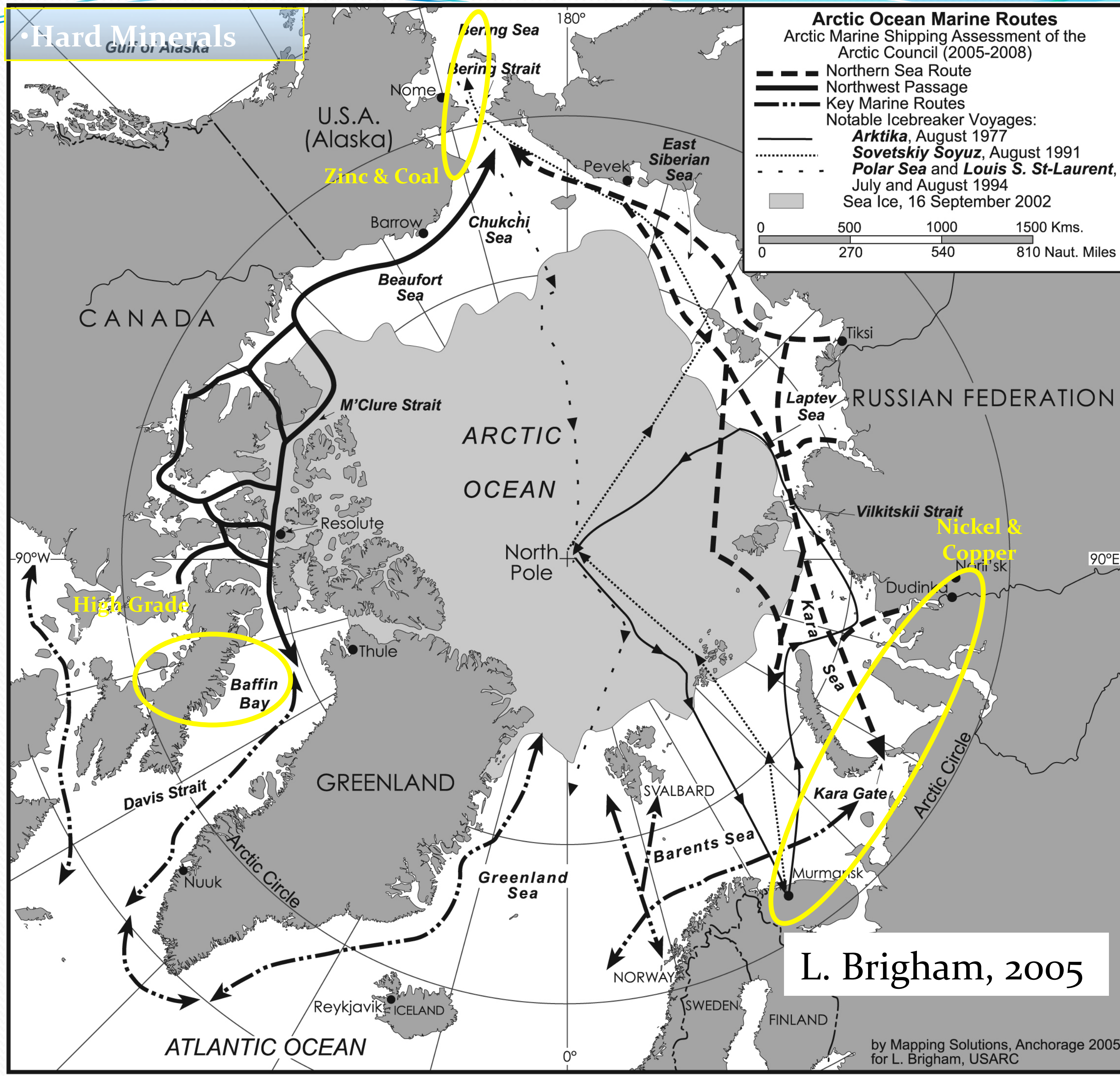
What is the Arctic?

There are different definitions of the Arctic Region.

This is 10°C air temperature isotherm in July.

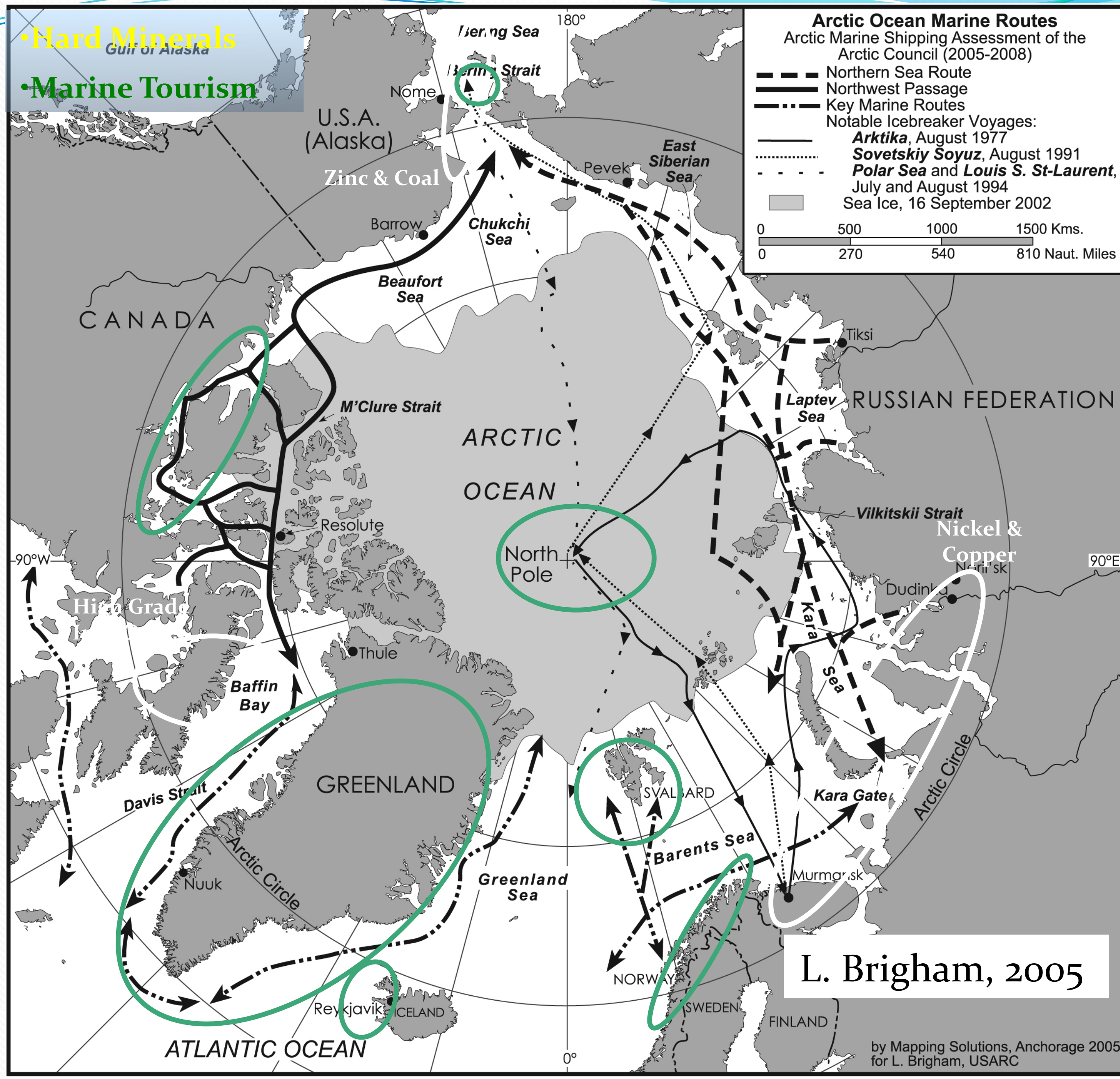
For "arctic storm surges" – this could be: where sea ice influences storm surges

Today's Arctic Marine Use

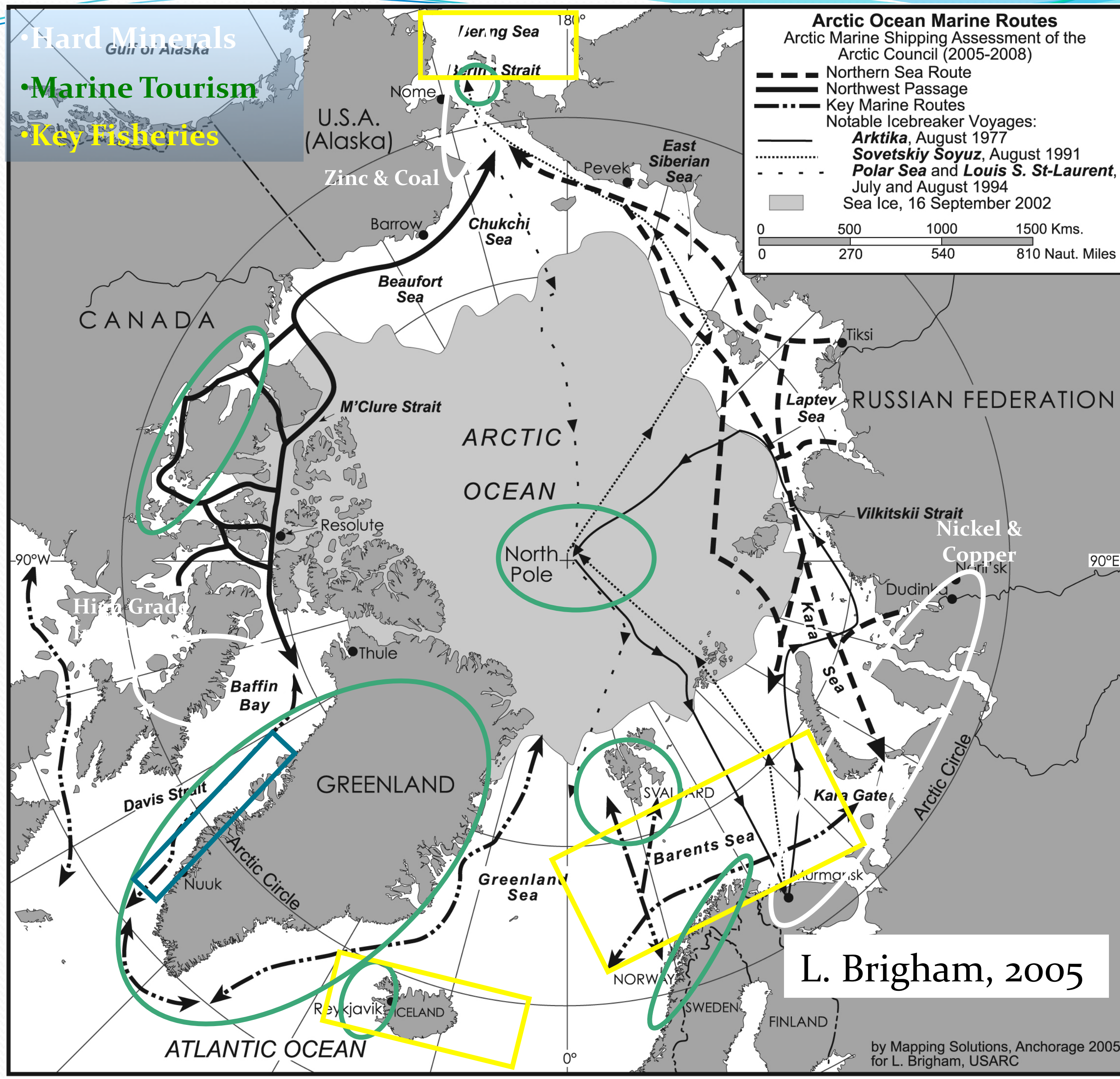


L. Brigham, 2005

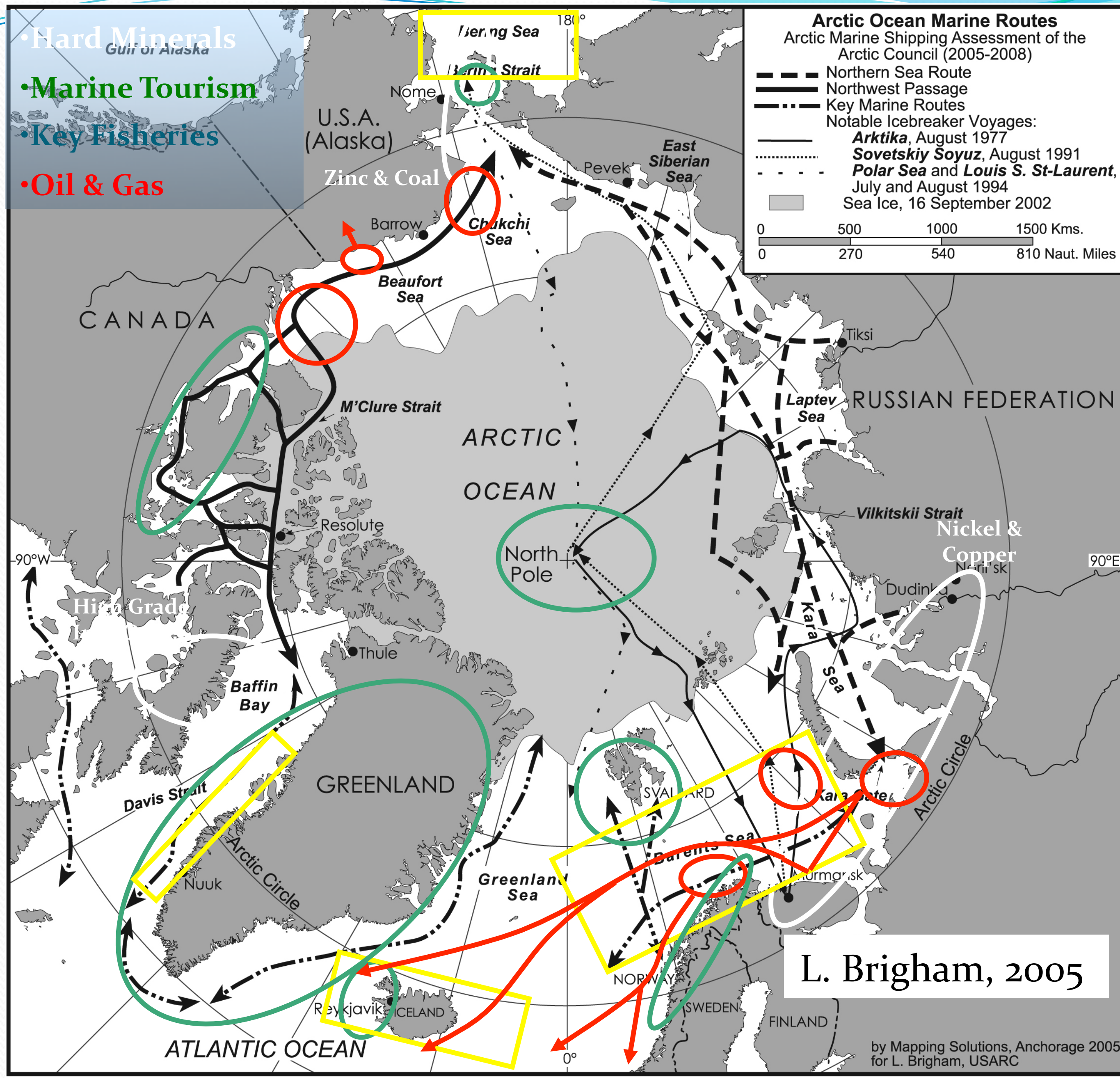
Today's Arctic Marine Use



Today's Arctic Marine Use



Today's Arctic Marine Use



- Coastal erosion… (October 2004)
  (Shishmaref on the Chukchi Sea coast)

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  (Shishmaref on the Chukchi Sea coast)

- … and flooding (inundation – storm and tsunami) (Teller, on the Bering Strait)

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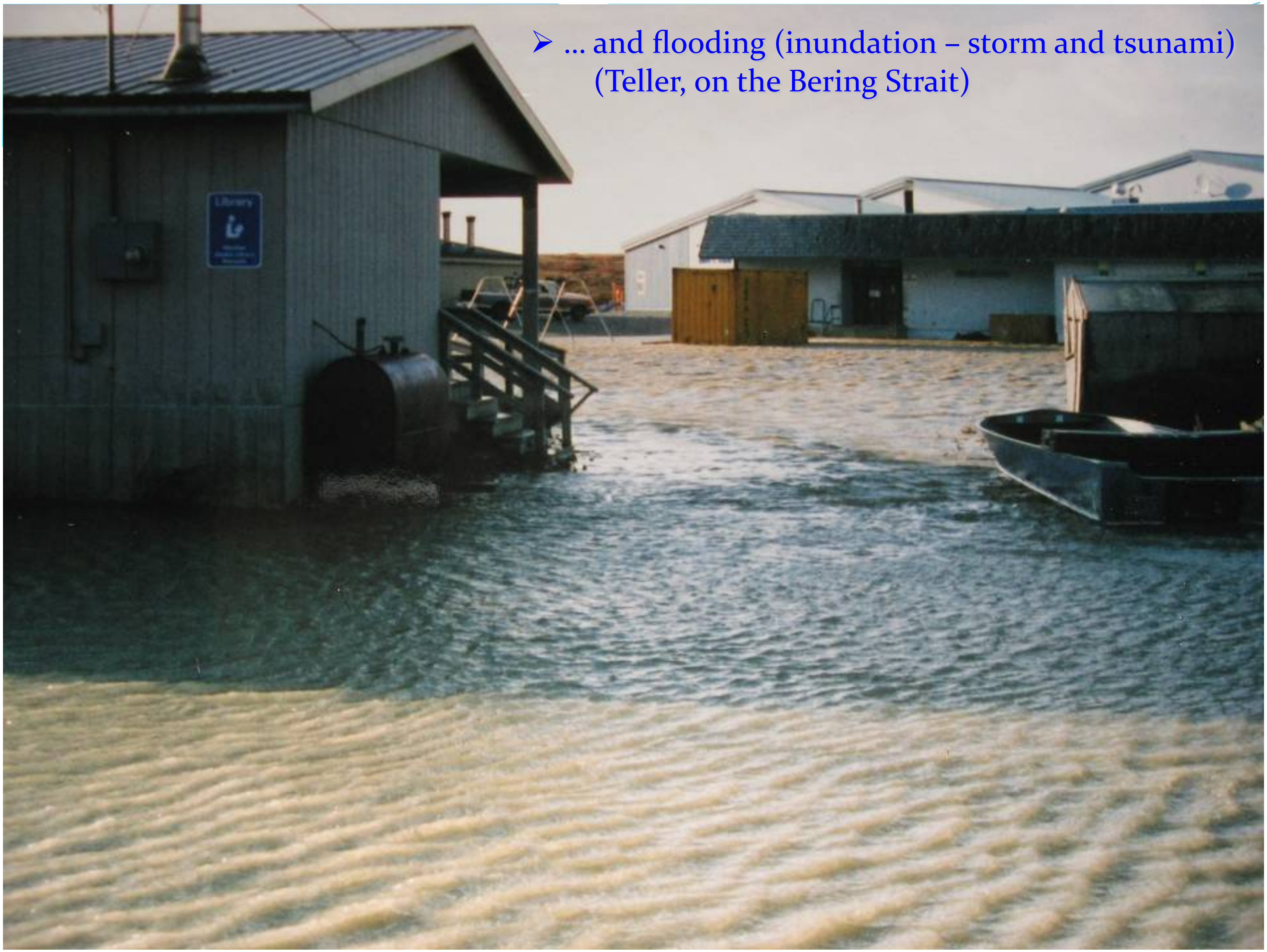
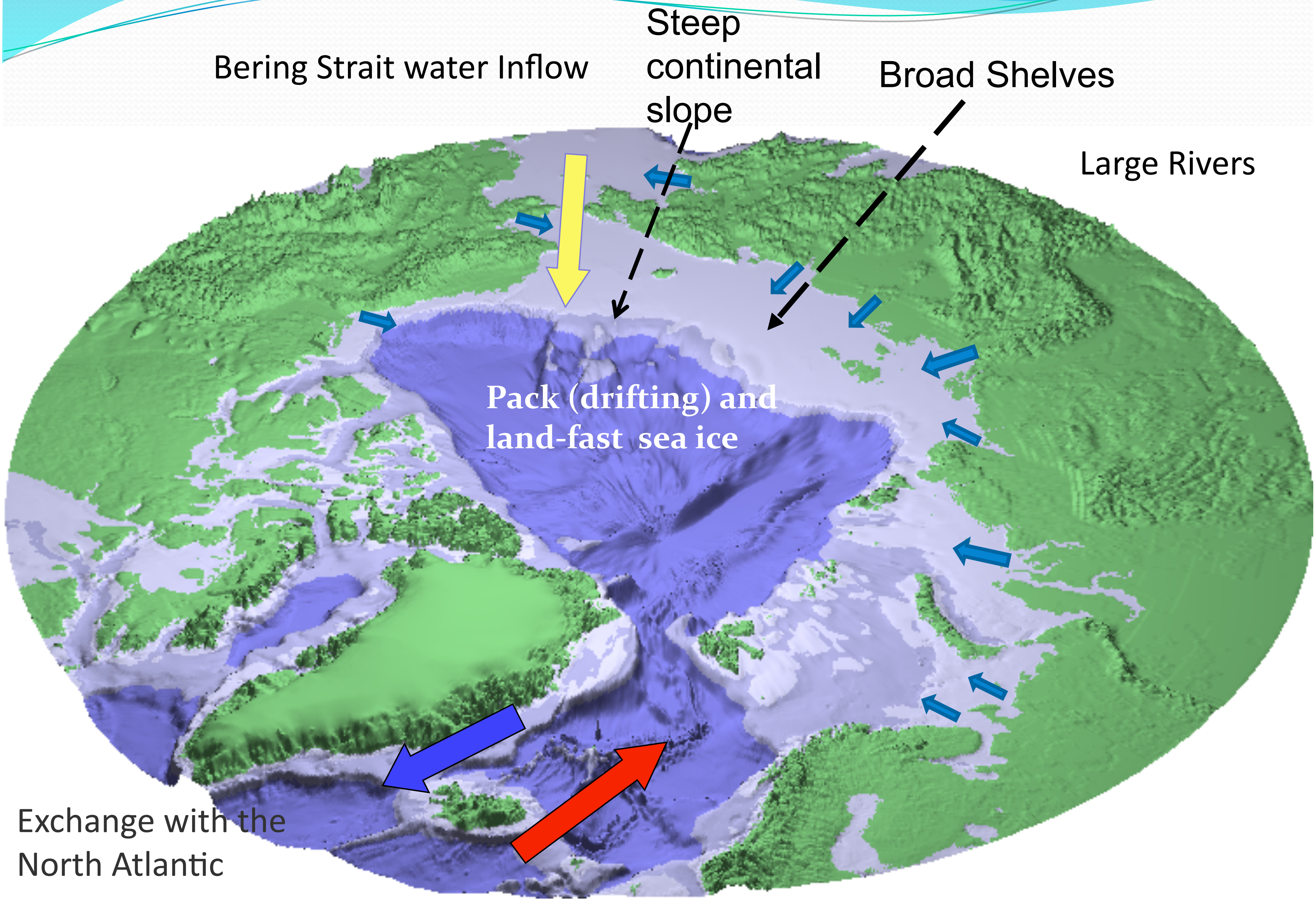


Shishmaref bluff retreat

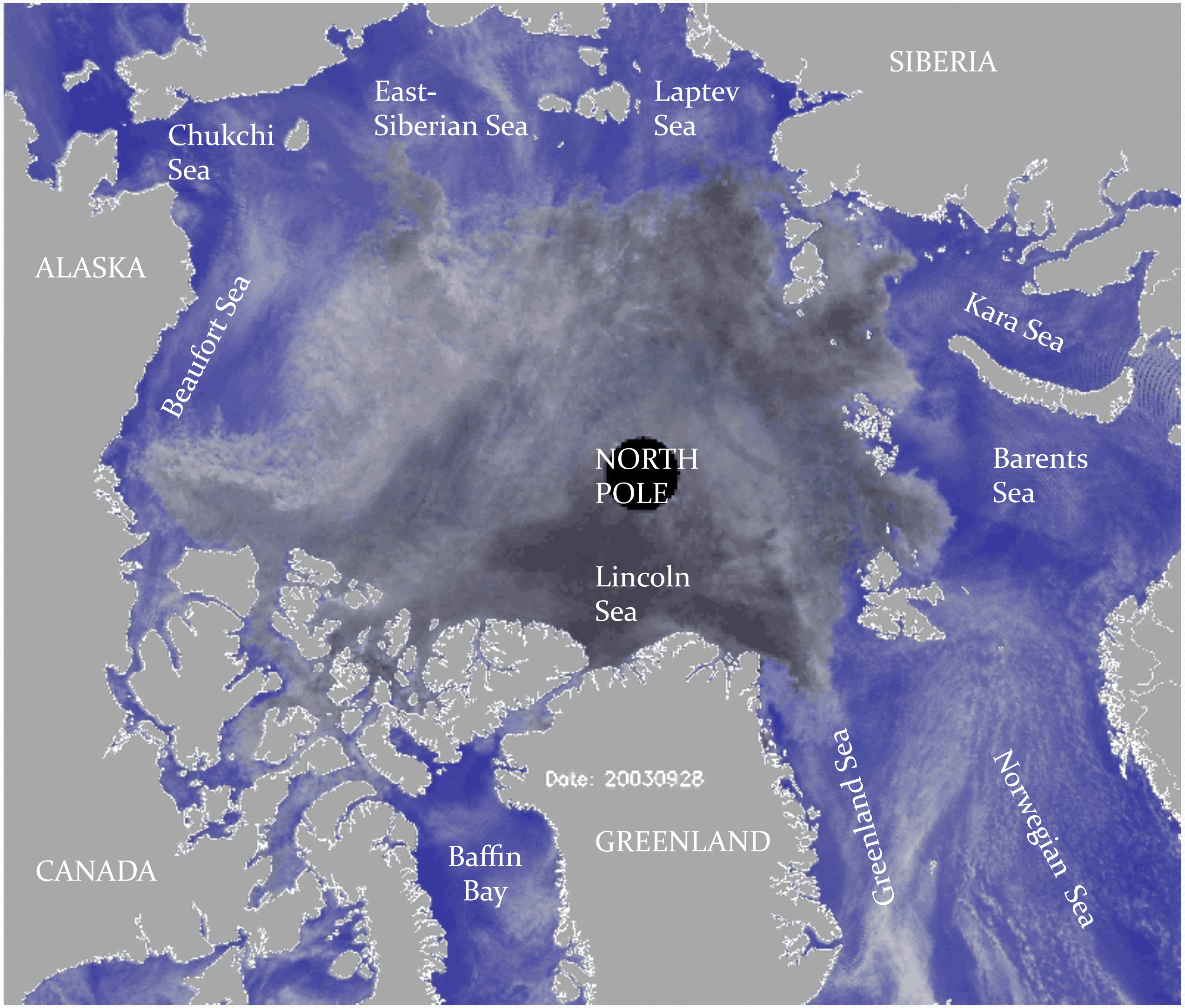
Photos by Julie Baltar , story in the Nome Nugget
Shishmaref, AK

Arctic Ocean features influencing storm surges



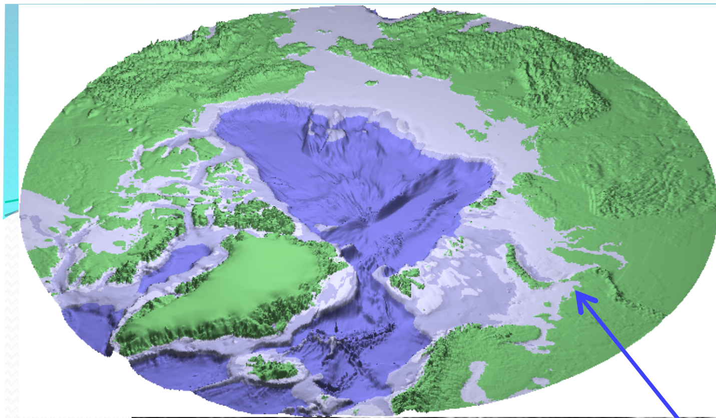
Origin

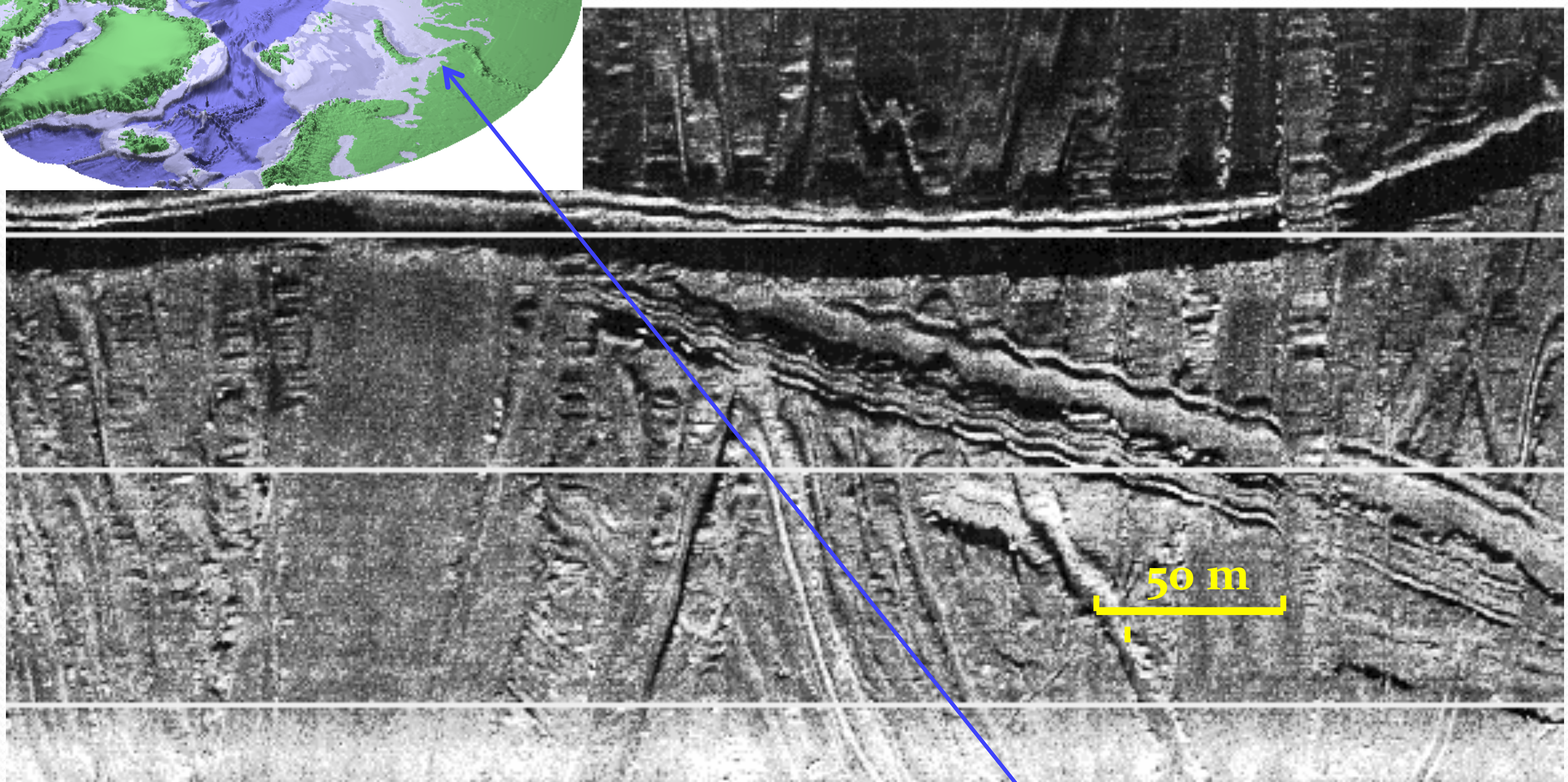
The major difference between storm surges in the Arctic and mid and low latitude oceans is the presence of sea ice which regulates momentum, heat and salt fluxes between the ocean and atmosphere.



SIBERIA
East-
Siberian Sea
Laptev
Sea
Chukchi
Sea
ALASKA
Beaufort Sea
Kara Sea
NORTH
POLE
Barents
Sea
Lincoln
Sea
Date: 20030928
Greenland Sea
Norwegian Sea
GREENLAND
Baffin
Bay
CANADA

Arctic stamukhi - thick ridges that become grounded during the winter and become part of the fast ice zone; while the rest of the fast ice melts during the summer, a stamukhi remains throughout the summer attached to the ocean bottom.



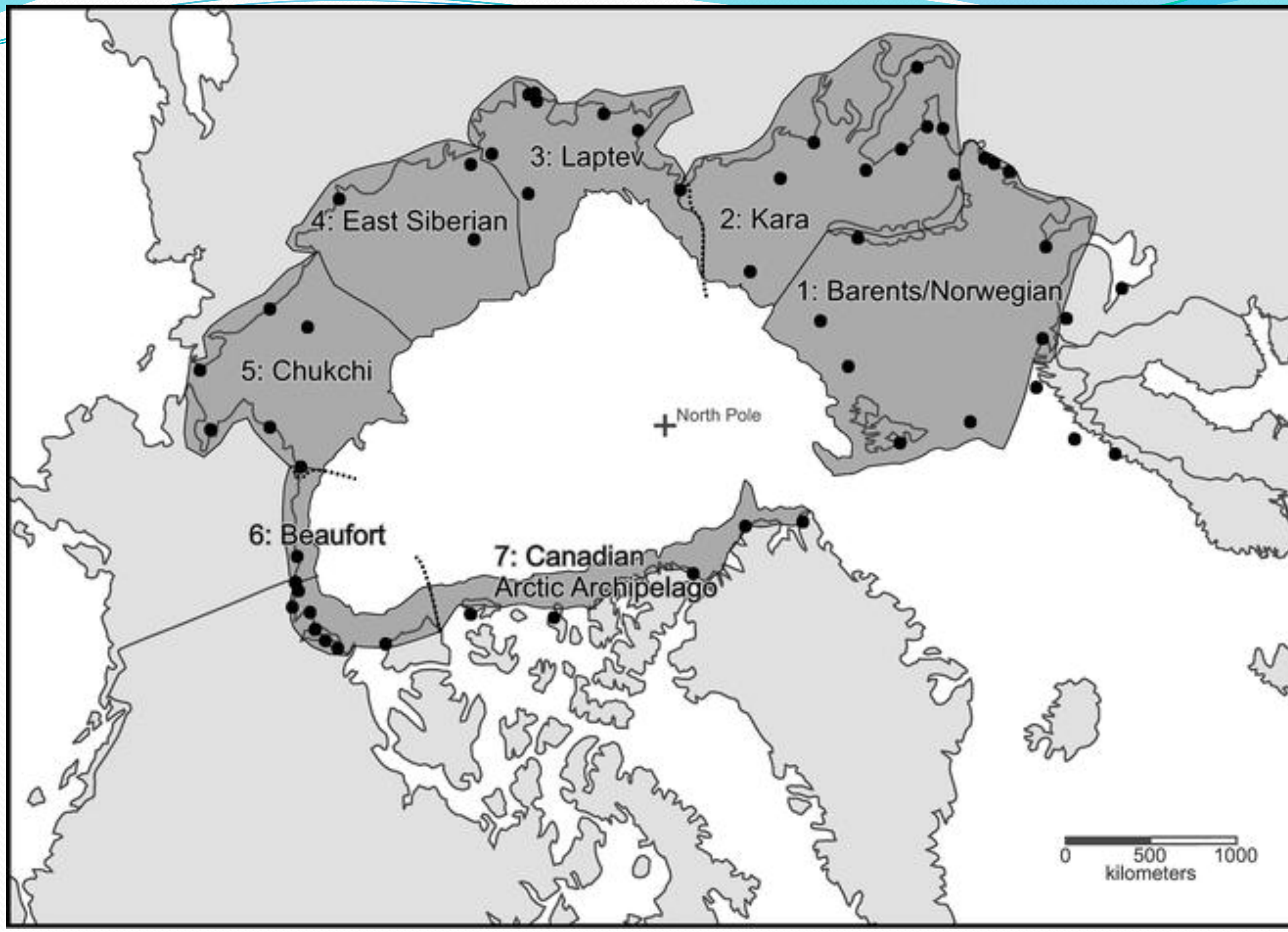


Ice gouges. Fragment of sonar records (Baydaratskaya Bay, 2007, 18 m depth)

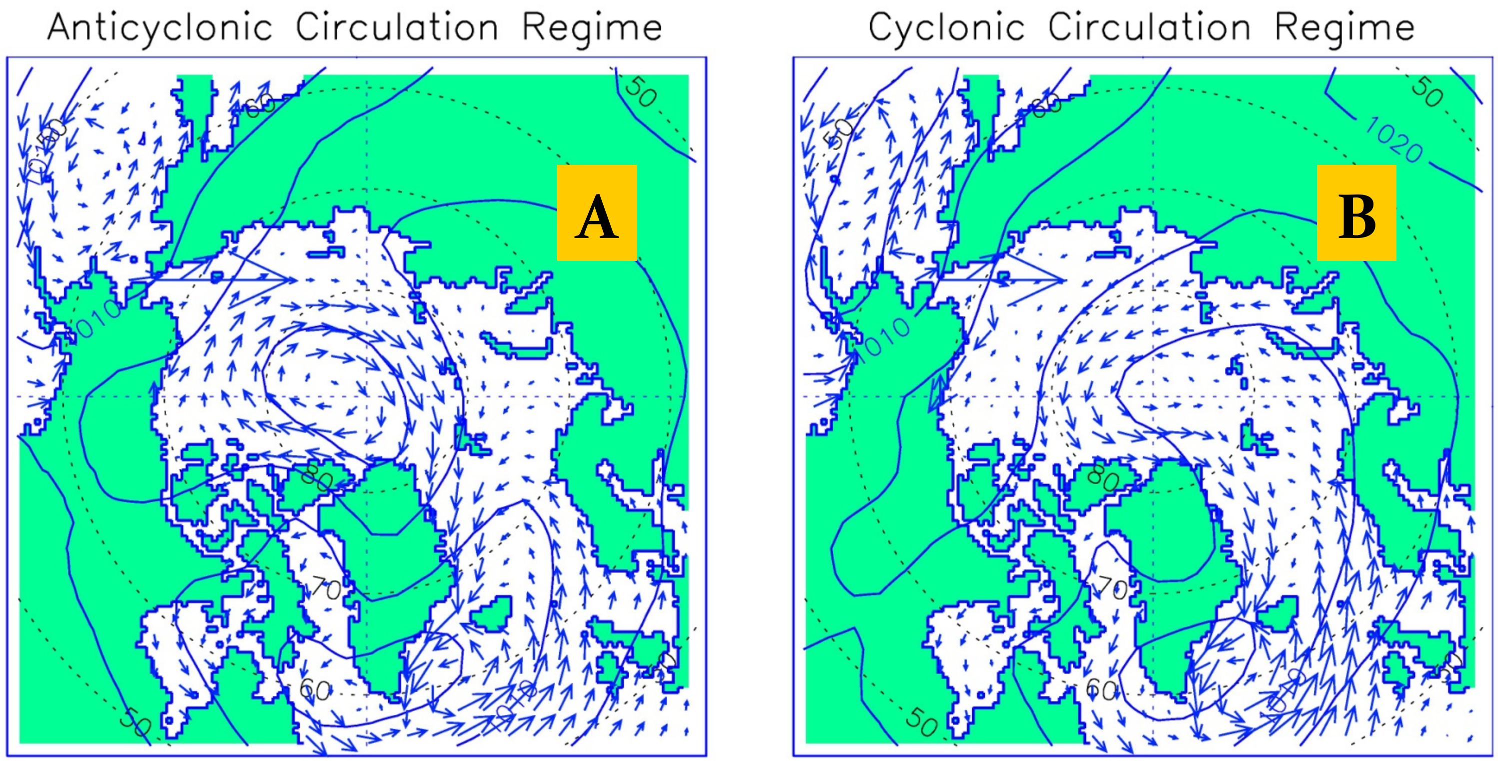
"The role of sea ice in coastal and bottom dynamics in the Baydaratskaya Bay, Kara Sea" by S.A.Ogorodov et al. (ARCTIC COASTAL ZONES AT RISK, Workshop Proceedings Tromsø, Norway, 1.-3.10.2007

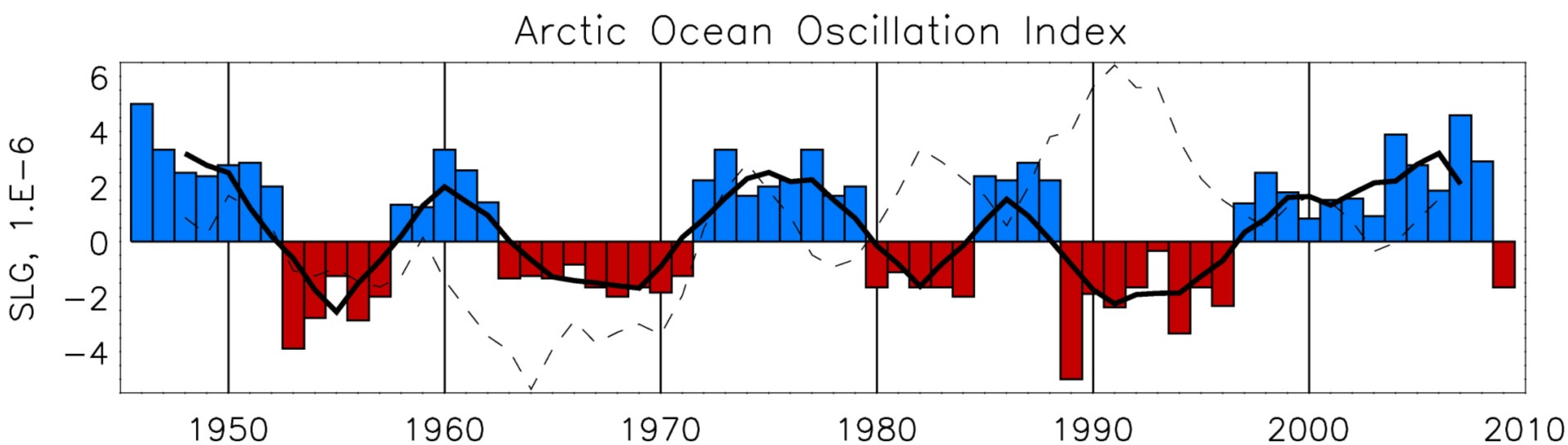
Grounded land-fast ice protects coastal erosion

Drifting pack ice destroys coastlines eroding hundreds of meters of shoreline

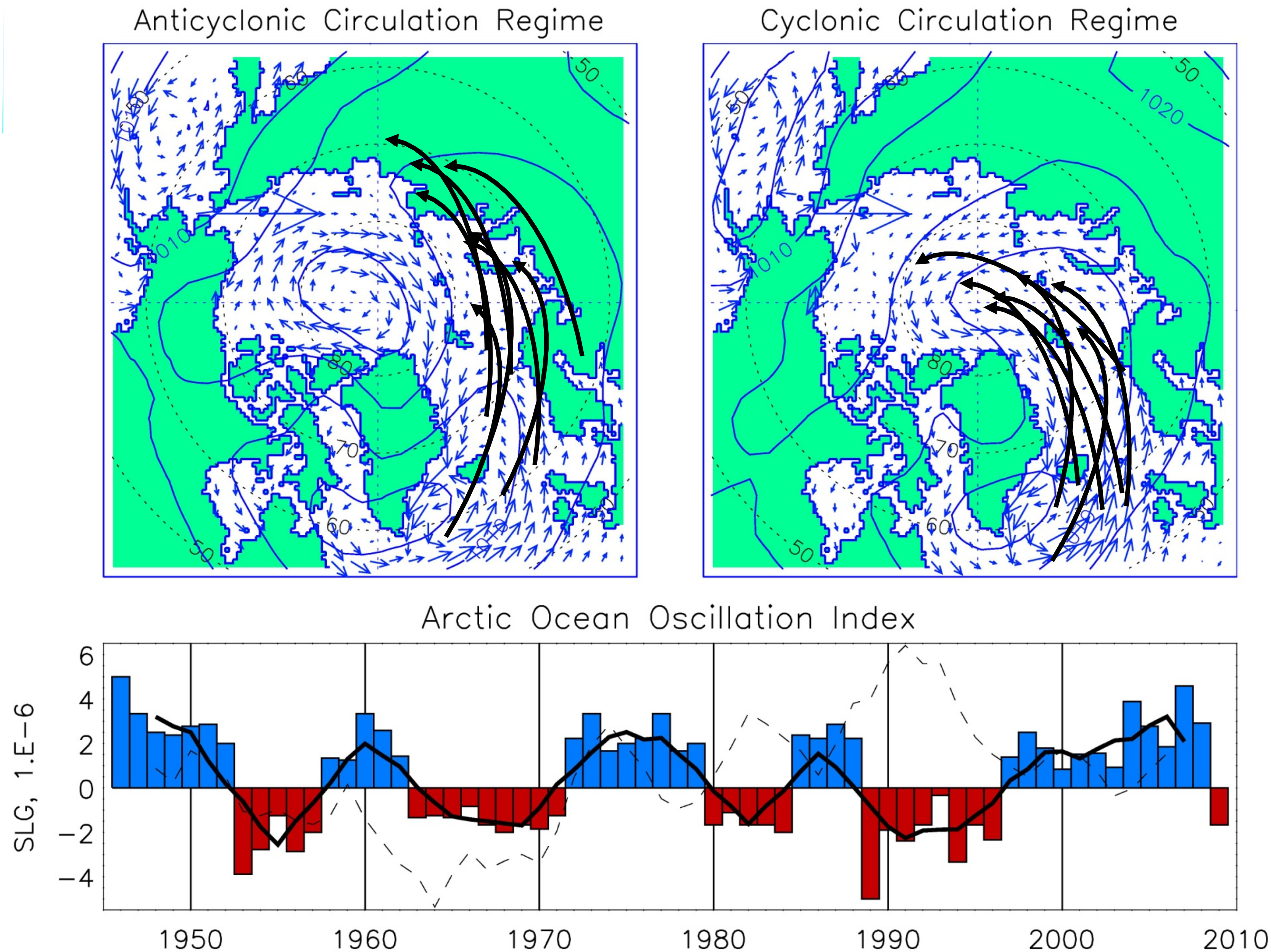


The circum-polar region. Sectors identified by the Arctic Coastal Dynamics project are shown as *grey zones*. Station locations are indicated by *black dots*. (courtesy of David Atkinson [2005]).



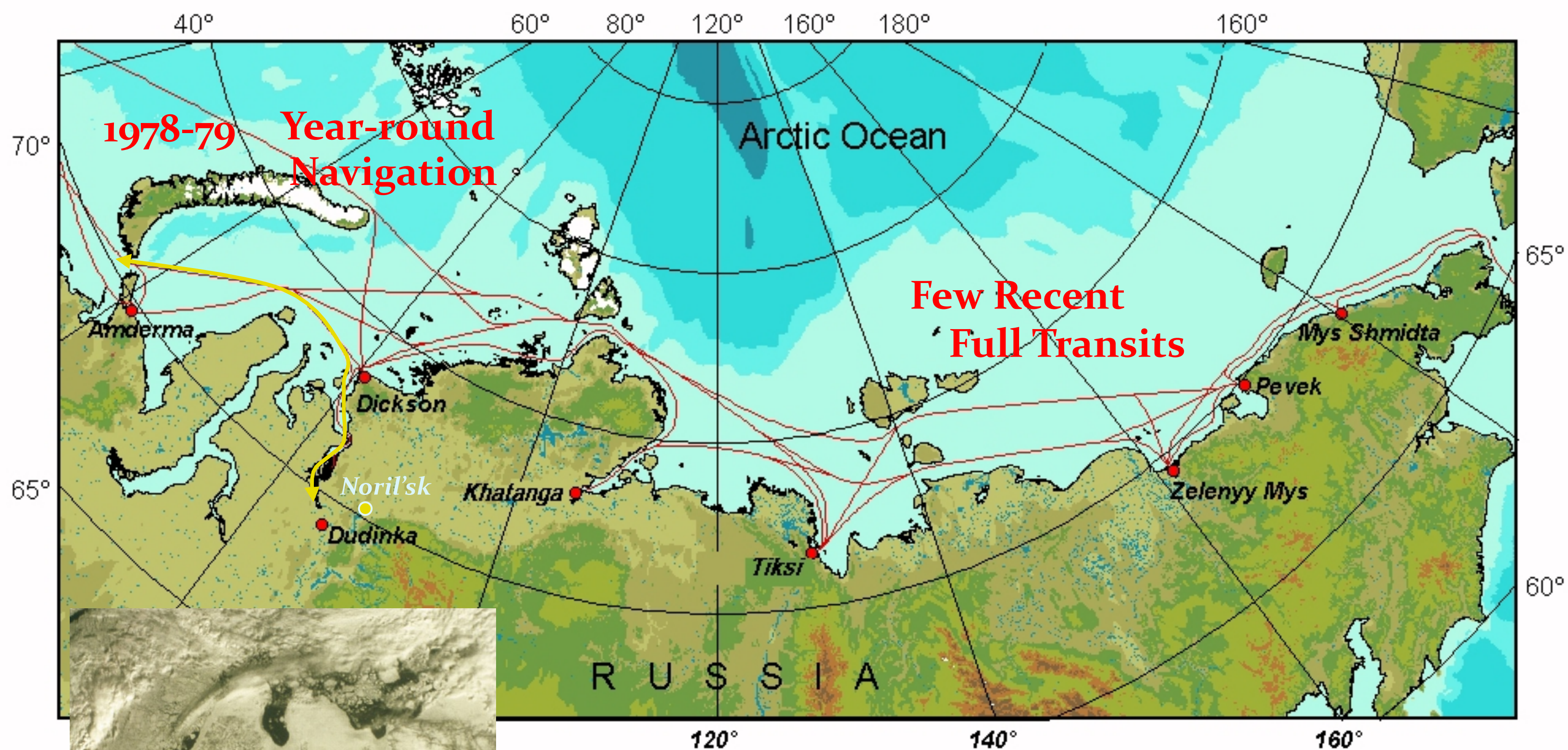


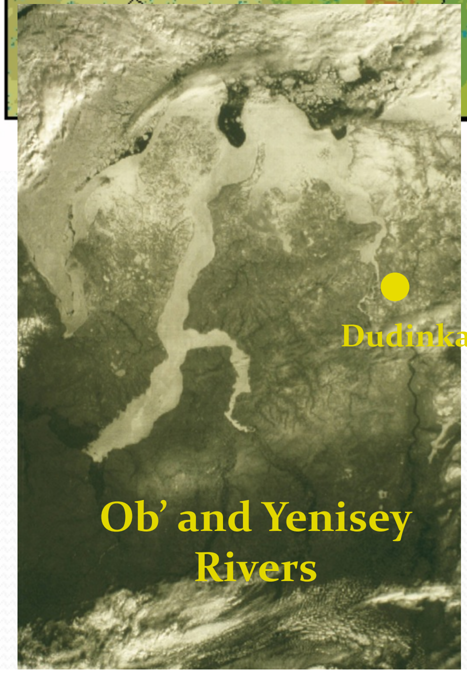
Proshutinsky and Johnson, 1997 (JGR) updated



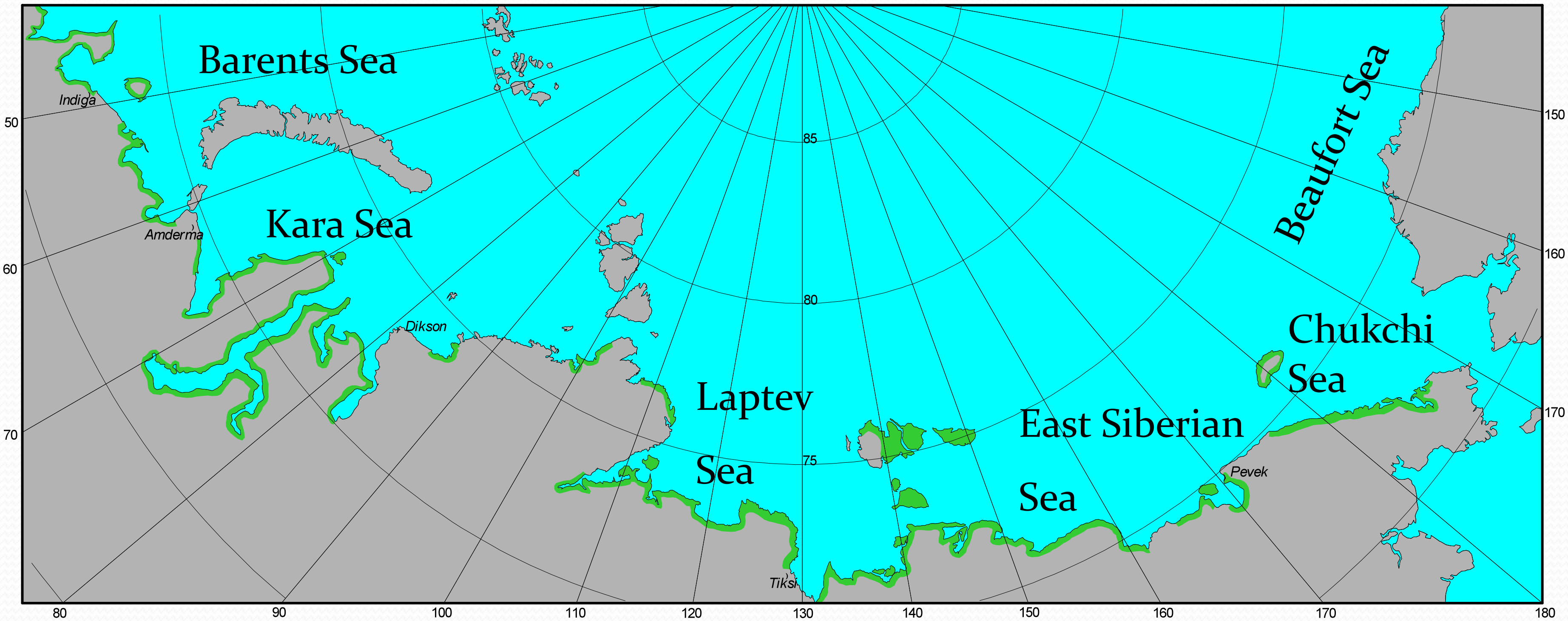
Anticyclonic Circulation Regime
Cyclonic Circulation Regime
Arctic Ocean Oscillation Index
SLG, 1.E−6
6
4
2
0
−2
−4
1950
1960
1970
1980
1990
2000
2010

The Northern Sea Route



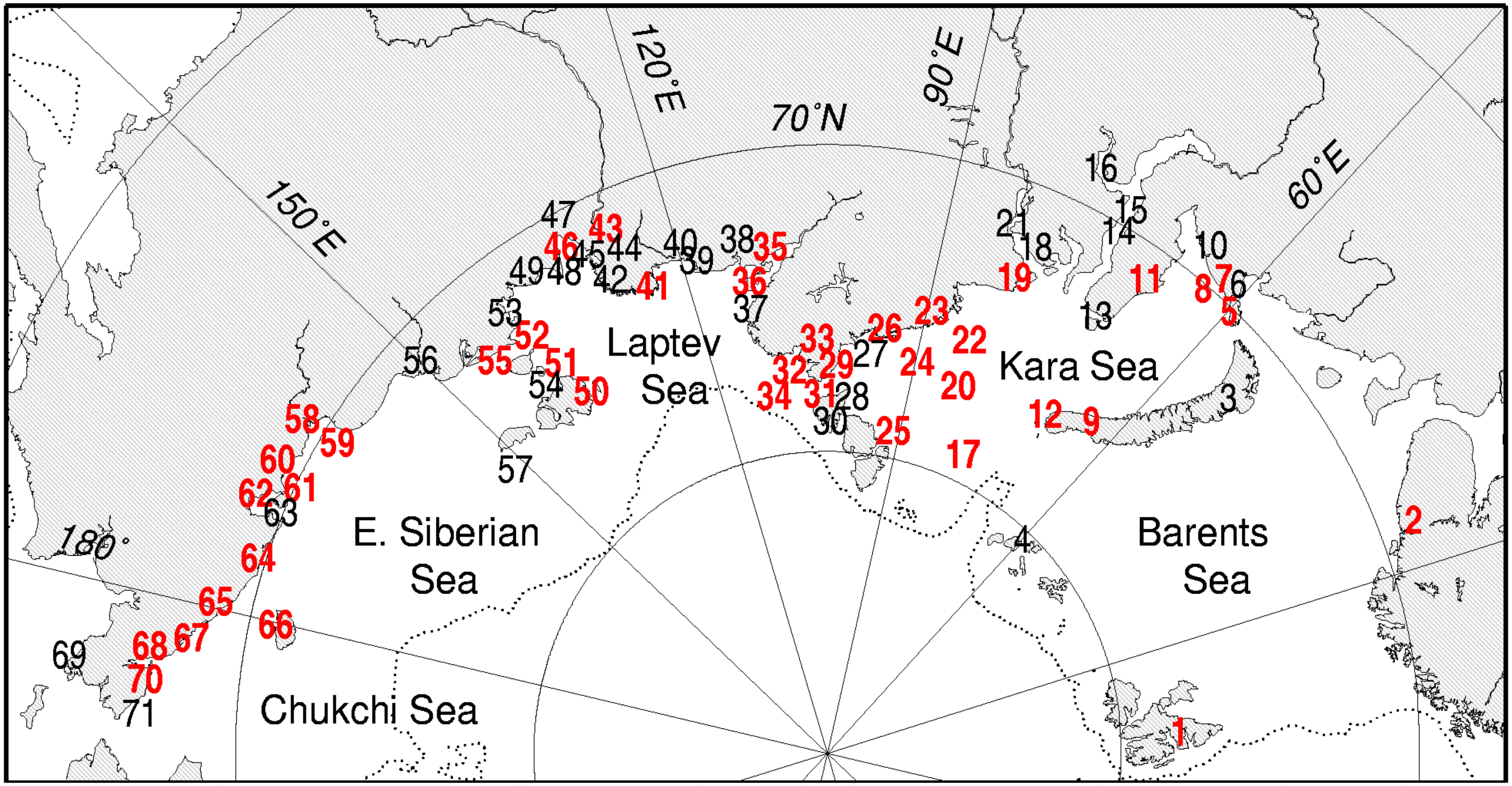


Coastal regions with low relief are significantly influenced by storm surges



The combination of waves and high water levels during late summer and fall storms before the development of significant sea-ice cover can be particularly damaging to shorelines

Sea Level data sources



Sea level data sets were collected by the Arctic and Antarctic Research Institute for 71 stations (see station numbers) located in the Barents and Siberian Seas. The time series of sea level variability generally cover the period between 1948 and 2000 but temporal coverage differs significantly from station to station. Red denotes stations with the most complete datasets.

http://www.whoi.edu/science/PO/arcticsealevel

INVESTIGATION OF
ARCTIC SEA LEVEL RISE

Overview | Participants | Data | Publications | Conclusions

Overview

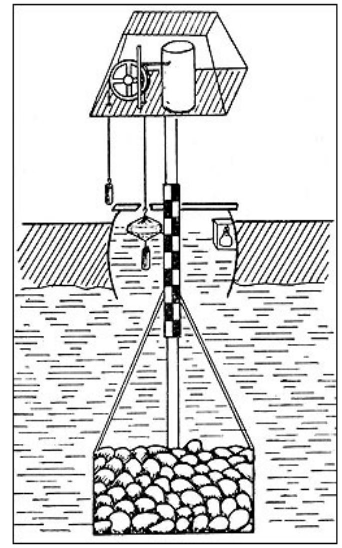


Diagram of a typical sea level gauge.

Sea level is a natural integral indicator of climate variability. It reflects changes in practically all dynamic and thermodynamic processes of terrestrial, oceanic, atmospheric, and cryospheric origin. The use of estimates of sea level rise as an indicator of climate change therefore incurs the difficulty that the inferred sea level change is the net result of many individual effects of environmental forcing. Since some of these effects may offset others, the cause of the sea level response to climate change remains somewhat uncertain. This project is focused on an attempt to provide first order answers to two questions, namely:

1) What is the rate of sea level change in the Arctic Ocean? and
2) What is the role of each of the individual contributing factors to observed Arctic Ocean sea level change?

Unlike most other manifestations of climate change, sea level rise is already a significant problem throughout the Arctic (ARCUS, 1997; Shaw et al., 1998; Brown and Solomon, 2000; Forman and Johnson, 1998; IASC, LOIRA, 2000; Smith and Johnson, 2000). Global warming and the anticipated sea level rise in the Arctic is expected to influence shoreline erosion, sediment transport, navigation conditions, oil and gas operations, hunting, and other human activities. In January 2000, the Alaska Science and Technology Foundation sponsored a workshop entitled "The Warming World: Effects on the Alaska Infrastructure" (University of Alaska Anchorage). Workshop participants concluded that sea levels will rise, storms will be stronger and more frequent, and coastal communities now struggling with erosion will see shoreline retreat accelerate (Smith and Johnson, 2000). The Intergovernmental Panel on Climate Change (IPCC, 2001) concluded that the rate of sea level rise in the 20th century was in the range 0.1-0.2 cm per year (http://www.ipcc.ch/).

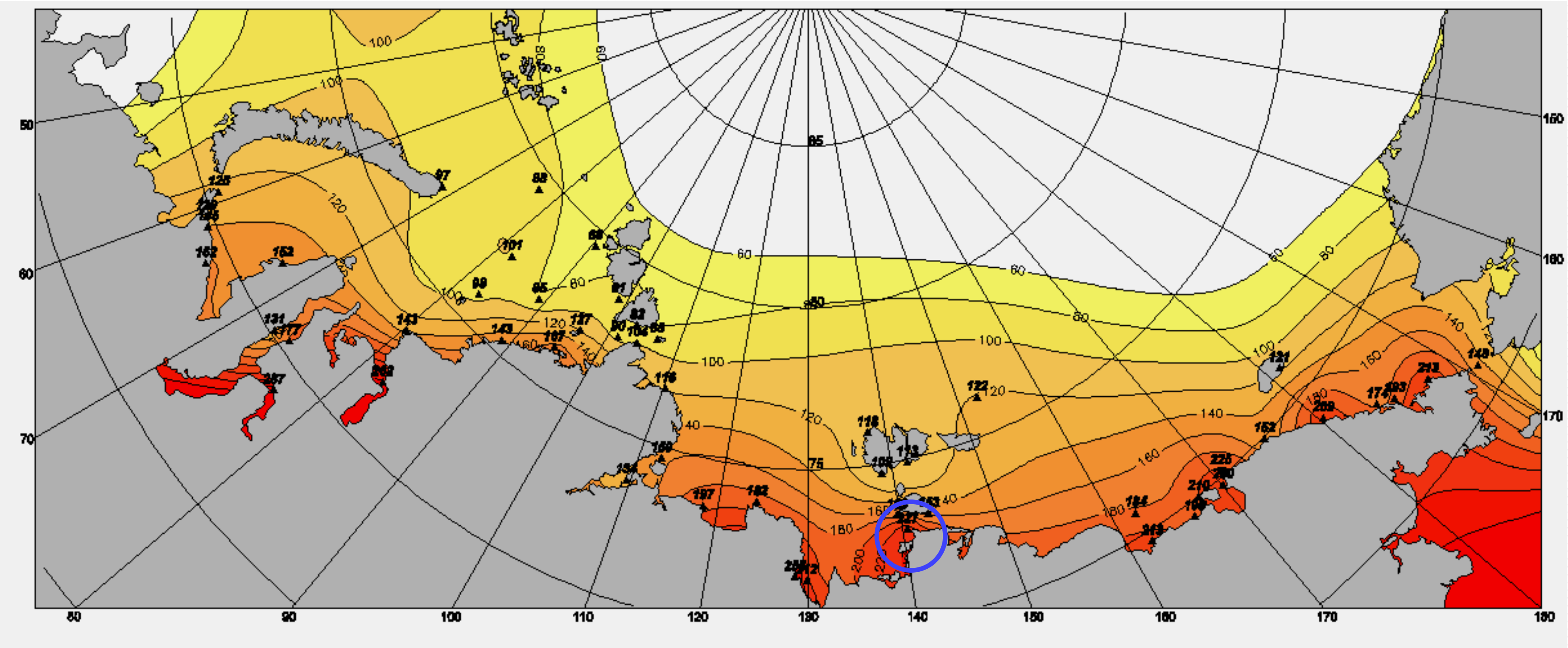
But what is the current rate of sea level rise in the Arctic Ocean and what is its cause? The search for an answer to this question constitutes a complex scientific problem because observed sea level change, if we are able to observe it accurately, is the net result of a myriad of individual effects of dynamic and thermodynamic processes of terrestrial, oceanic, atmospheric, and cryospheric origin.

A fundamental problem in determining the rate of sea level change in the Arctic has been the lack of accurate data from sites along the Arctic Ocean coastline. With the recent (January 2003) release of the data for the Russian sector of the Arctic this circumstance has improved dramatically. Approximately 70 tide-gauge stations in the Barents Sea and Siberian Seas (Kara, Laptev, East Siberian, and Chukchi Seas) have recorded sea level changes from the 1950s through the 1990s. Preliminary analysis has shown that over this 50-year period, most of these stations have a positive trend in sea level (e.g. Proshutinsky et al., 2001). These sea level data were collected by the Arctic and Antarctic Research Institute (AARI), St. Petersburg, Russia. The data sets have been made available for analysis by the international community and the monthly mean relative sea level records for all gauges are now included in the Permanent Service for Mean Sea Level archive (http://www.pol.ac.uk/psmsl/pub/nucat.dat).

The existing sea level data sets in the Arctic are relatively short for the analysis of global sea level rise. Peltier and Tushingham (1989), and Douglas (1991, 1992, 1997) have stressed the importance of employing very long records for this purpose (more than 60 years). Following a detailed analysis of the sea level rise detection problem, Douglas (2000), in particularly, concluded: "What is needed for an understanding of global sea level and its relation to climate is an accurate budget of the contributors to sea level rise...". Indeed, a major goal of the present contribution is to begin this task by calculating and assessing an accurate budget of the various contributions to sea level rise in the Arctic.

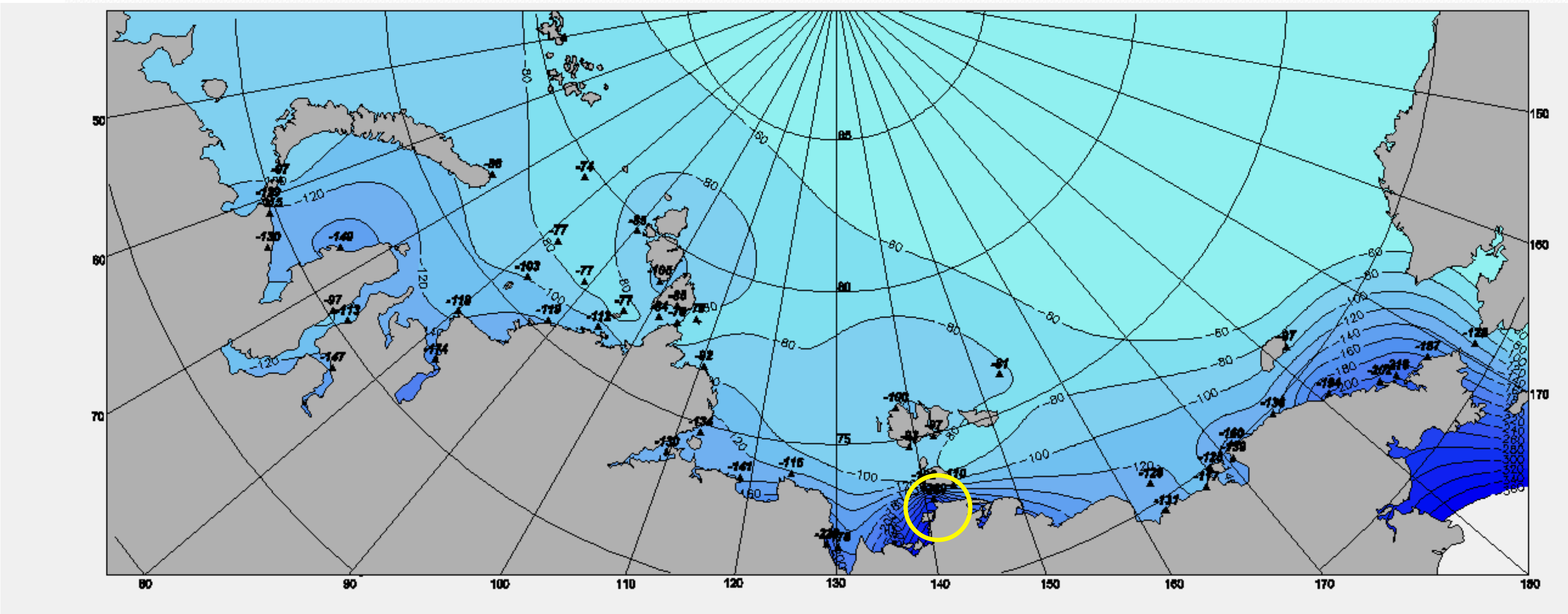
The study of sea level variability in the Arctic Ocean is important in its own right, primarily, because of its practical importance for people living and working in Arctic coastal regions. For them the current rates of local sea level rise are already causing severe problems. In addition, the variability of sea level in the Arctic Ocean can be used as an indicator of changes in ocean circulation (Proshutinsky and Johnson, 1997), water, ice and sediment transport, coastal erosion, and many other processes.

Observed maximum sea levels due to storm surges



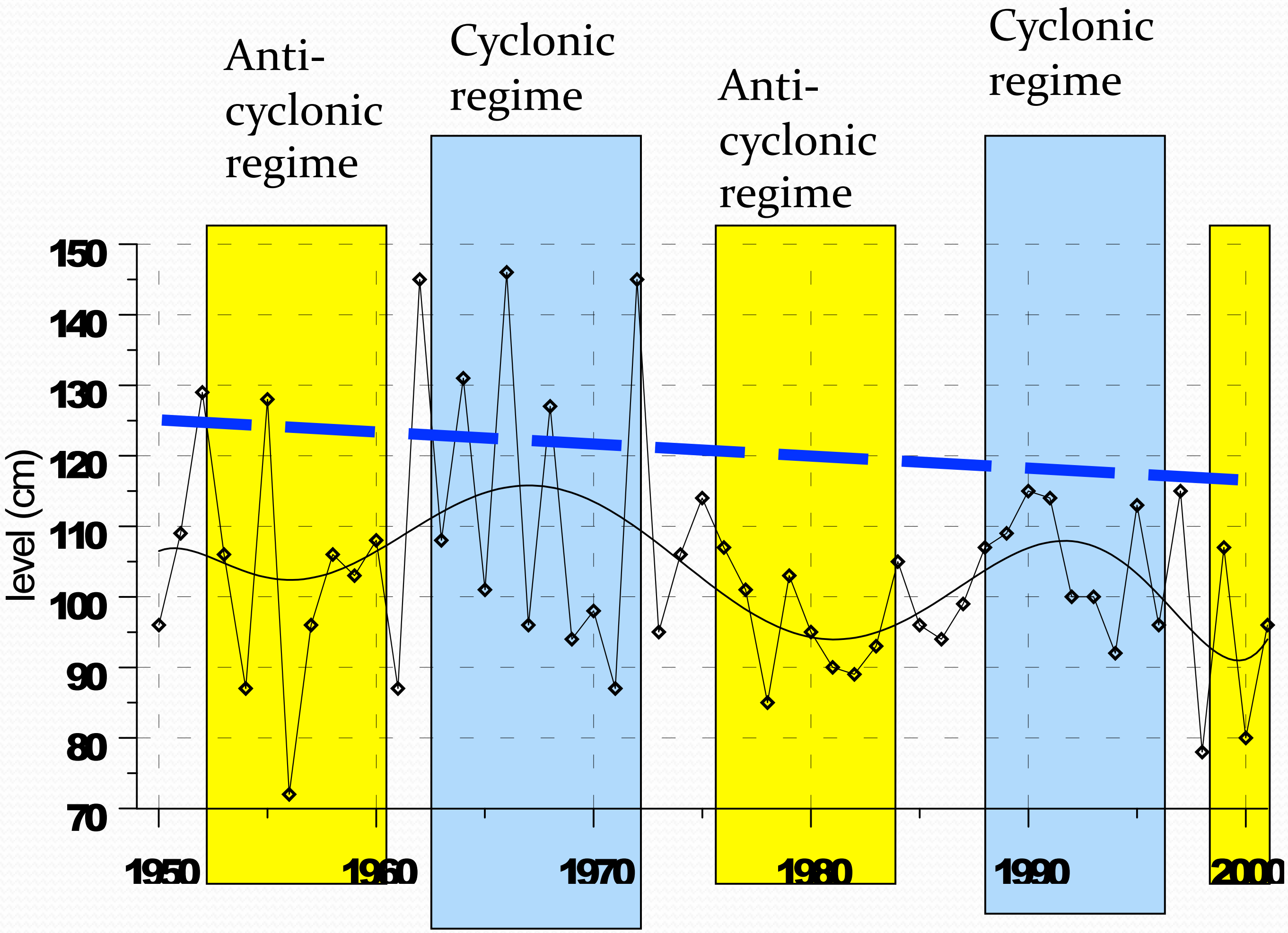
This figure shows distribution of maximum sea surface heights measured by coastal stations in the Siberian sector of the Arctic Ocean. The absolute maximum was observed in the southern part of the Laptev Sea.

Observed maximum sea levels due to storm surges



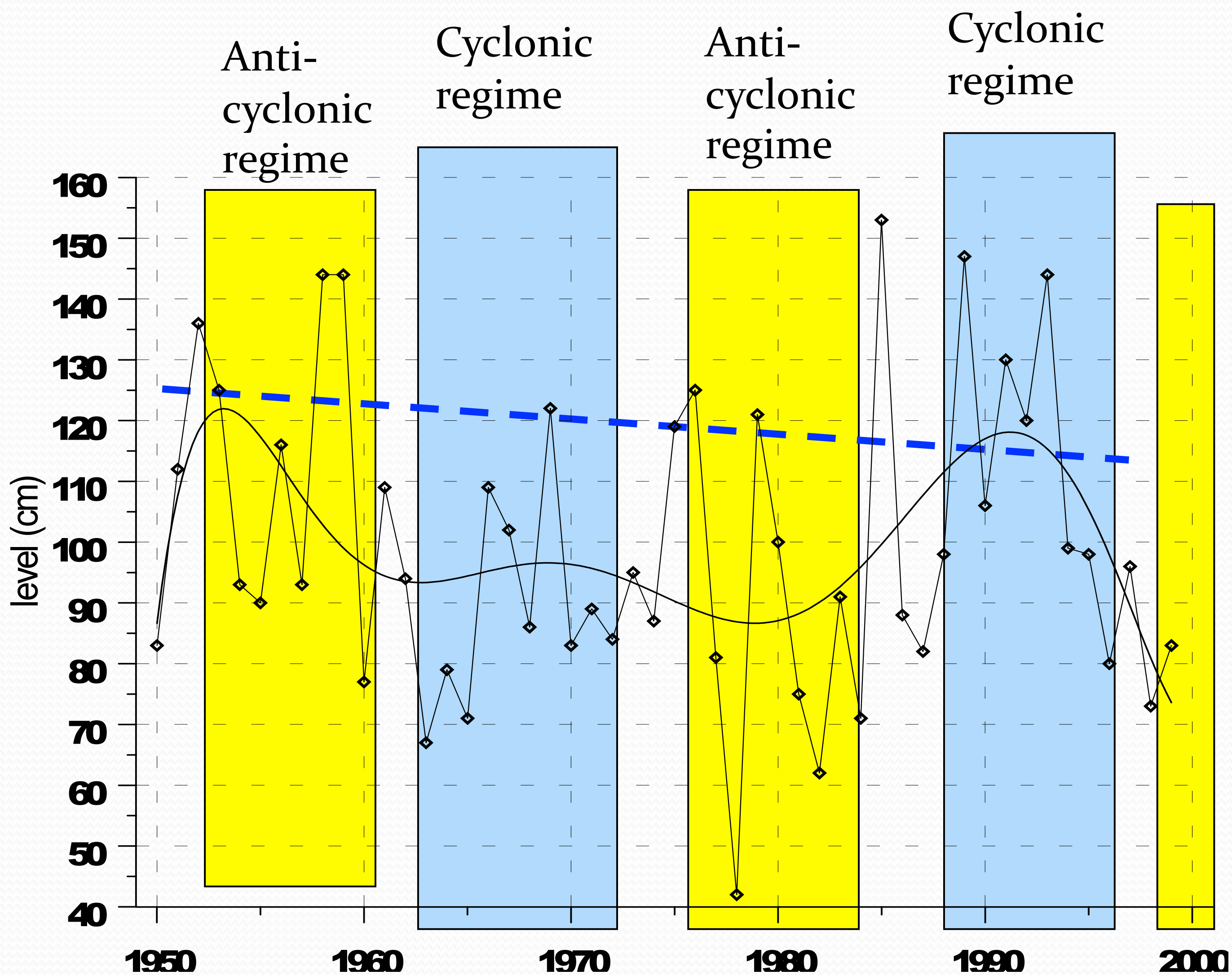
This figure shows distribution of minimum sea surface heights measured by coastal stations in the Siberian sector of the Arctic Ocean. The absolute minimum was observed in the southern part of the Laptev Sea.

Extreme sea levels for storm surges in the Kara Sea

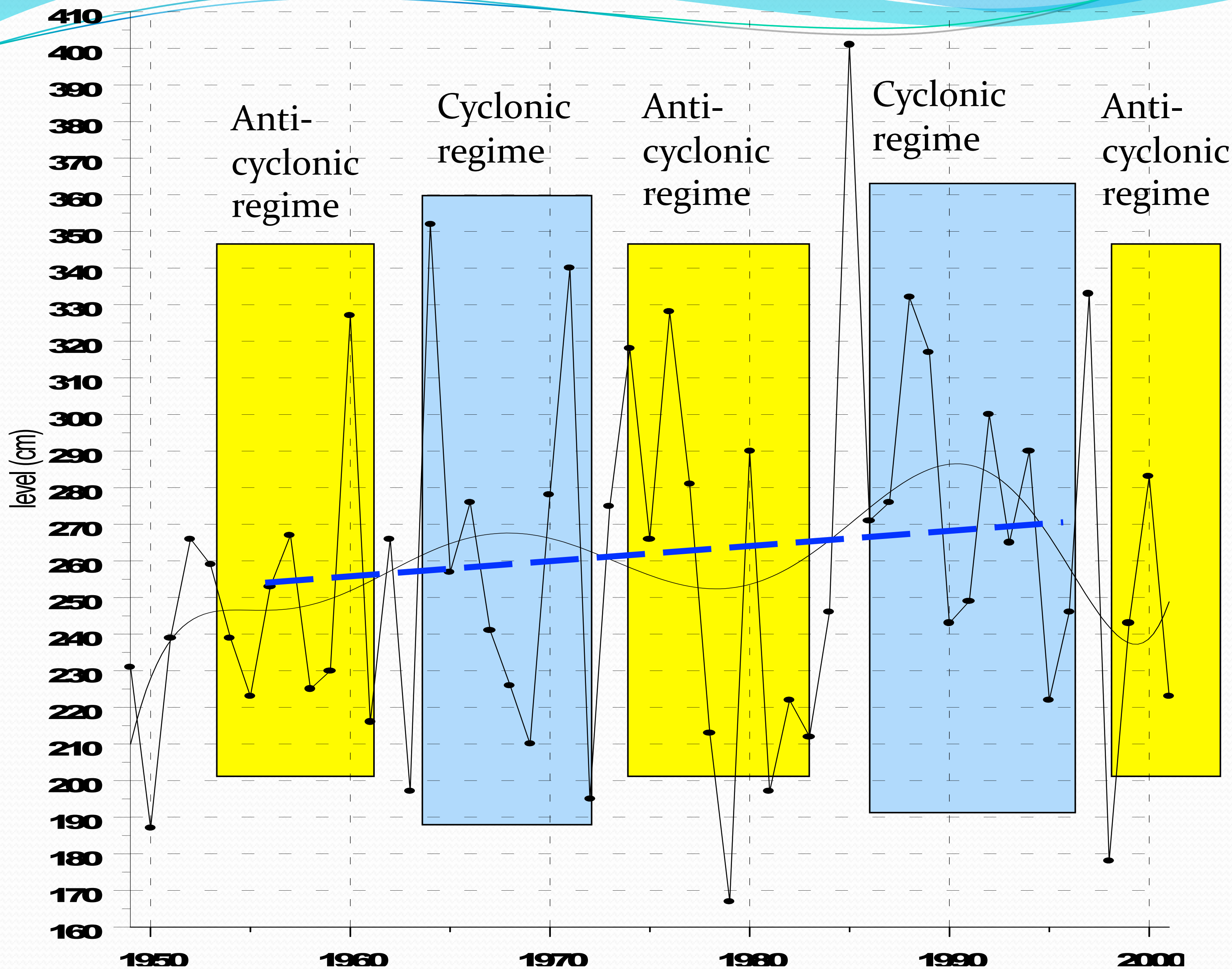


Years with prevailing cyclonic (blue) and anticyclonic (yellow) circulation regimes

Extreme sea levels for storm surges in the East-Siberian Sea

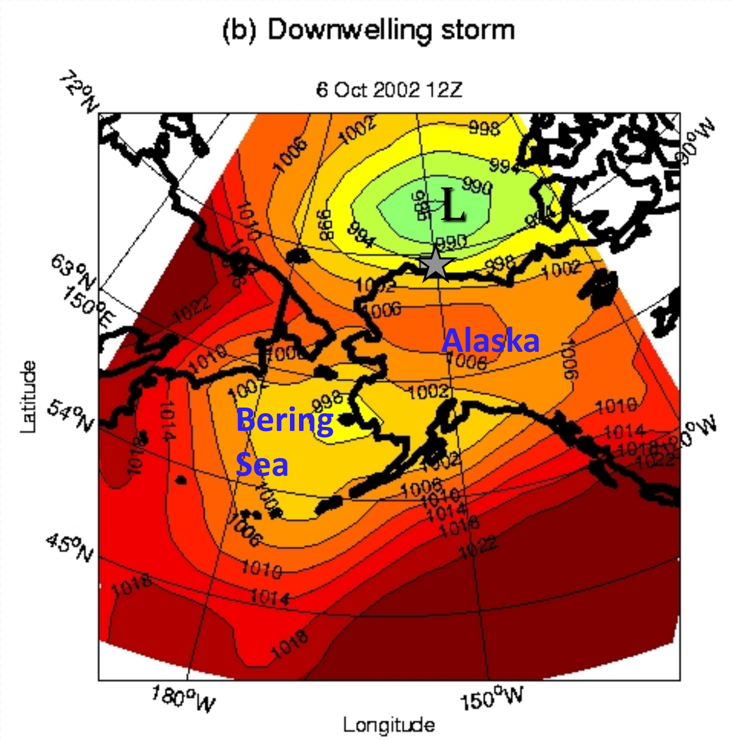


Extreme sea levels for storm surges in the Laptev Sea

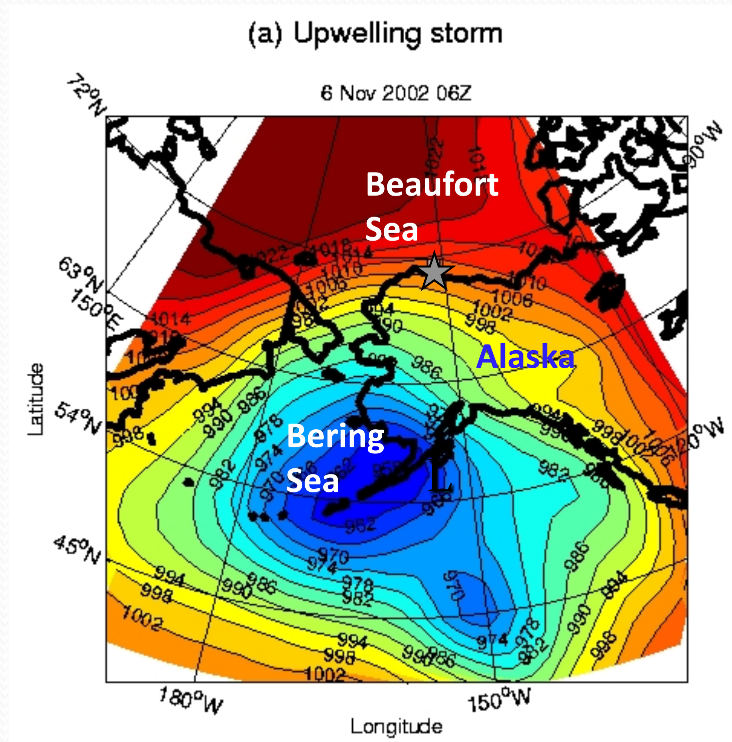


Storms impacting the Beaufort Sea

Arctic-born storm (downwelling)

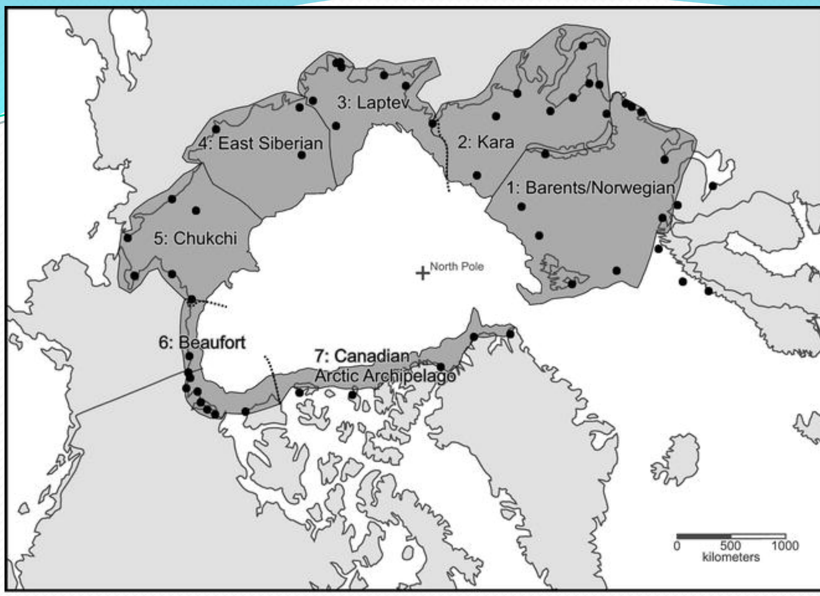


Pacific-born storm (upwelling)

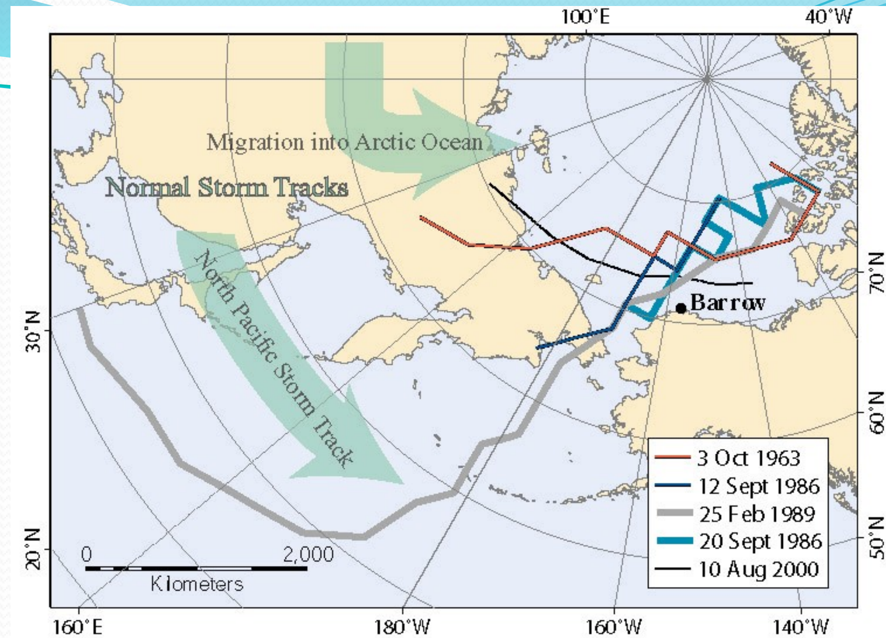


28 upwelling and 7 downwelling storms in 2002-3 alone!

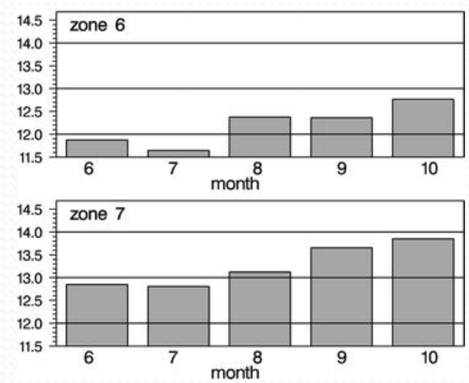
Pickart, R. S., G. W. K. Moore, D. J. Torres, P. S. Fratantoni, R. A. Goldsmith, and J. Yang (2009), Upwelling on the continental slope of the Alaskan Beaufort Sea: Storms, ice, and oceanographic response, J. Geophys. Res., 114, C00A13, doi:10.1029/2008JC005009.



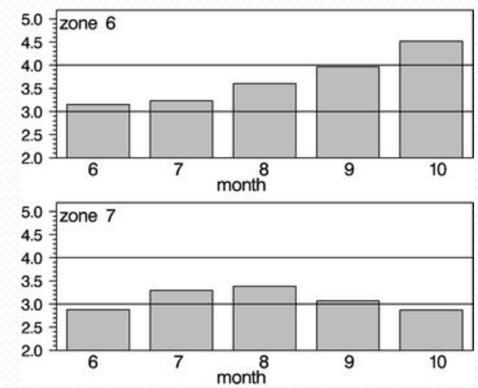
The circum-polar region. Sectors identified by the Arctic Coastal Dynamics project are identified as *grey zones*. Minor modifications adopted in this report are indicated with heavier *dashed lines*. Station locations are indicated by *black dots*. In some cases, two stations are located very close together and appear as *one dot* (D. Atkinson [2005]).



Normal and Selected Storm Tracks Near Barrow (adapted from Brunner et al., 2004).

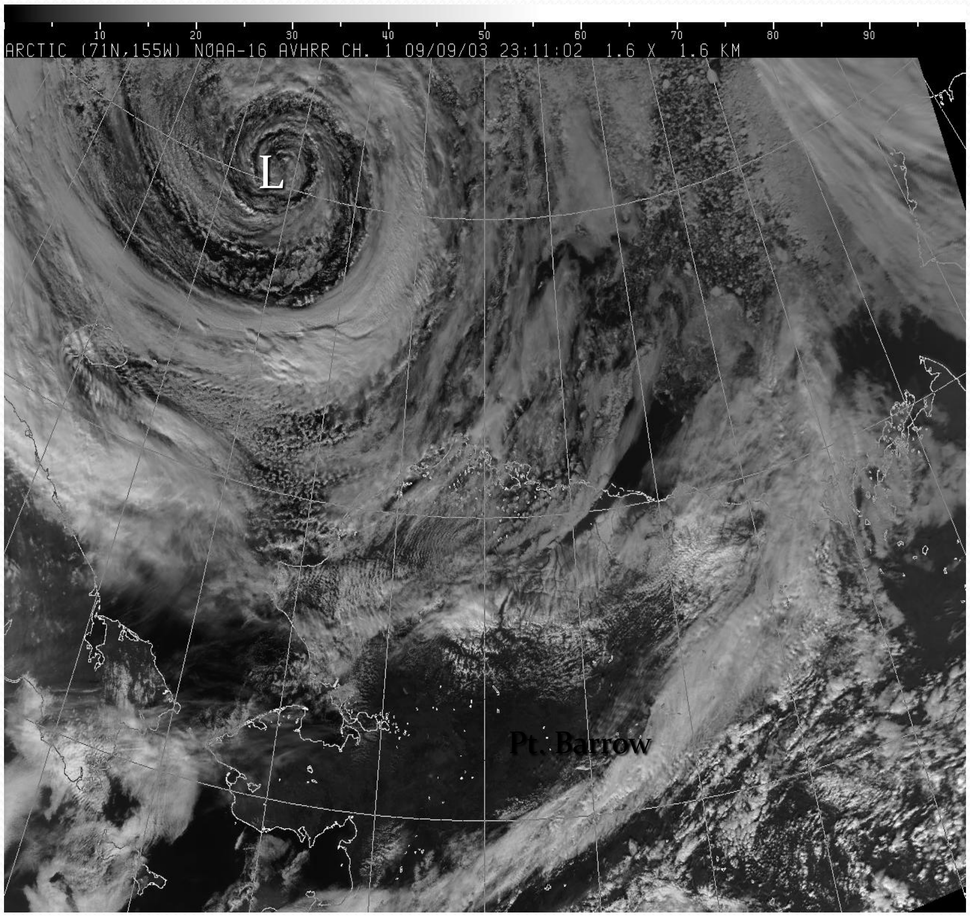


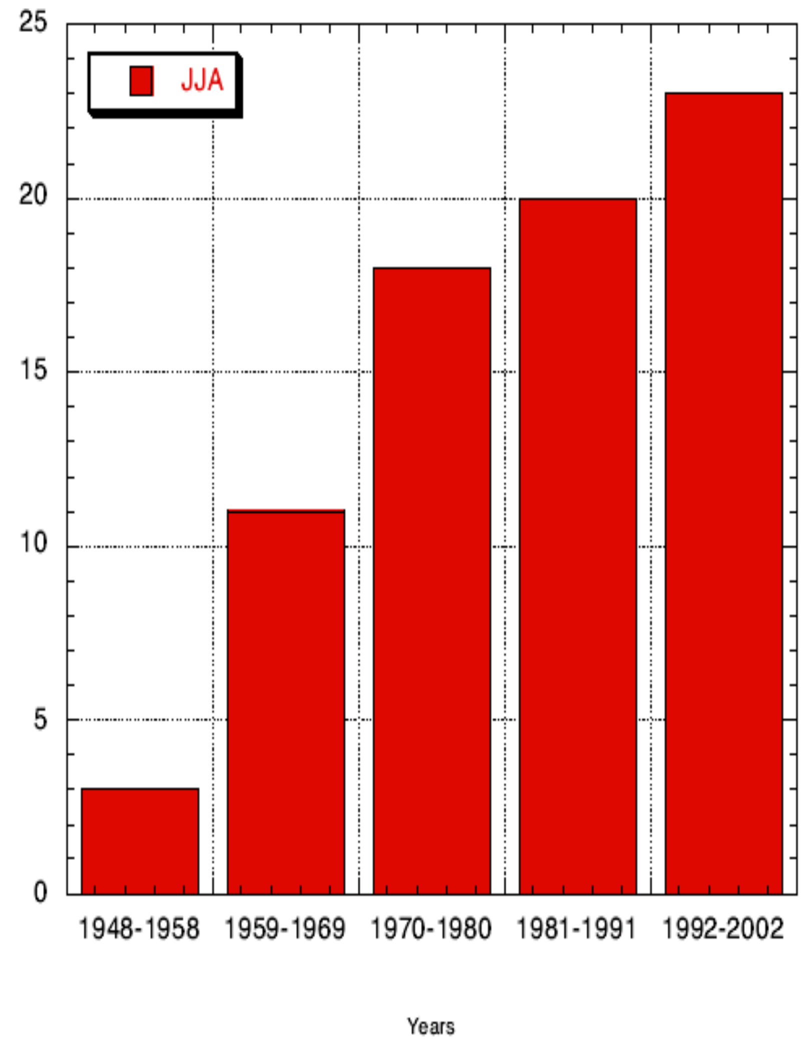
Mean annual storm event counts by month



Mean storm maximum wind speed (m/s) by month for the Beaufort Sea region (zone 6) and North of Greenland (zone 7). Adapted from Atkinson [2005].

Number of storms in western Arctic





R. Pickart (2009): More frequent and intense storms.

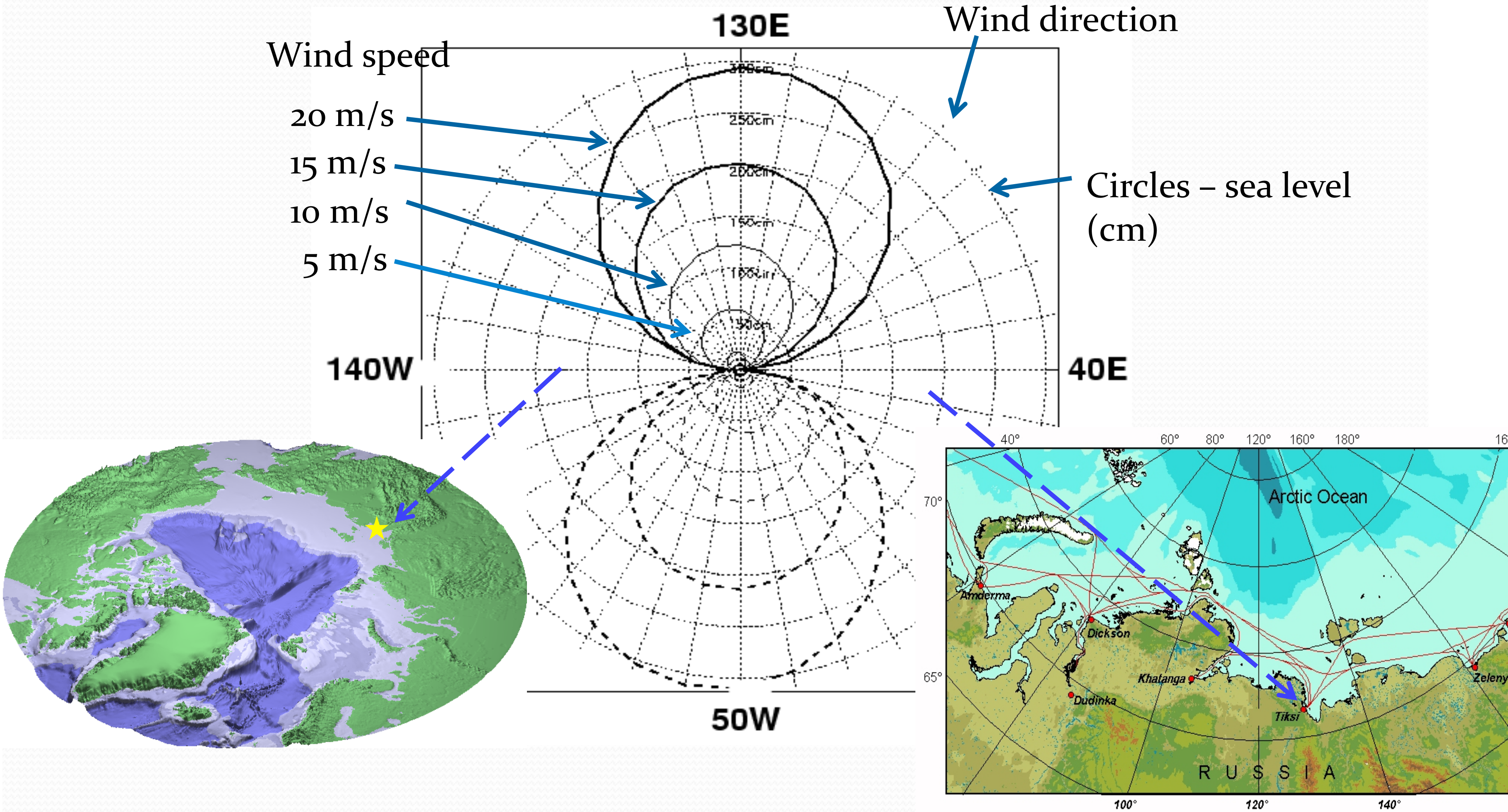
Predicting systems

The first sea ice forecasts for the Russian Arctic were seasonal forecasts made in the 1920's and provided a general description of expected sea ice conditions and sea level changes. The prediction methods used statistical relations and major understanding of the Arctic seasonality. As traffic along the Northern Sea Route (NSR) increased, the need for more detailed short-term forecasts arose.

Short-term (1-5 days) forecasts are required for planning navigation operations. One of the factors of importance of navigation along the NSR is the forecasting of storm surges and tides. Storm surge effects dominate over tides in the Arctic and are strongest in July-October, when sea ice cover is retreated.

Until 1986, statistical models for different arctic ports were employed for predictions of storm surges . After 1986, a set of numerical regional (entire arctic) and local models (for the Barents, White, Kara, Laptev, East-Siberian and Chukchi Seas) were developed and used until present.

Diagram for predicting of sea levels in Tiksi Bay (the Laptev Sea) depending on wind direction and wind speed after 12 hours of wind action



2-D coupled ice-ocean model

We use a system of equations of motion and continuity written in vector notation and in the stereographic polar coordinates:

$$\frac{d\mathbf{U}}{dt} + f\mathbf{k} \times \mathbf{U} =$$

$$-gDm\nabla\zeta + N_h m^2 \nabla^2 \mathbf{U} + \frac{c\mathbf{T}_i + (1-c)\mathbf{T}_s - \mathbf{T}_b}{\rho} + Dm\mathbf{P_a} \tag{1}$$

$$\frac{\partial \zeta}{\partial t} = -m^2 \nabla(\mathbf{U}/m) \tag{2}$$

and the equations of motion and continuity for ice,

$$\frac{d\mathbf{u}_i}{dt} + f\mathbf{k} \times \mathbf{u}_i = -gm\nabla\zeta + \frac{\mathbf{T}_{is} - \mathbf{T}_i}{\rho_i h_i} + \mathbf{F}_i \tag{3}$$

$$\frac{\partial c}{\partial t} = -m^2 \nabla(\mathbf{u}_i/m) \tag{4}$$

Proshutinsky, 1986

Model initiation and forcing:

This model is forced by:

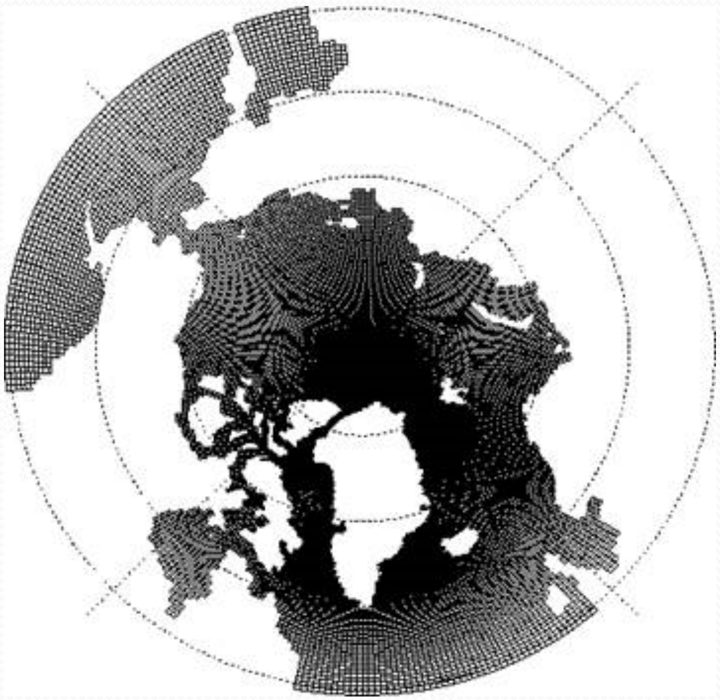
- winds and sea level atmospheric pressure fields derived from European Center for Medium-Range Weather Forecasts

- river runoff and Bering Strait transport are prescribed for rivers based on river runoff predictions or based on climatology.

Initial sea ice conditions (climatologic ice thickness corrected by available observations) and real sea ice concentration derived from satellite data are used to start each model run.

The prediction system provides forecasts :
of sea surface heights, ice drift and ocean currents for the Arctic Ocean model domain with horizontal resolution of 13.89 km.

3-D model

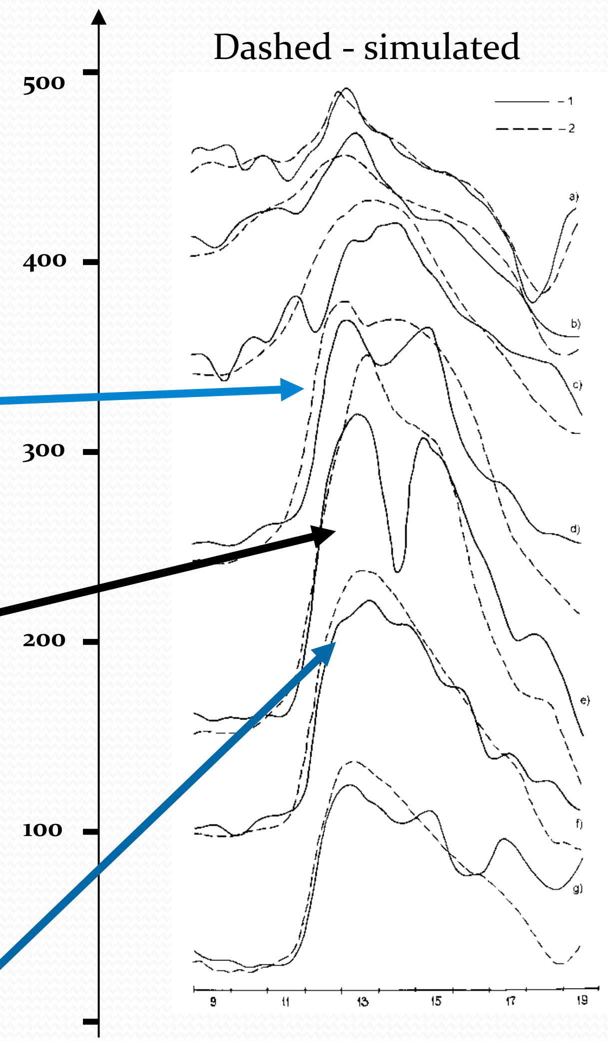


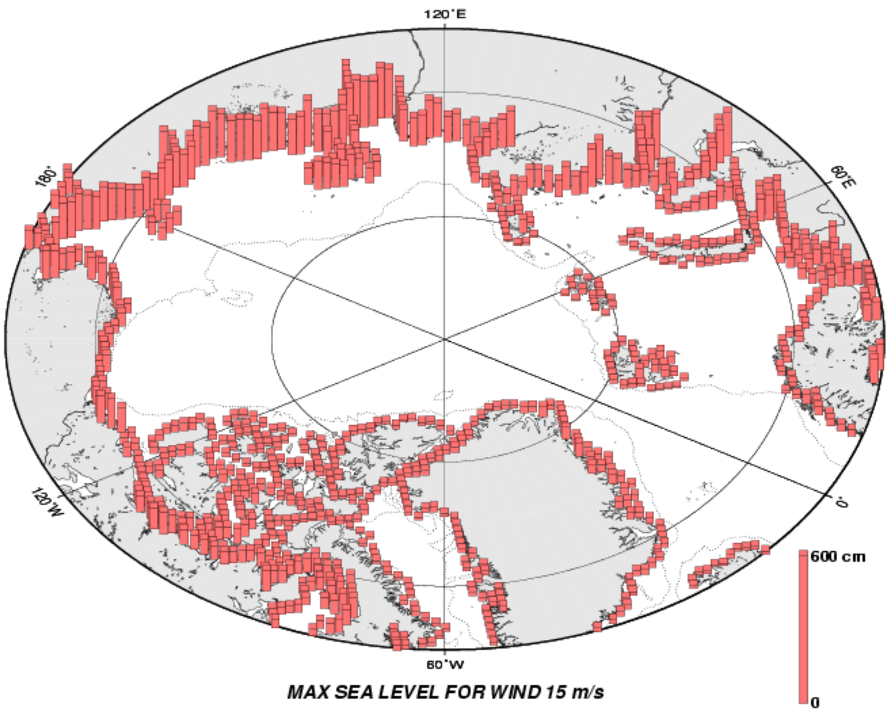
The UW model is a variant of the Global Parallel Ocean and Ice Model (POIM) [Zhang and Rothrock, 2003]. This is a so called super regional POIM with a southern open boundary along the latitude of 45N. The POIM couples the POP with a sea ice model of Zhang and Rothrock [2003]. The mean model horizontal resolution is 22 km for the Arctic, Barents, and GIN (Greenland-Iceland-Norwegian) seas, and Baffin Bay. The model was driven by daily NCEP/NCAR reanalysis data. The calculations of surface momentum and radiation fluxes follow Zhang and Rothrock [2003] and differ from the specifications for the AOMIP coordinated runs. No climate restoring is allowed. The open boundary conditions are from a global POIM driven also by the reanalysis. Additional information about some of the ocean parameters can be found in Zhang and Steele [2007].

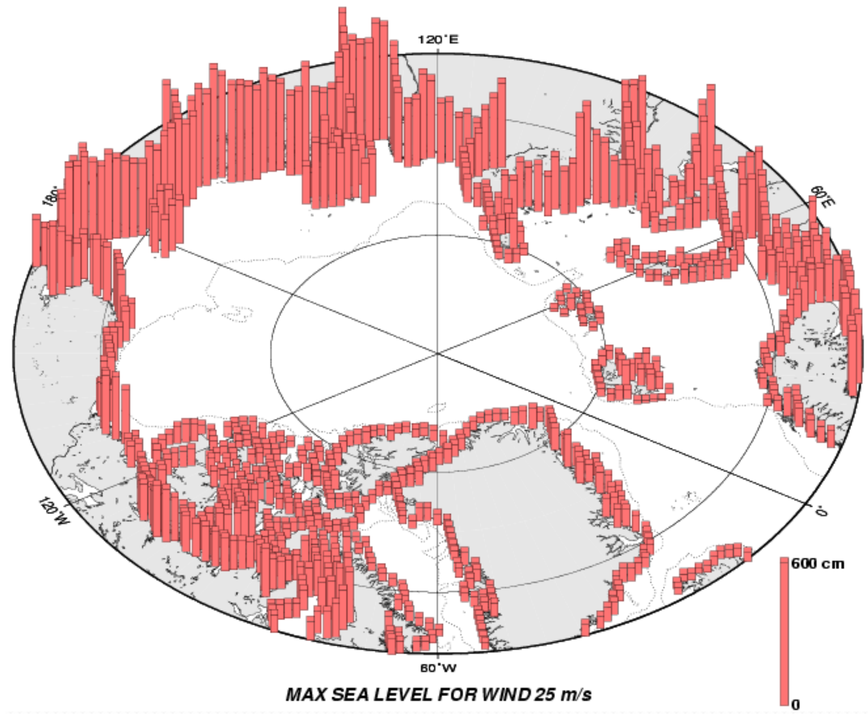
Model calibration and validation

The Laptev Sea, station Tiksi:

Dates	Experiment conditions	Observed SSH, cm	Simulated, SSH cm	Mean absolute error, cm	MSR error, Cm^2	Correlation coefficient
1-11 01.71	No ice	76	141	24.9	29.2	0.86
	With ice	76	73	13.9	13.9	0.89
13-16 12.84	No ice	109	178	32.2	40.4	0.89
	With ice	109	129	20.0	25.1	0.85
9-19 09.90	No ice	117	133	13.6	17.4	0.94
	With ice	117	131	13.3	16.9	0.94



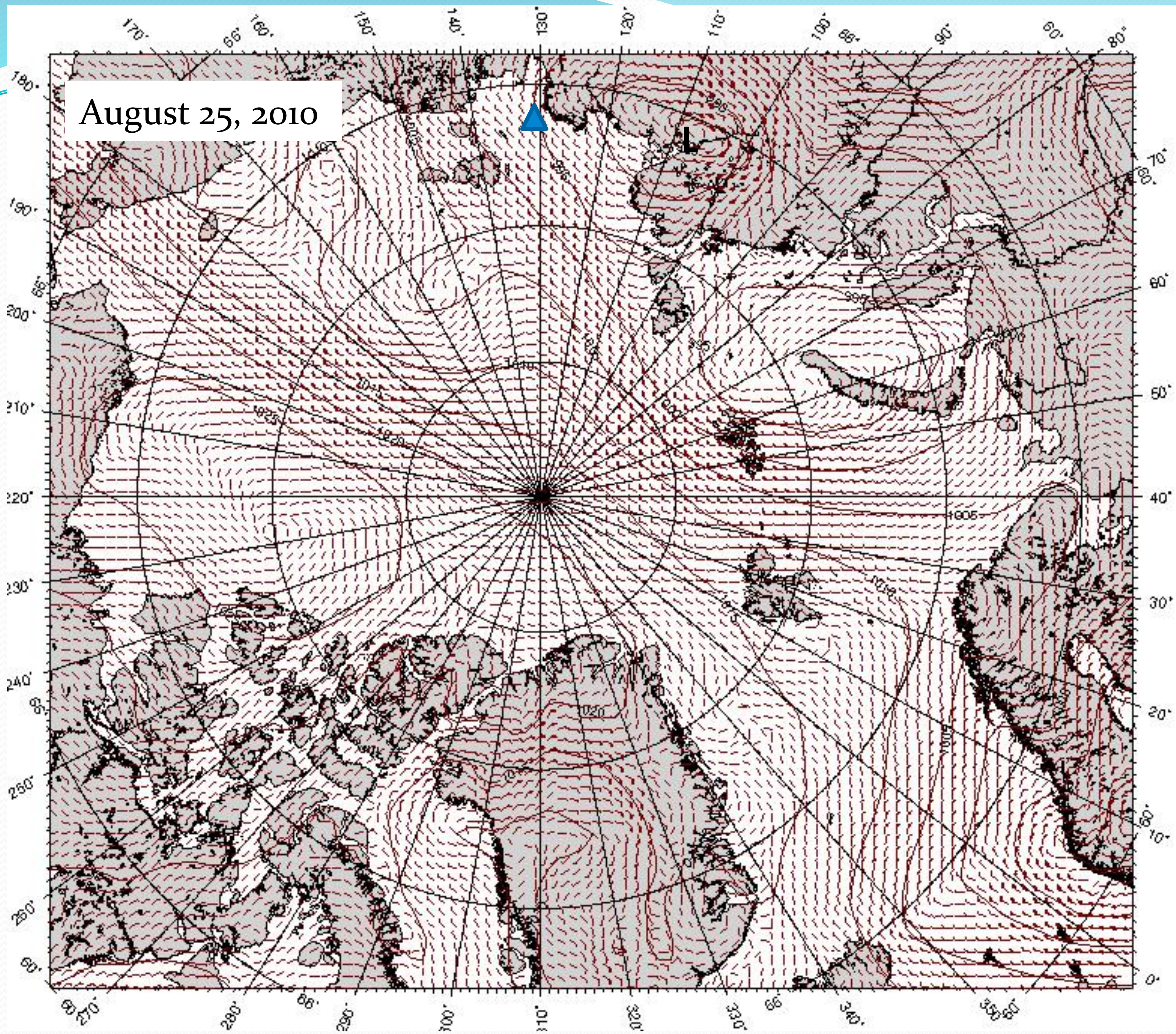


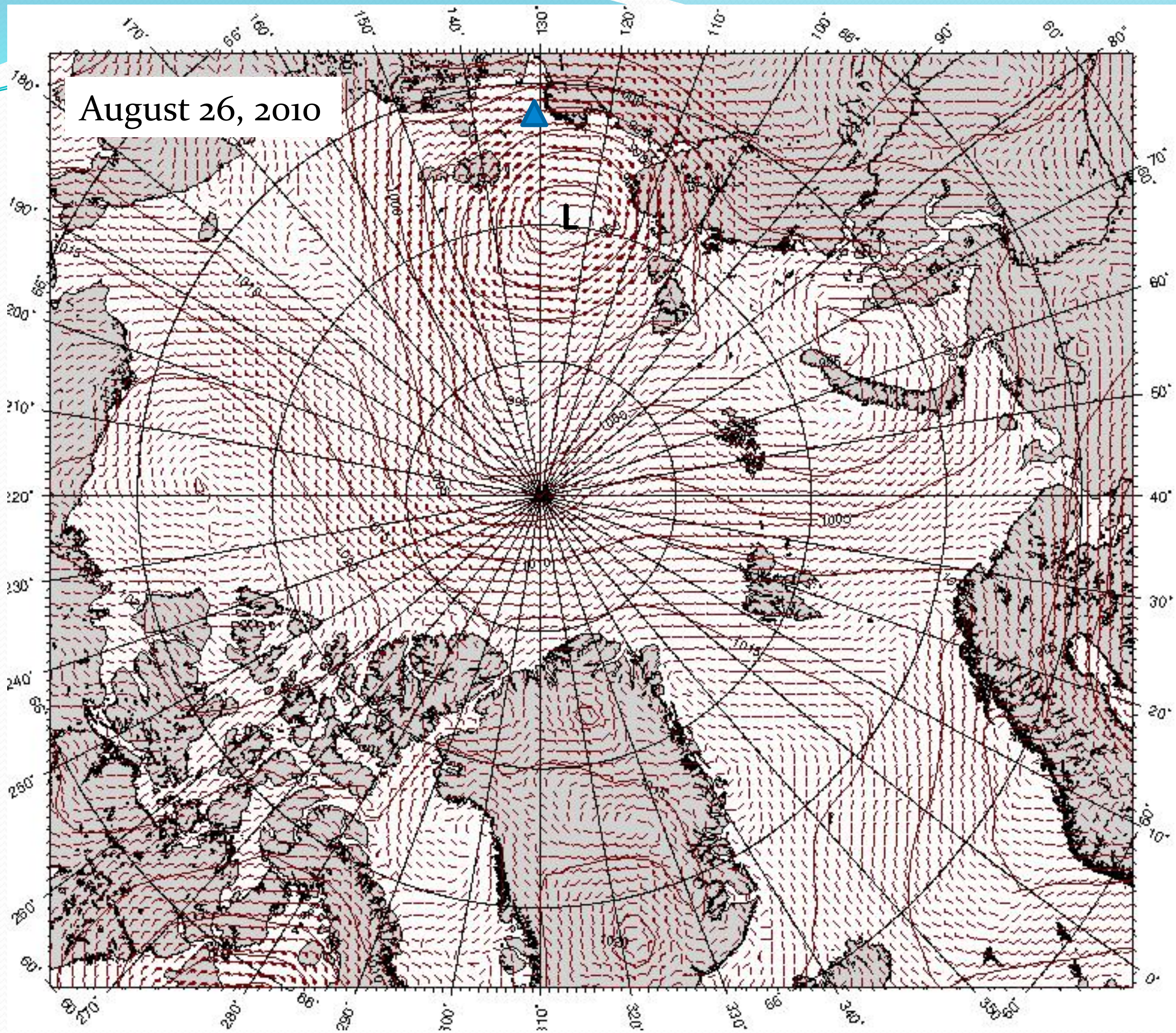


Theoretically possible sea level elevations of sea level under forcing of winds of approximately 15 m/s.

Theoretically possible sea level elevations of sea level under forcing of winds of approximately 25 m/s.

20 miles off the town of Tiksi in the Sakha republic on August 27. Three crewmembers from 14th were saved after a tanker rushed to the sinking ...


August 25, 2010


August 26, 2010
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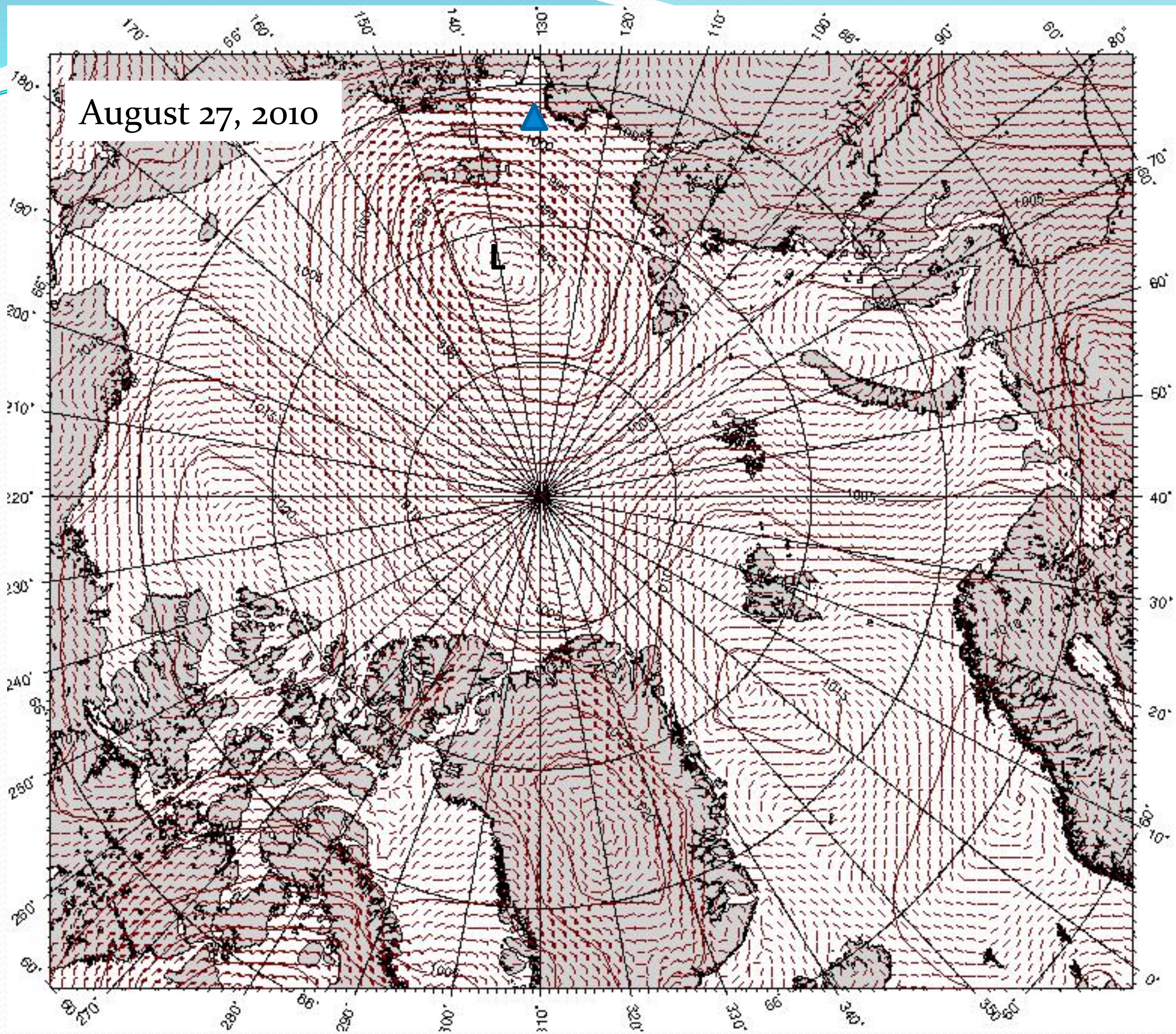
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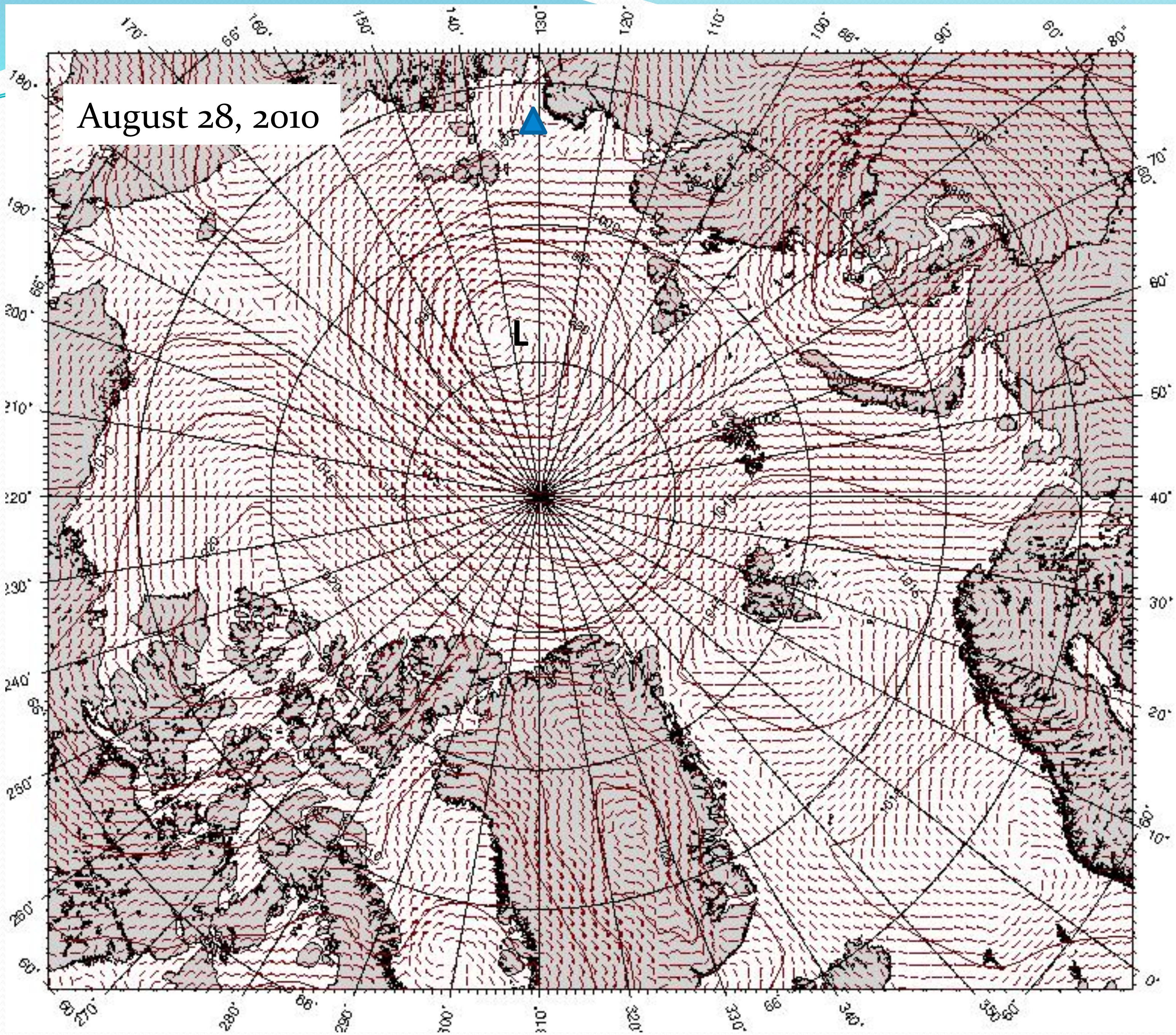
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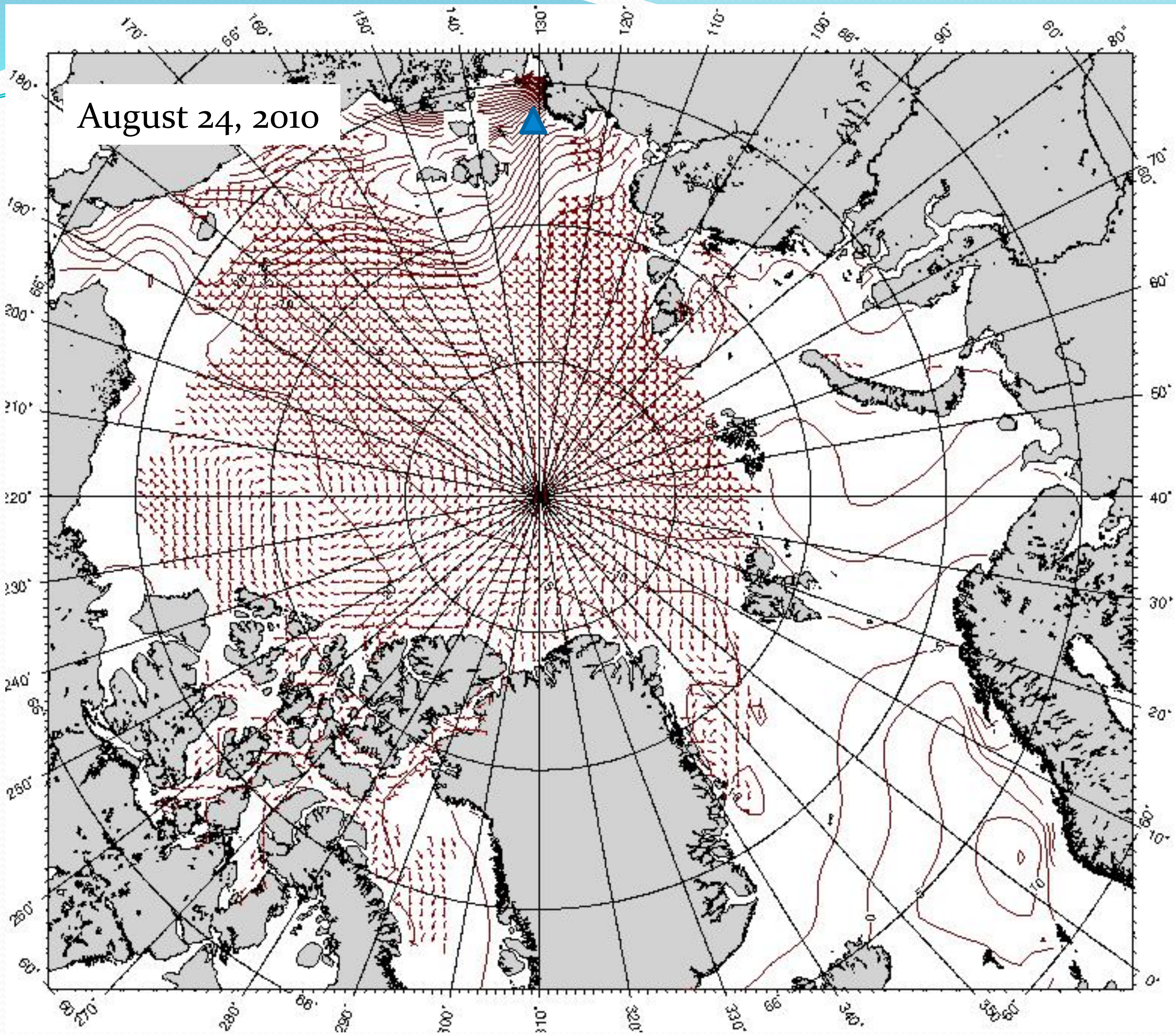
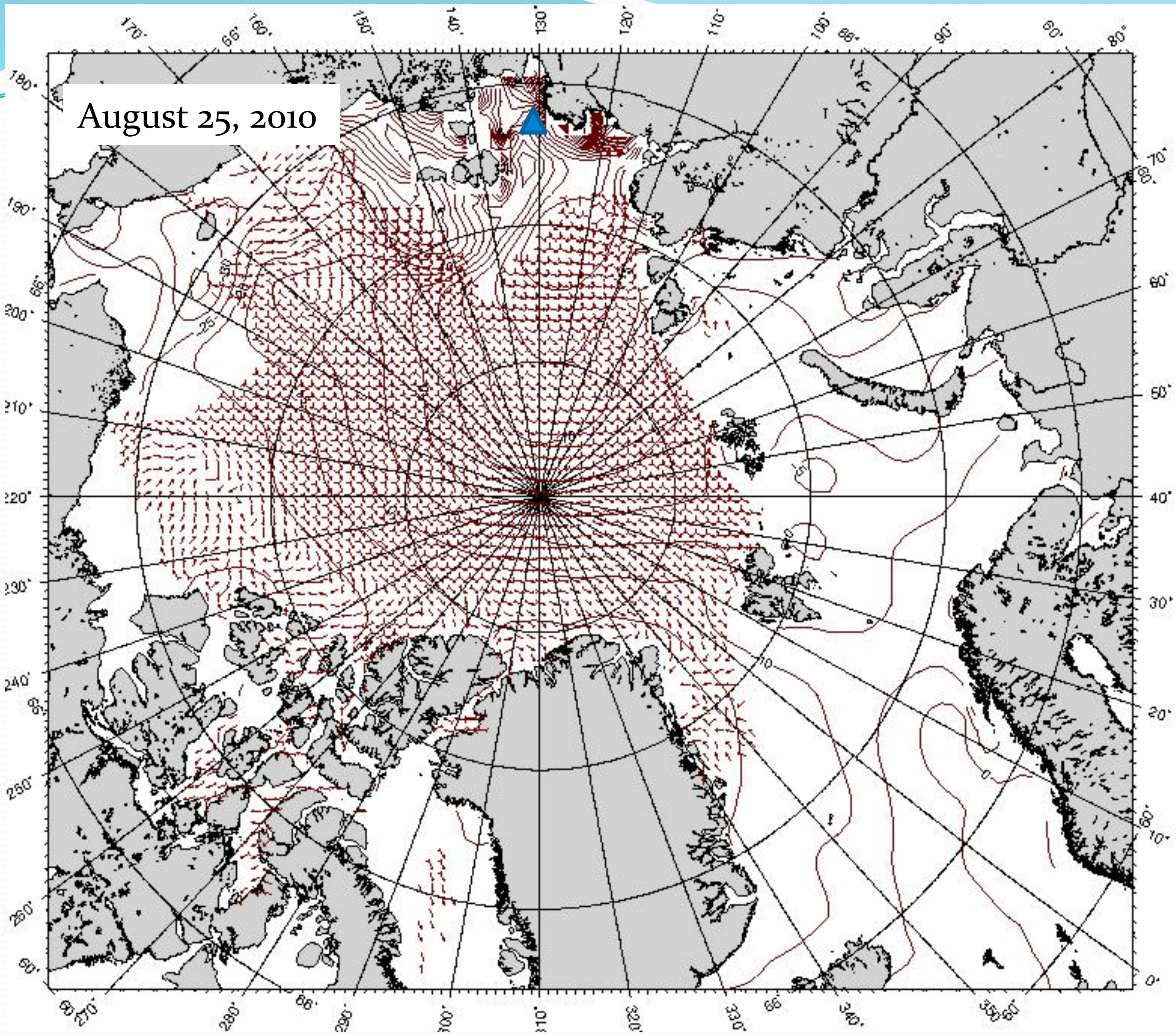
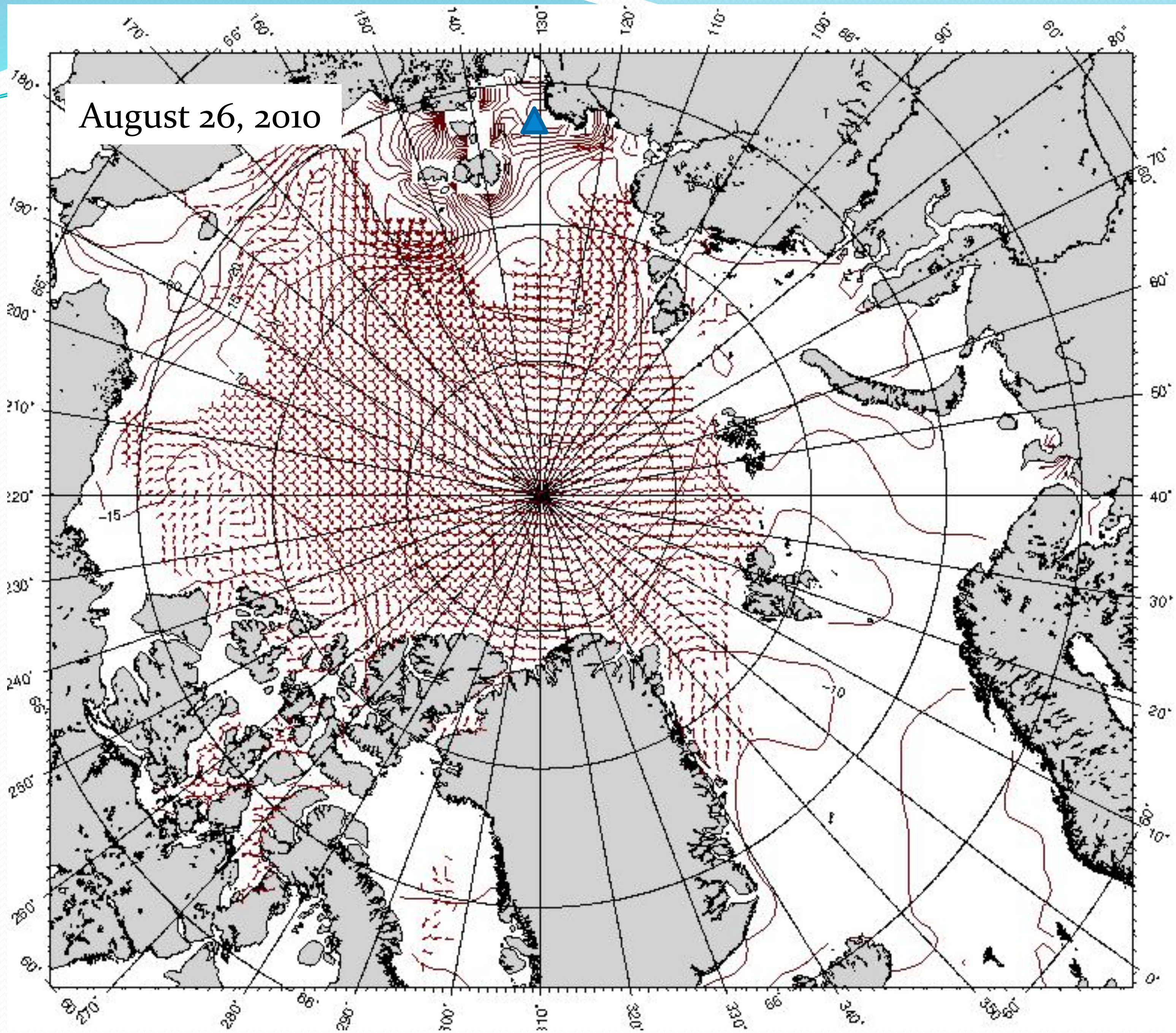

August 24, 2010


August 25, 2010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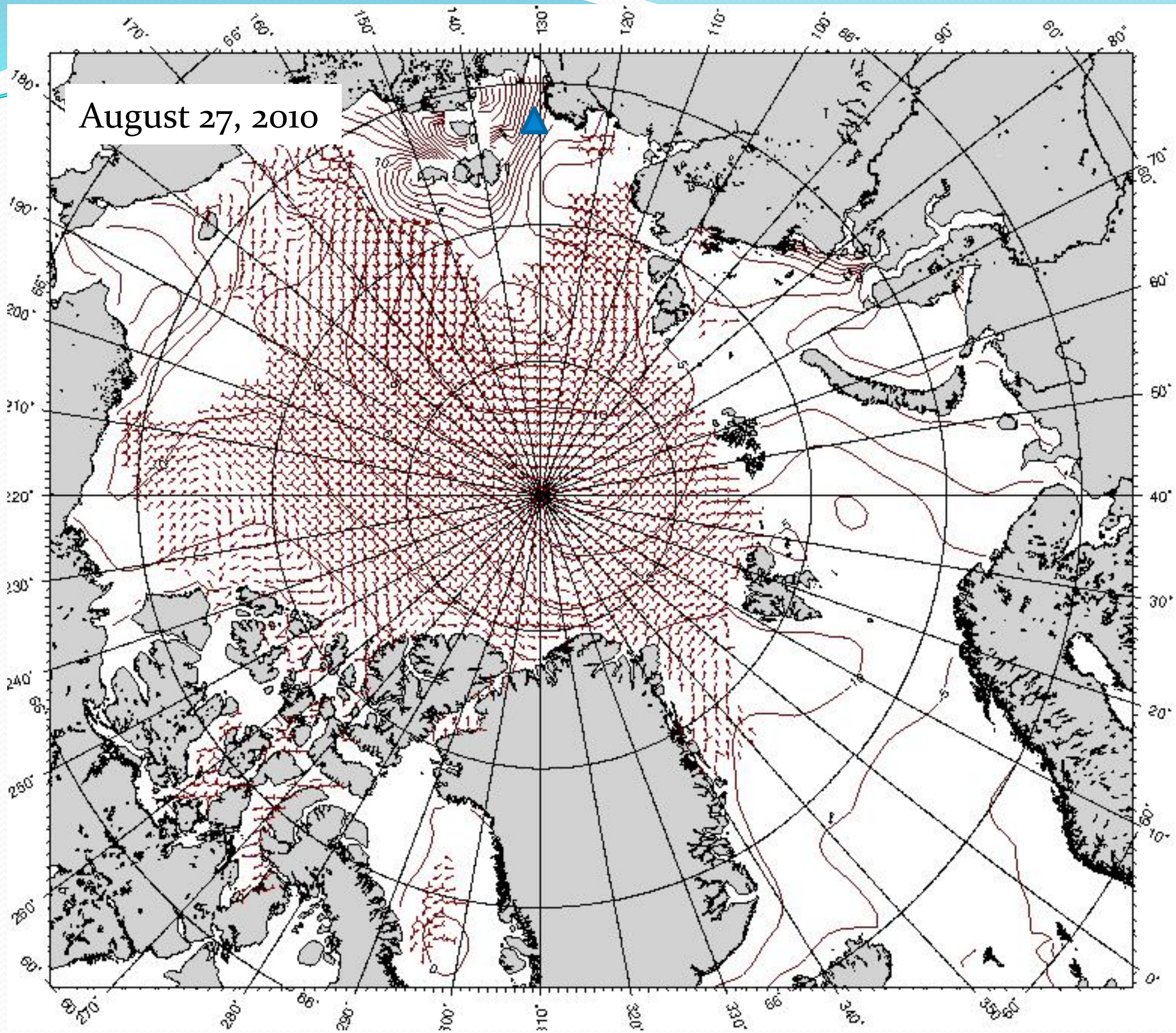
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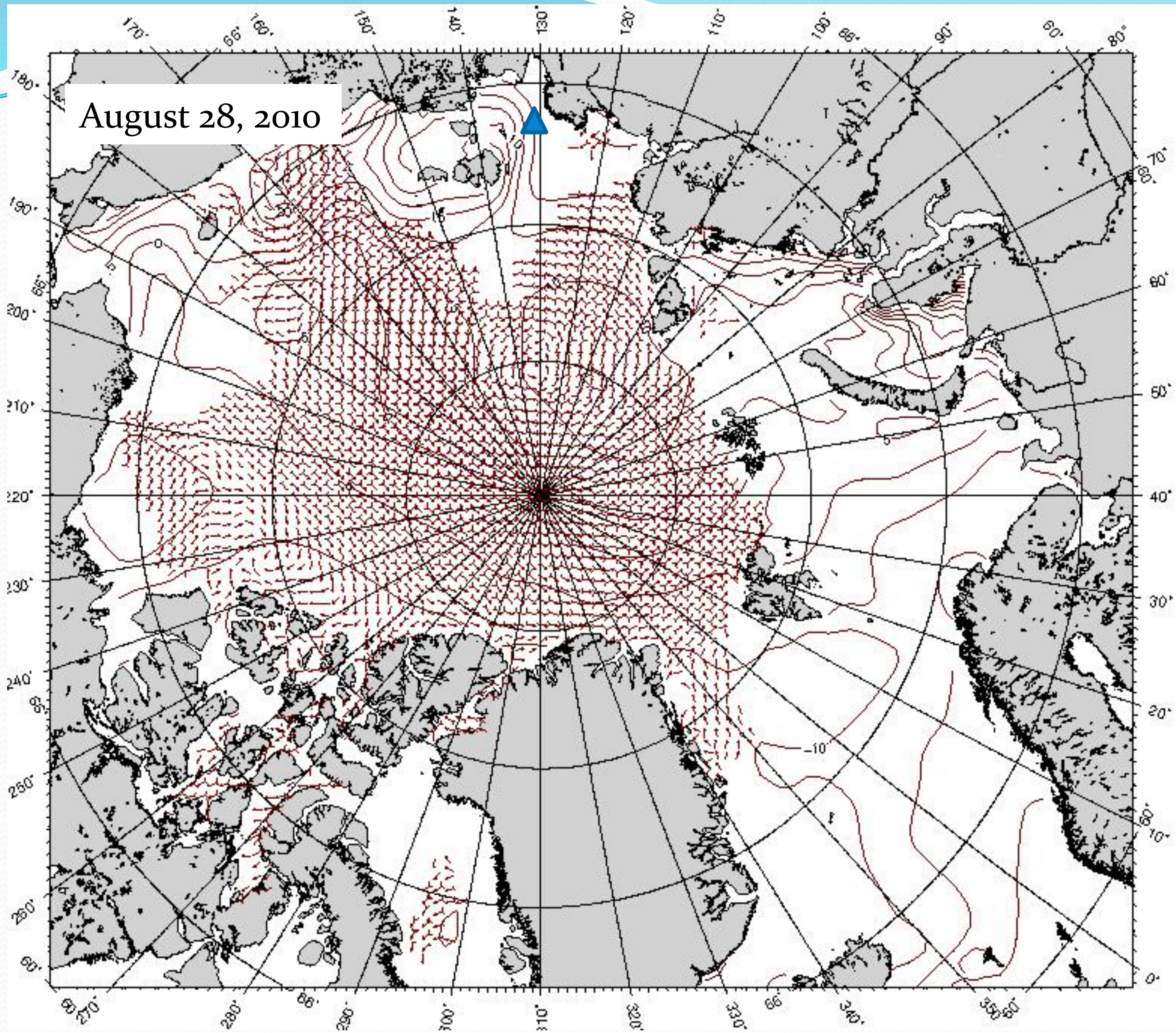
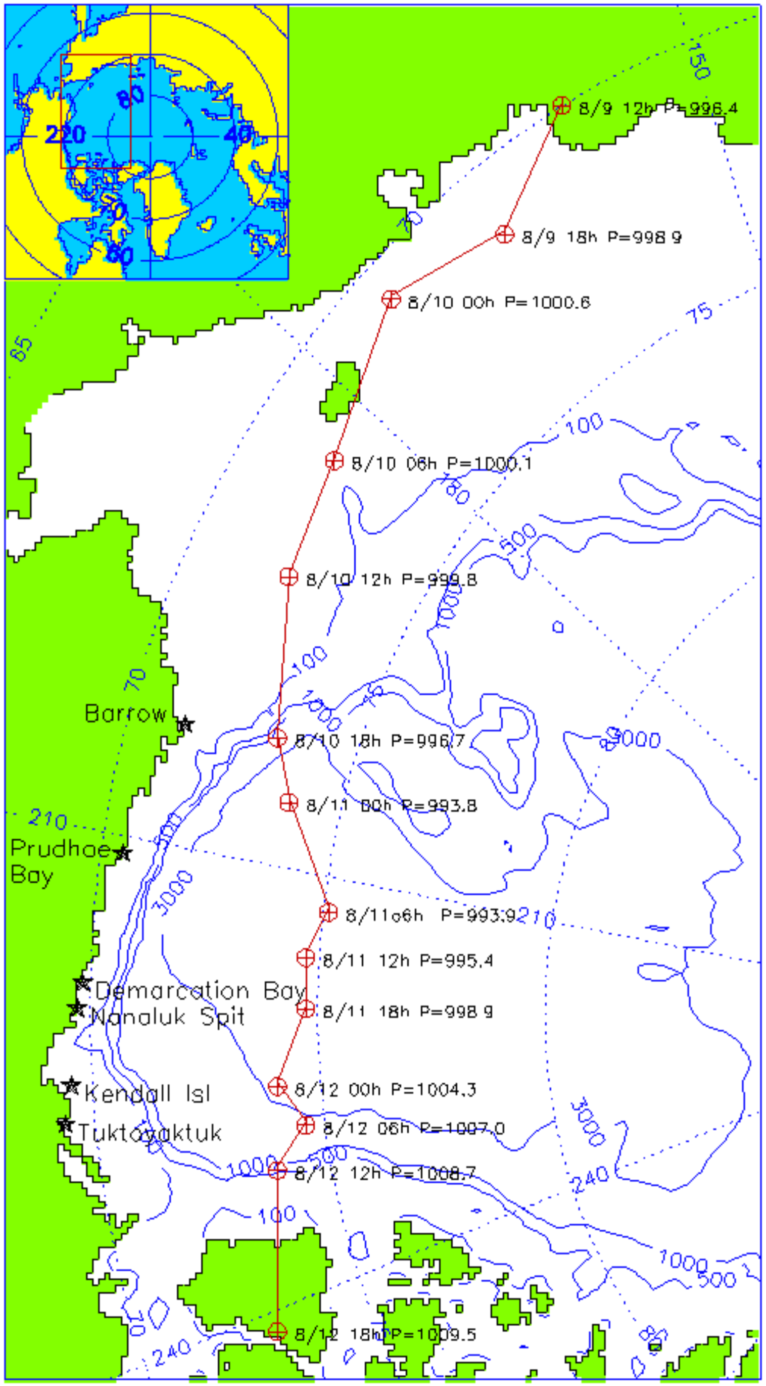

August 28, 2010



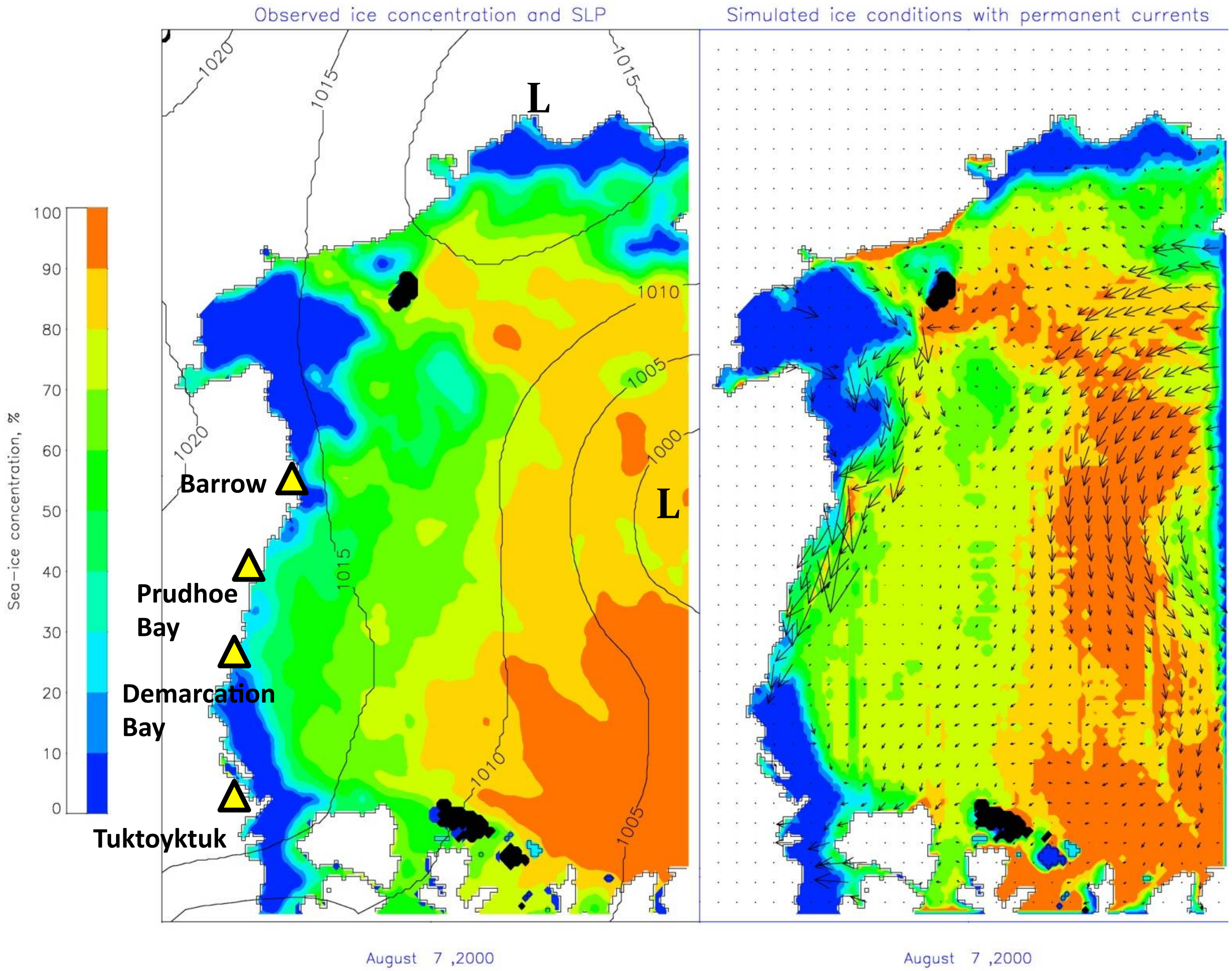
ALASKA:
2000 August storm

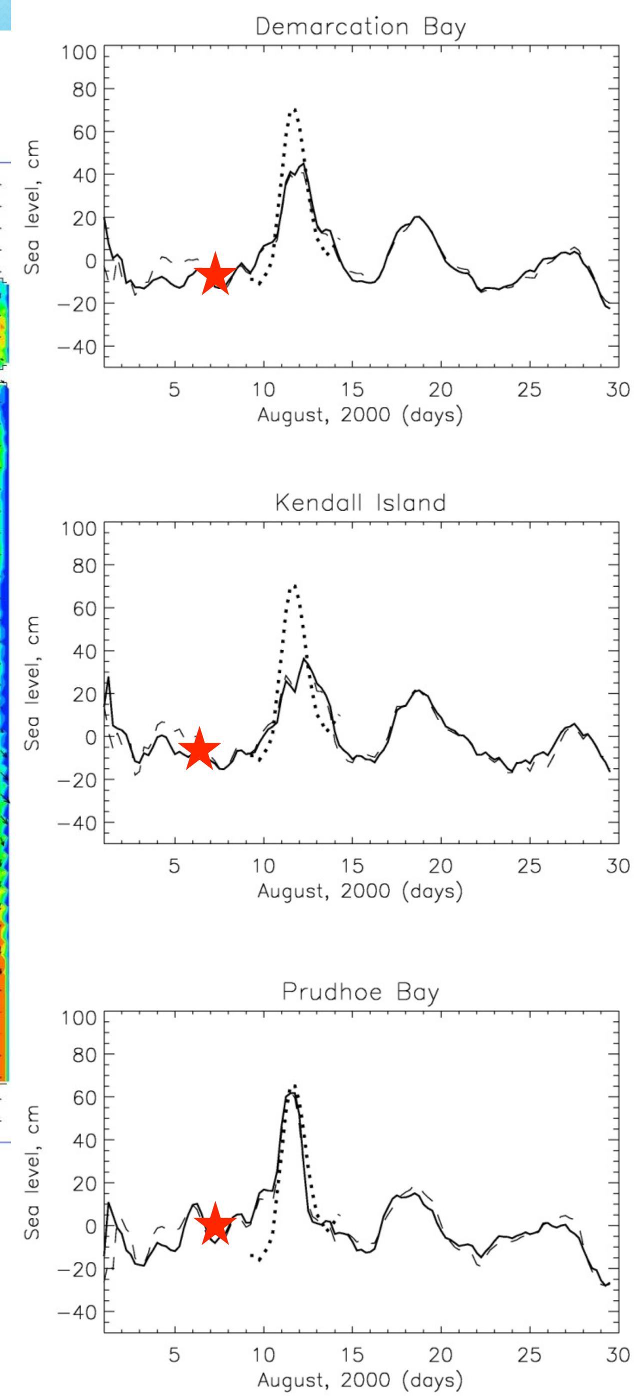
The storm strengthened to 996 millibars by August 11, when its center was positioned north of Prudhoe Bay (Fig. 1), and it developed a very strong pressure gradient to the west. The strong pressure gradient generated observed winds of 70 kts (36m/s), which caused the storm to develop heavy sea states that included a moderate surge and high waves.

The storm also initiated rapid cooling that was fairly uniformly expressed at all sites, despite their varying distances from the coast. At all sites 30cm ground temperature dropped from 4C to 1C which, at the coastal sites, did not return to pre-storm summer levels before the initiation of winter despite two subsequent warm periods.

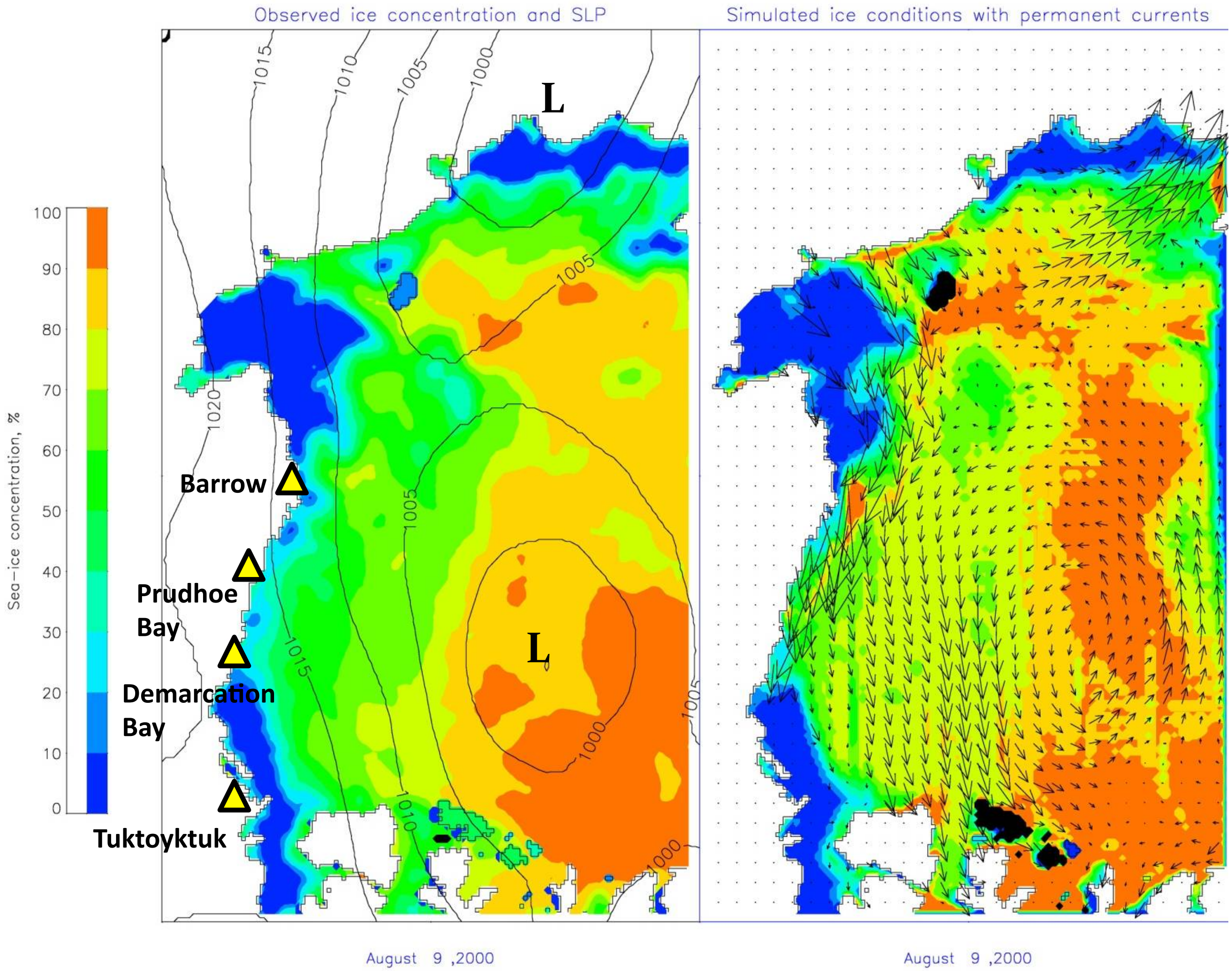
All told, this event caused $7.7 million dollars in infrastructure damages along the North Slope, including the sinking of a barge (Koslow 2000). Unusual for Alaska, this event also caused substantial wind damage in the form of roof failure.

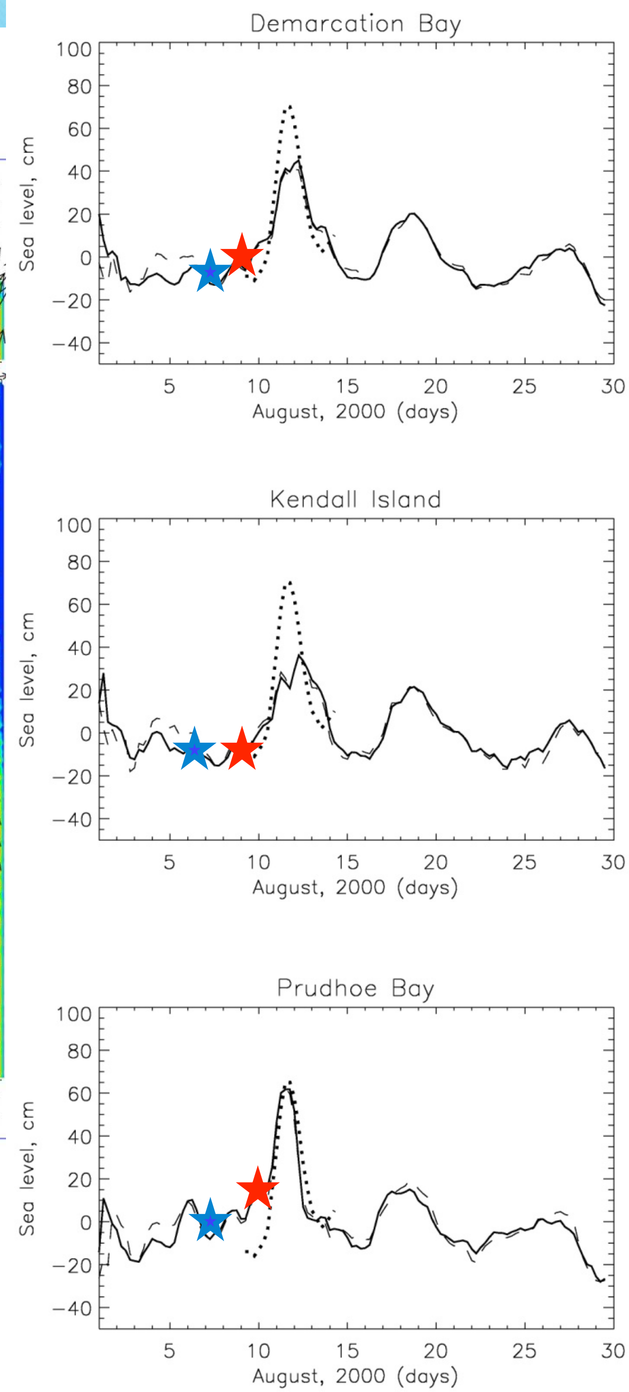
2D model results



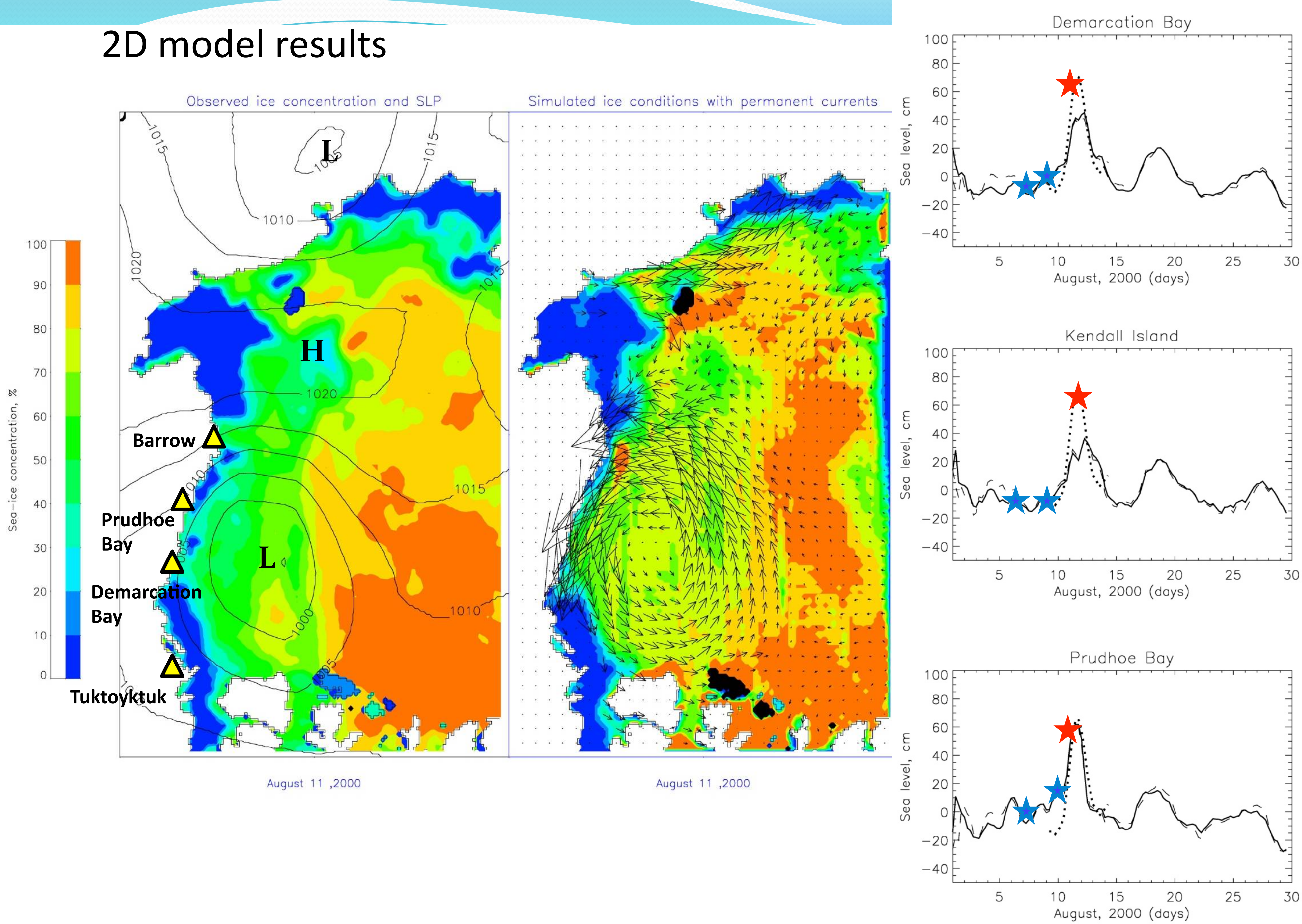


2D model results

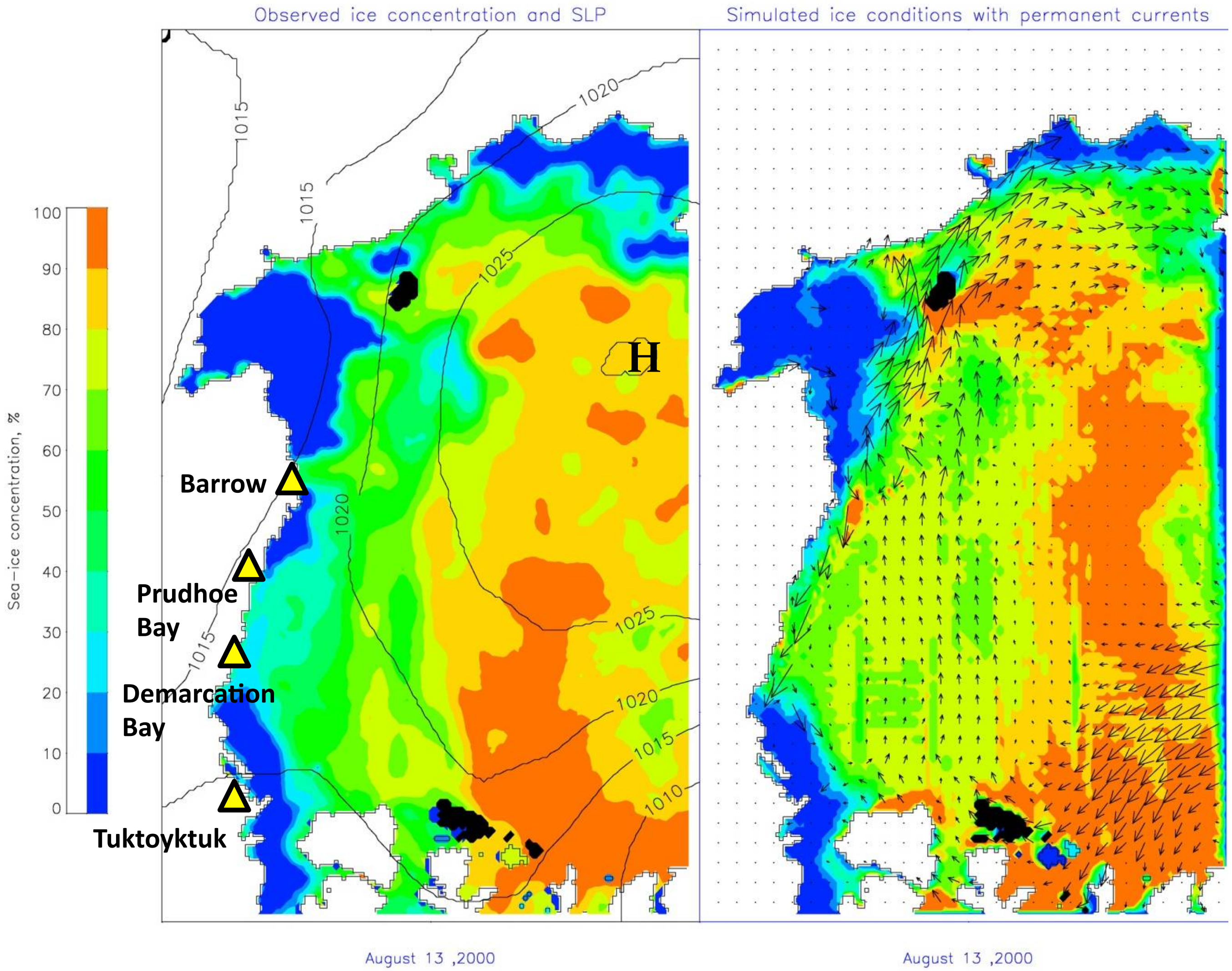


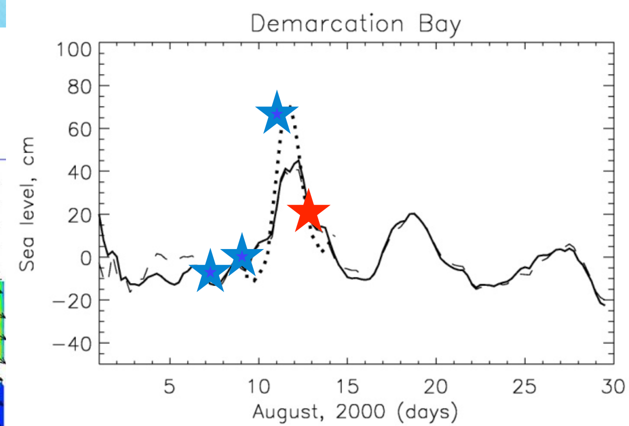


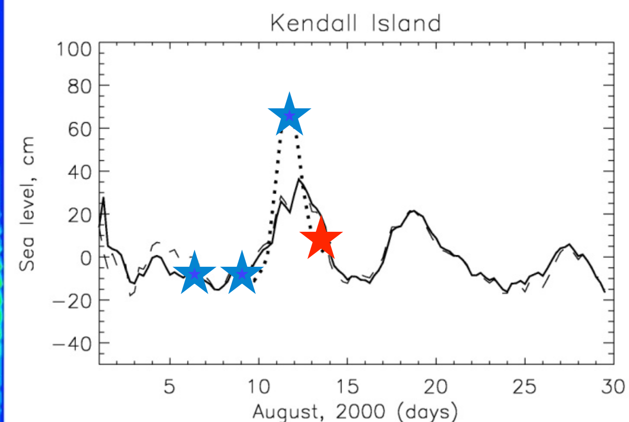
2D model results

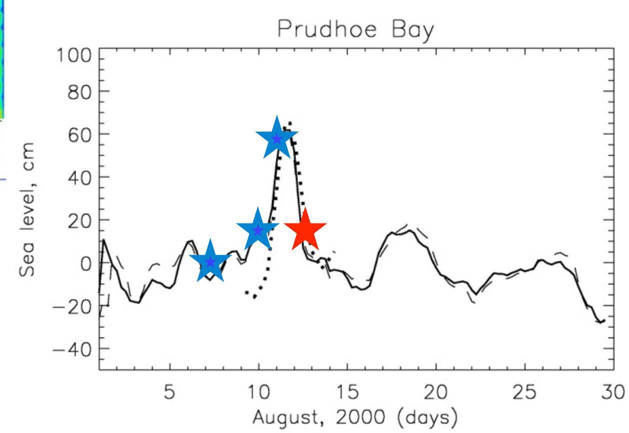


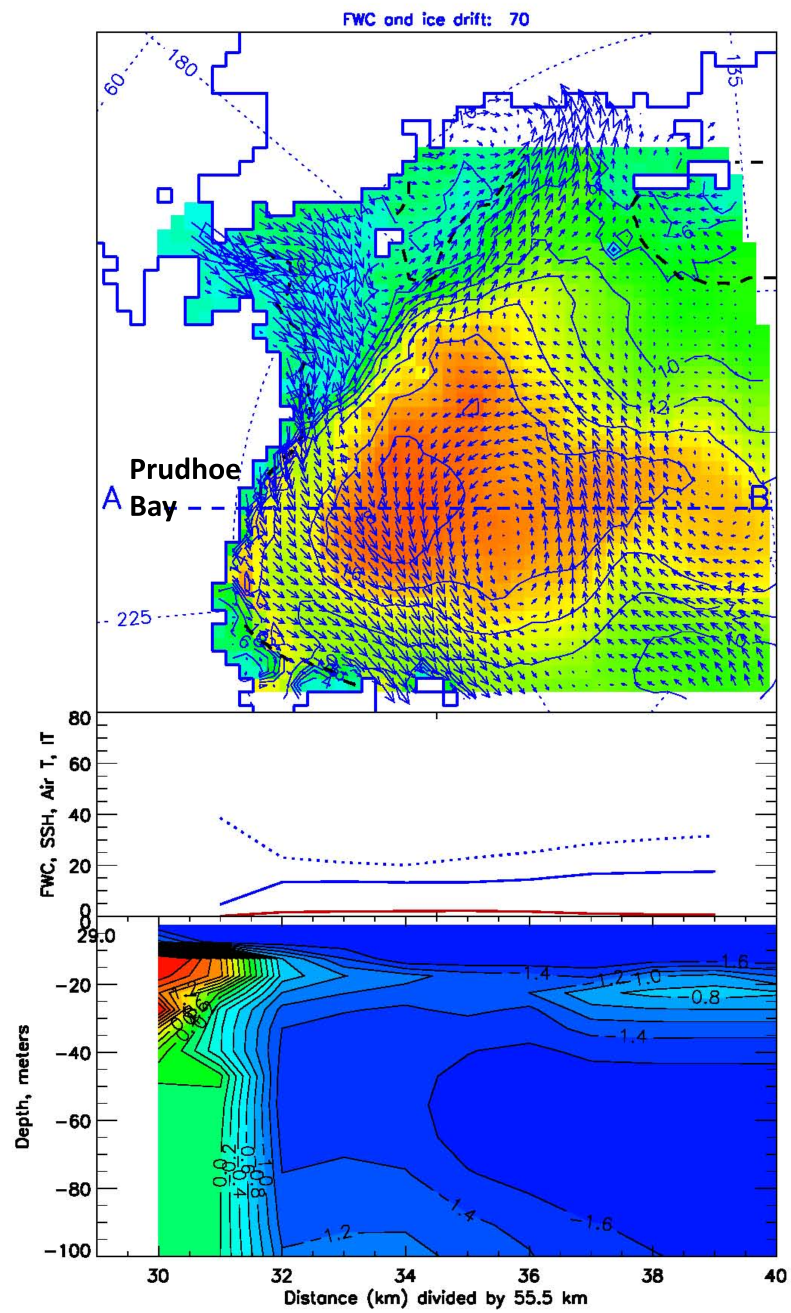
2D model results



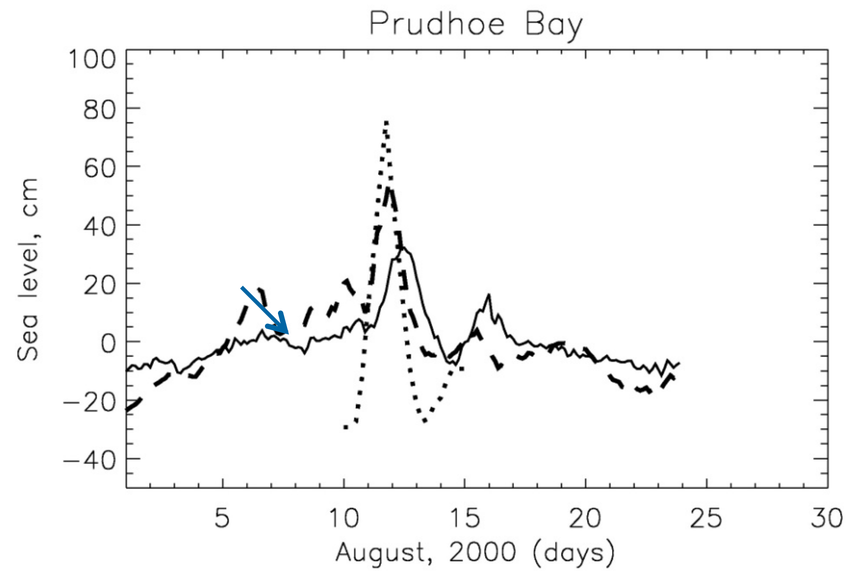






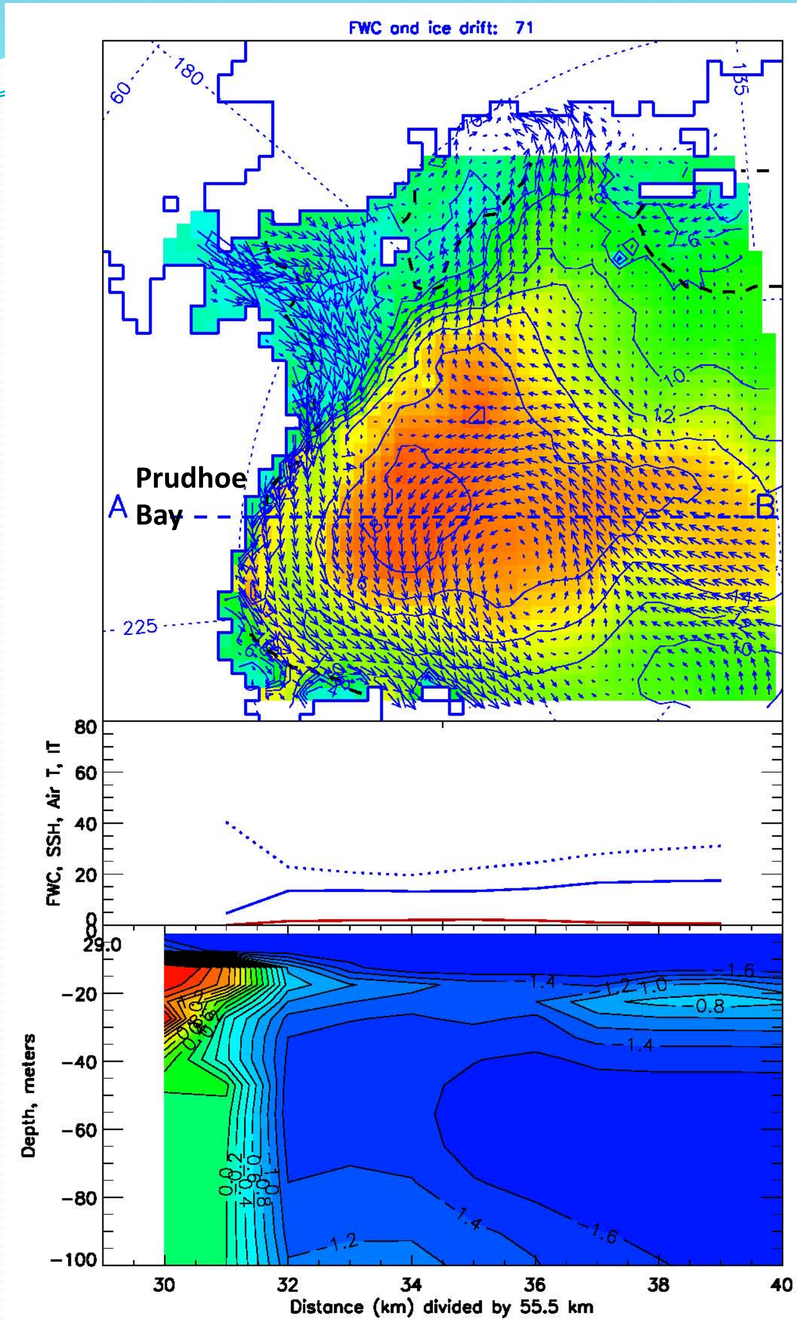


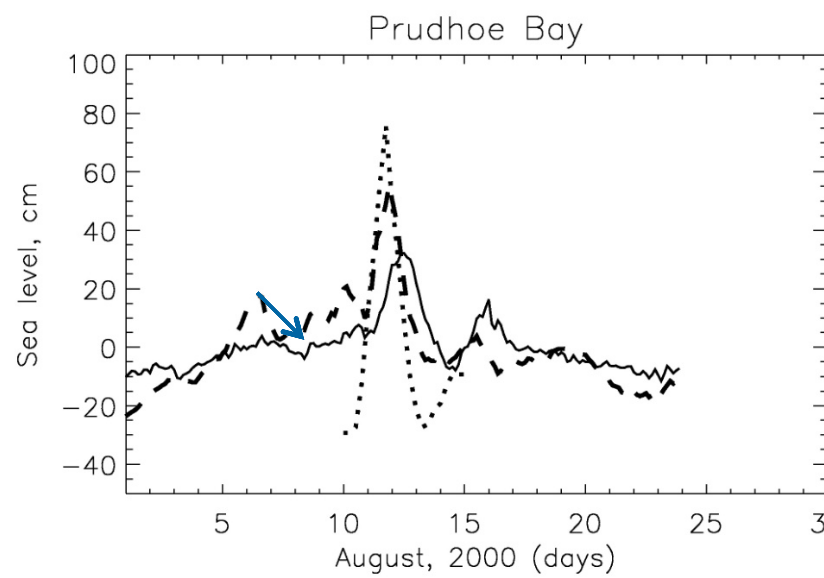
Prudhoe Bay: August 08, 3:00 pm



3D model results

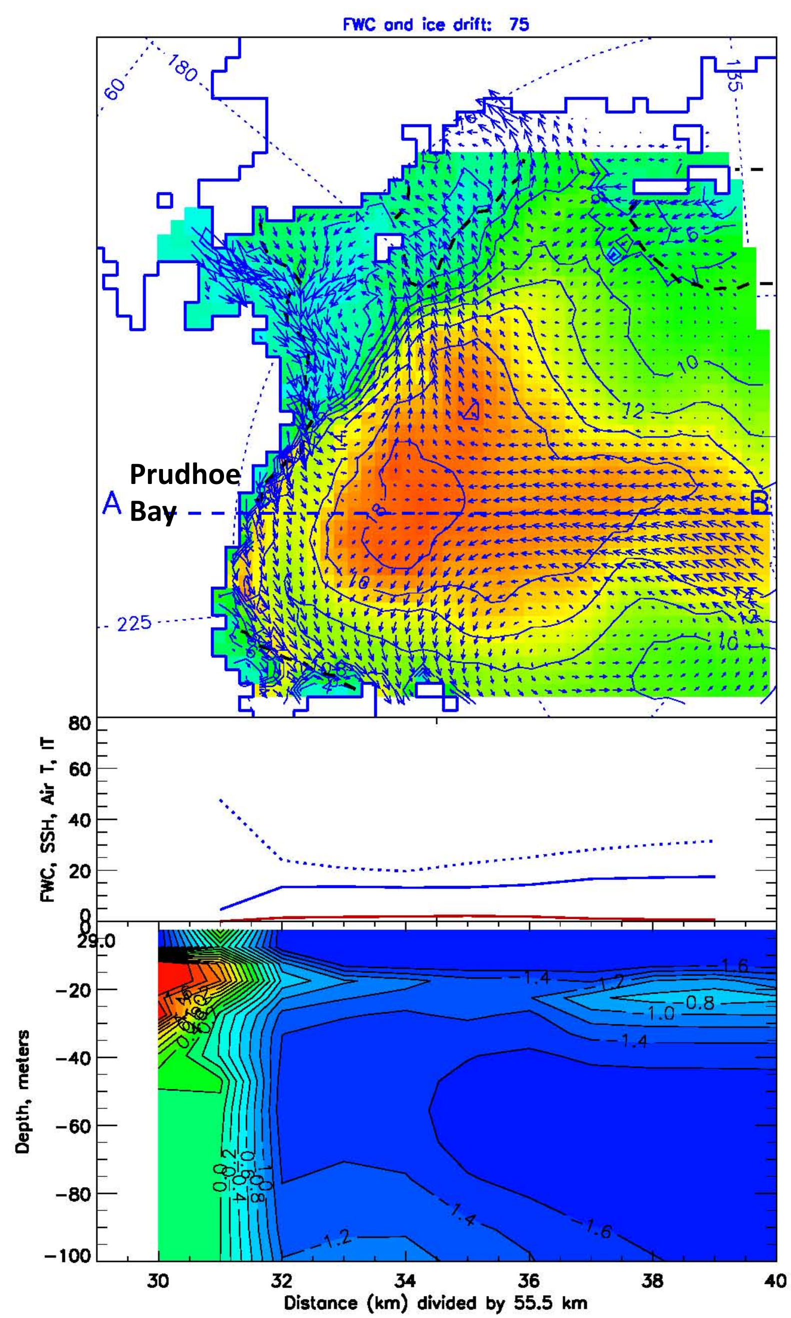
Prudhoe Bay: August 08, 9:00 pm

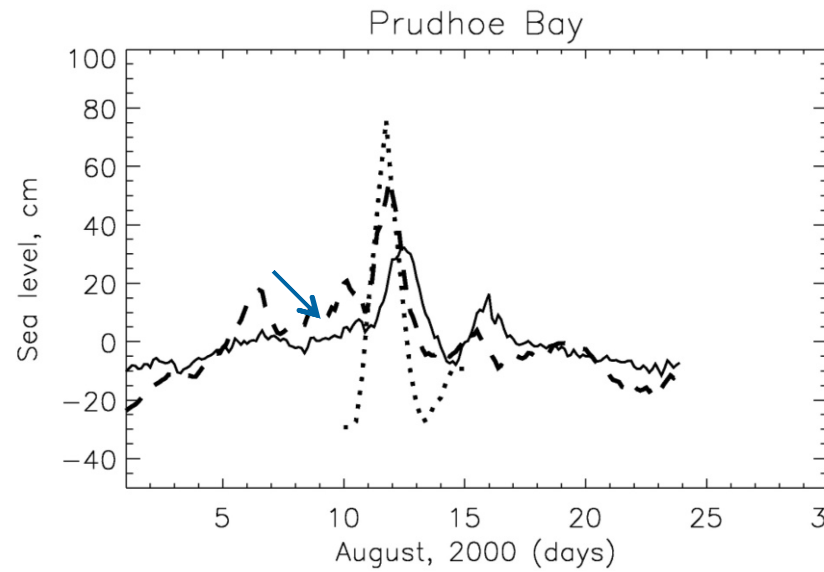




3D model results

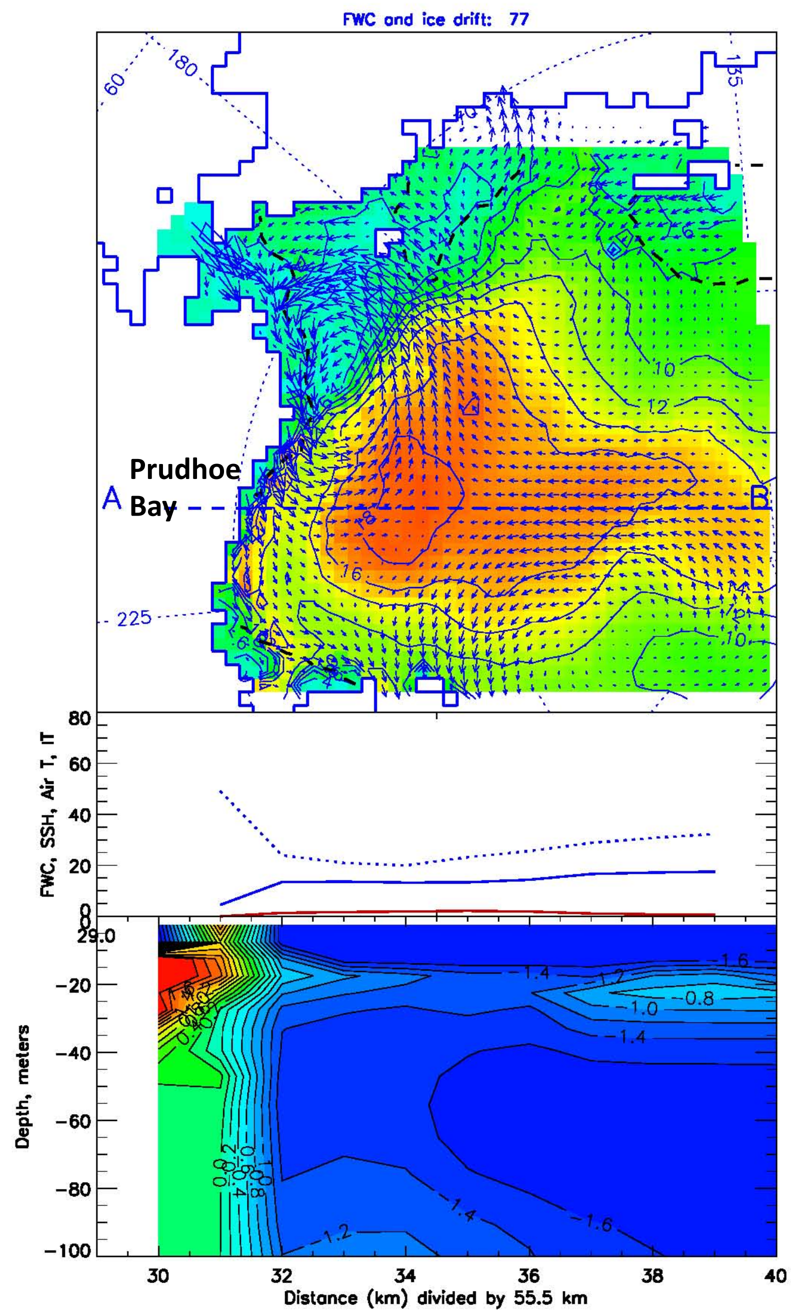
Prudhoe Bay: August 09, 9:00 pm

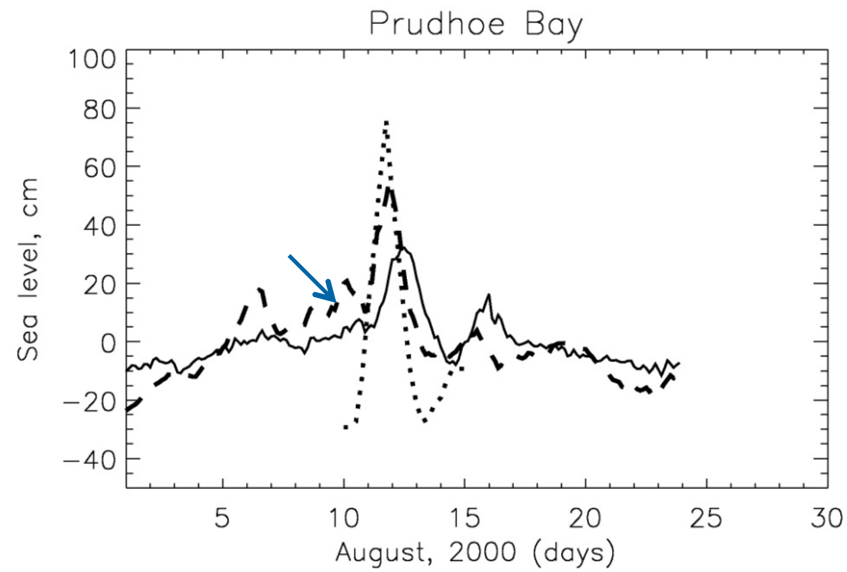




3D model results

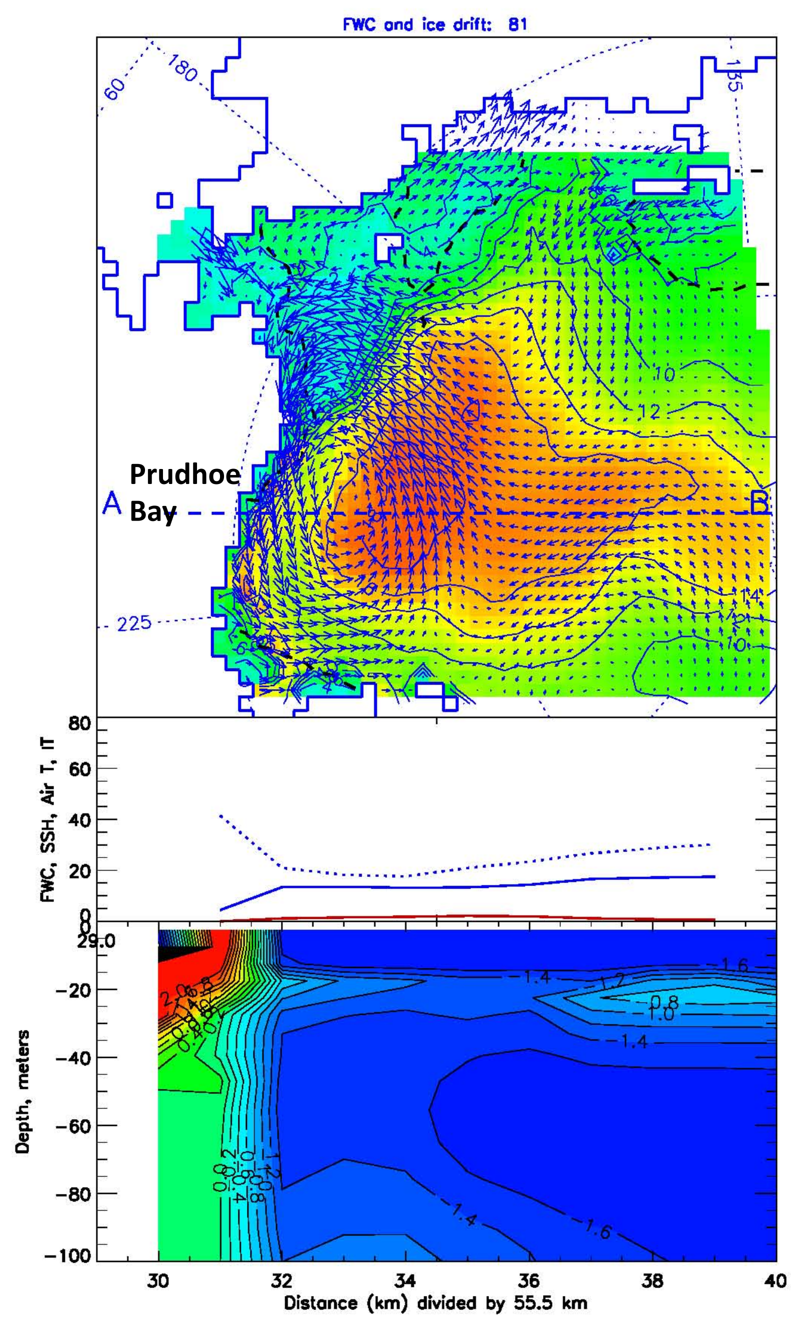
Prudhoe Bay: August 10, 3:00 am

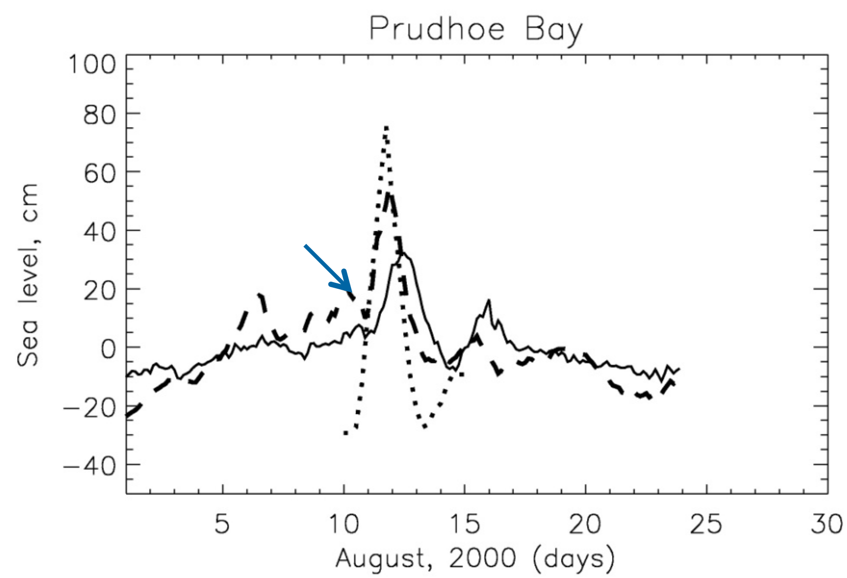




3D model results

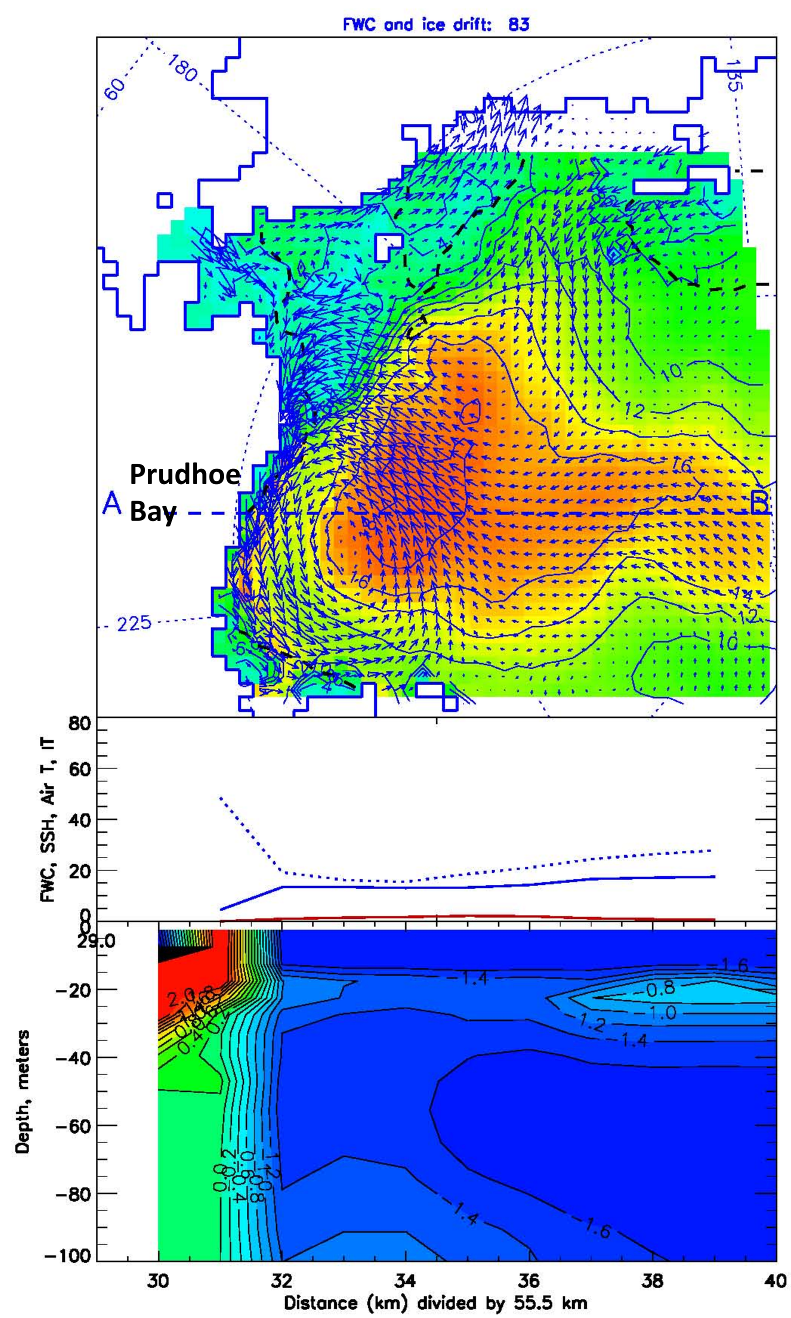
Prudhoe Bay: August 10, 3:00 pm

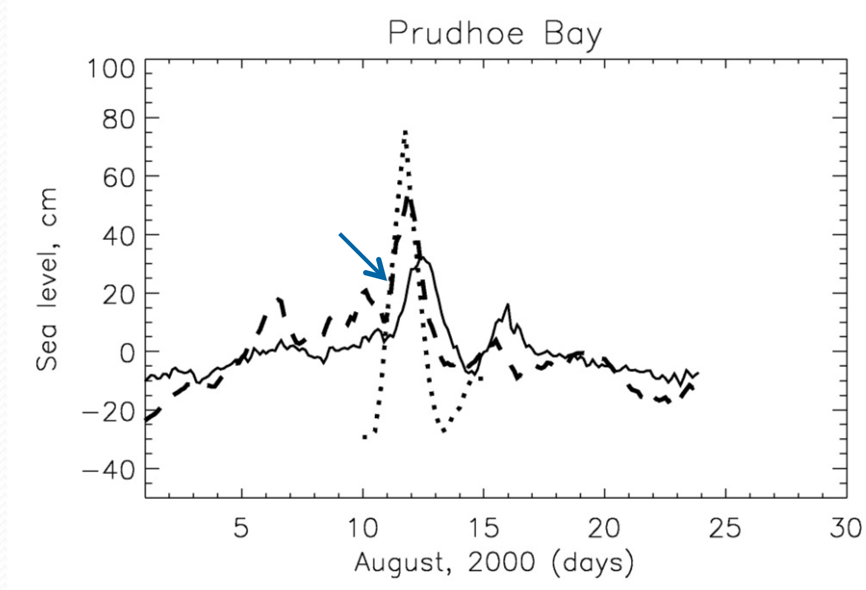




3D model results

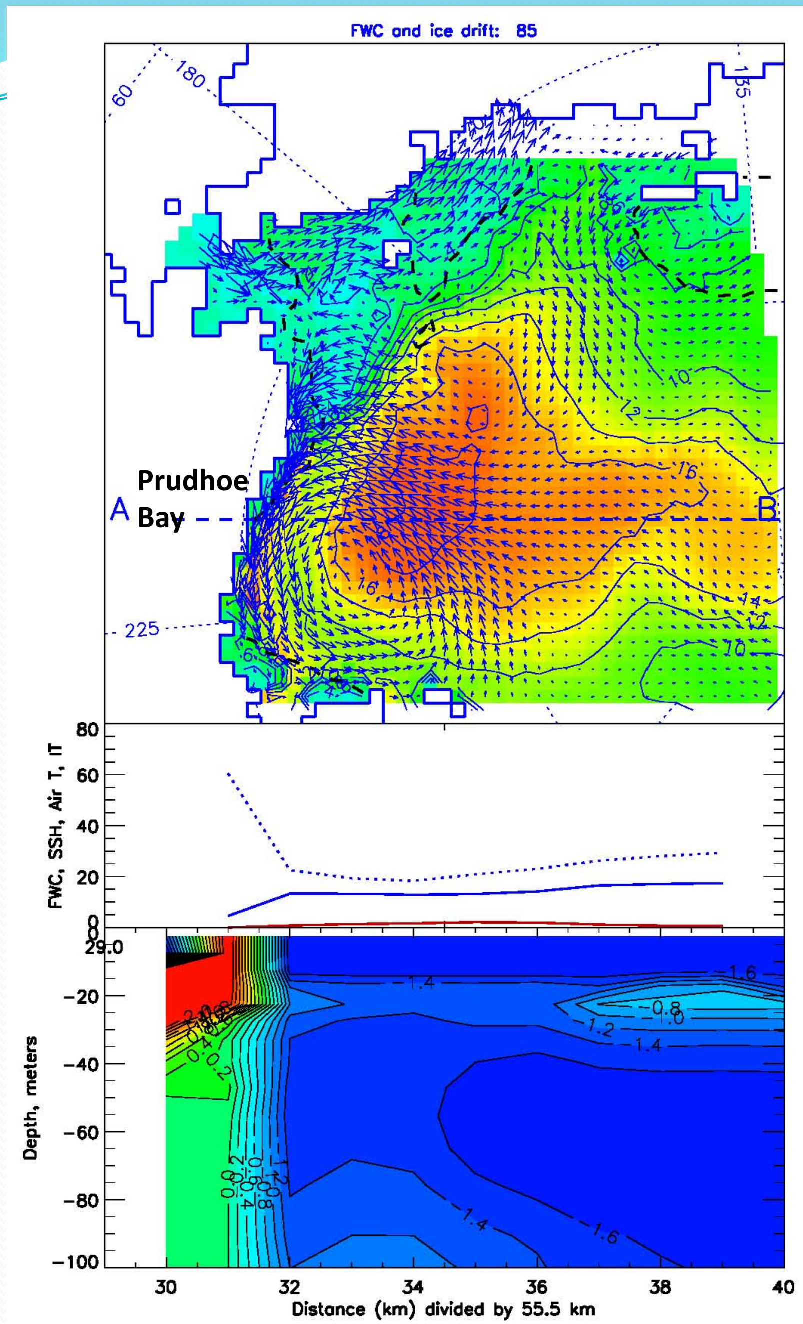
Prudhoe Bay: August 10, 9:00 pm

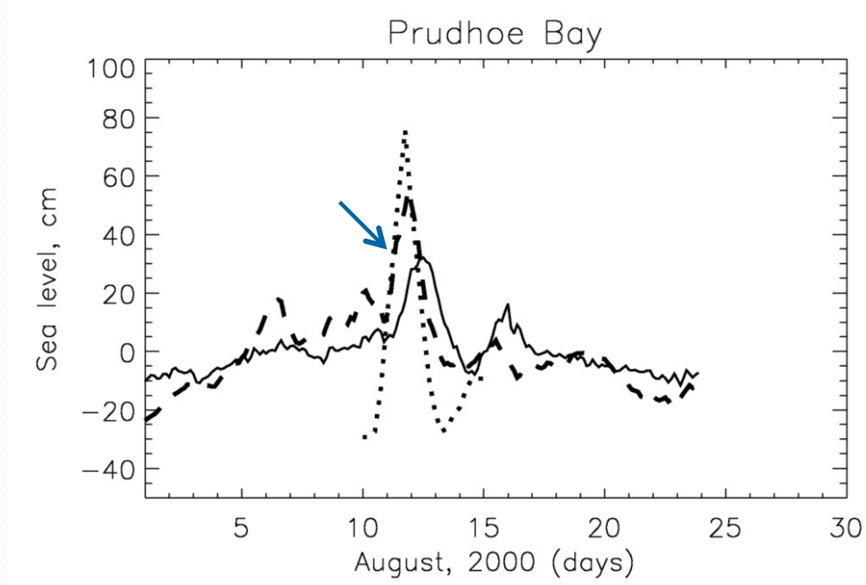




3D model results

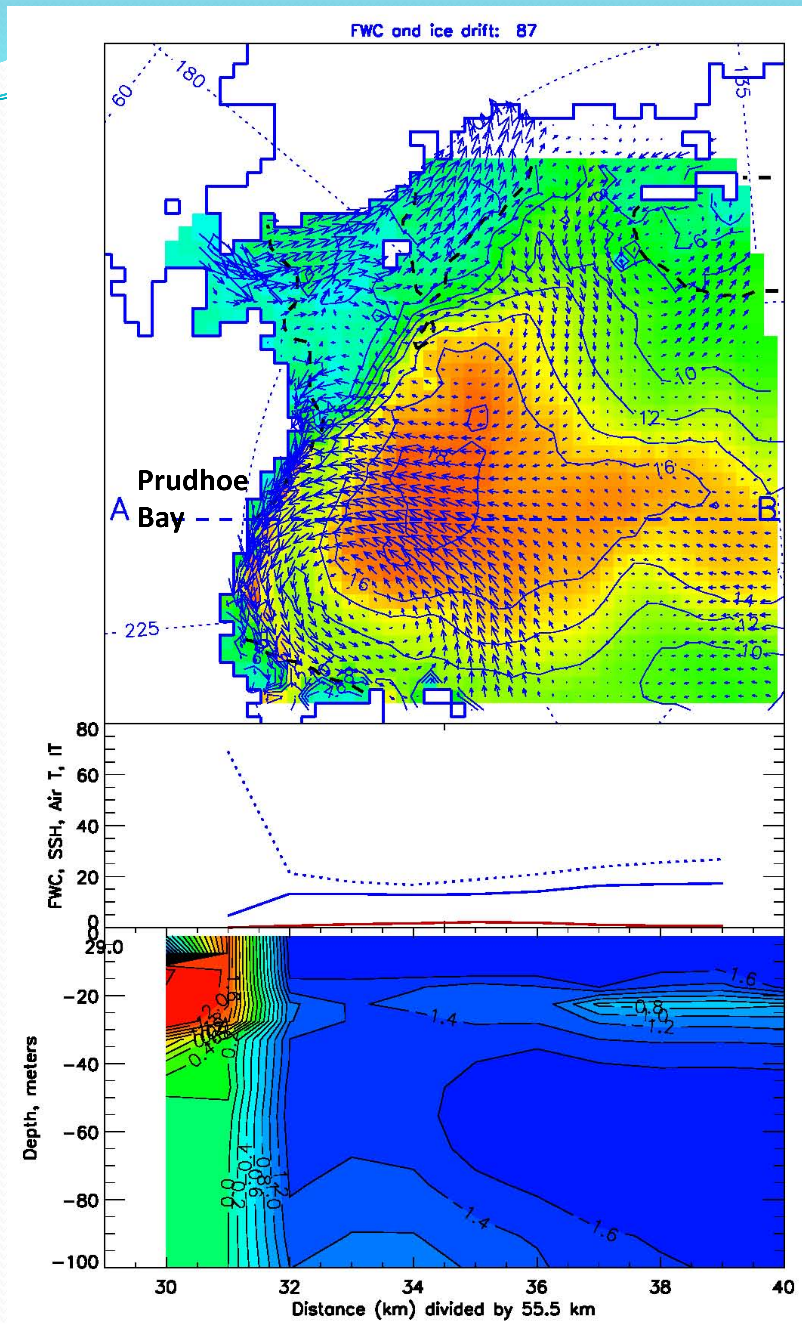
Prudhoe Bay: August 11, 3:00 am

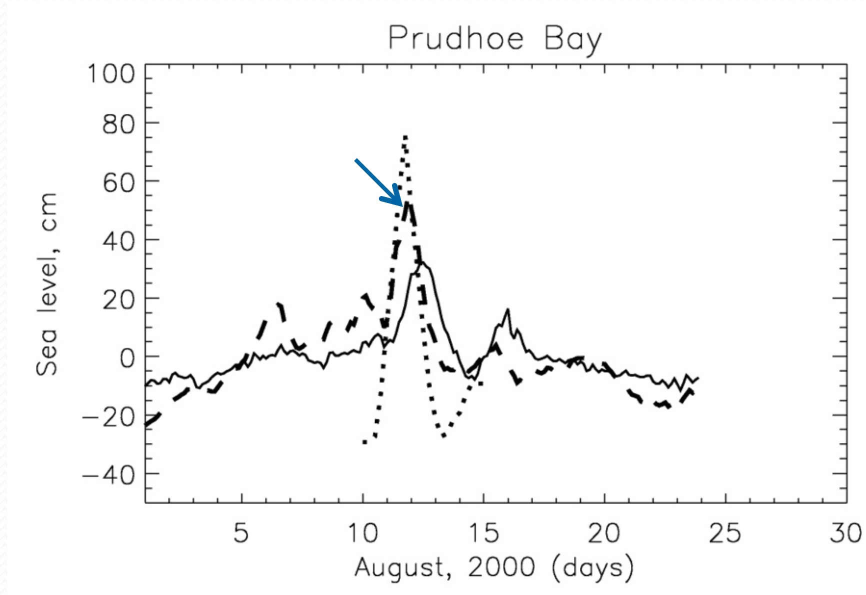




3D model results

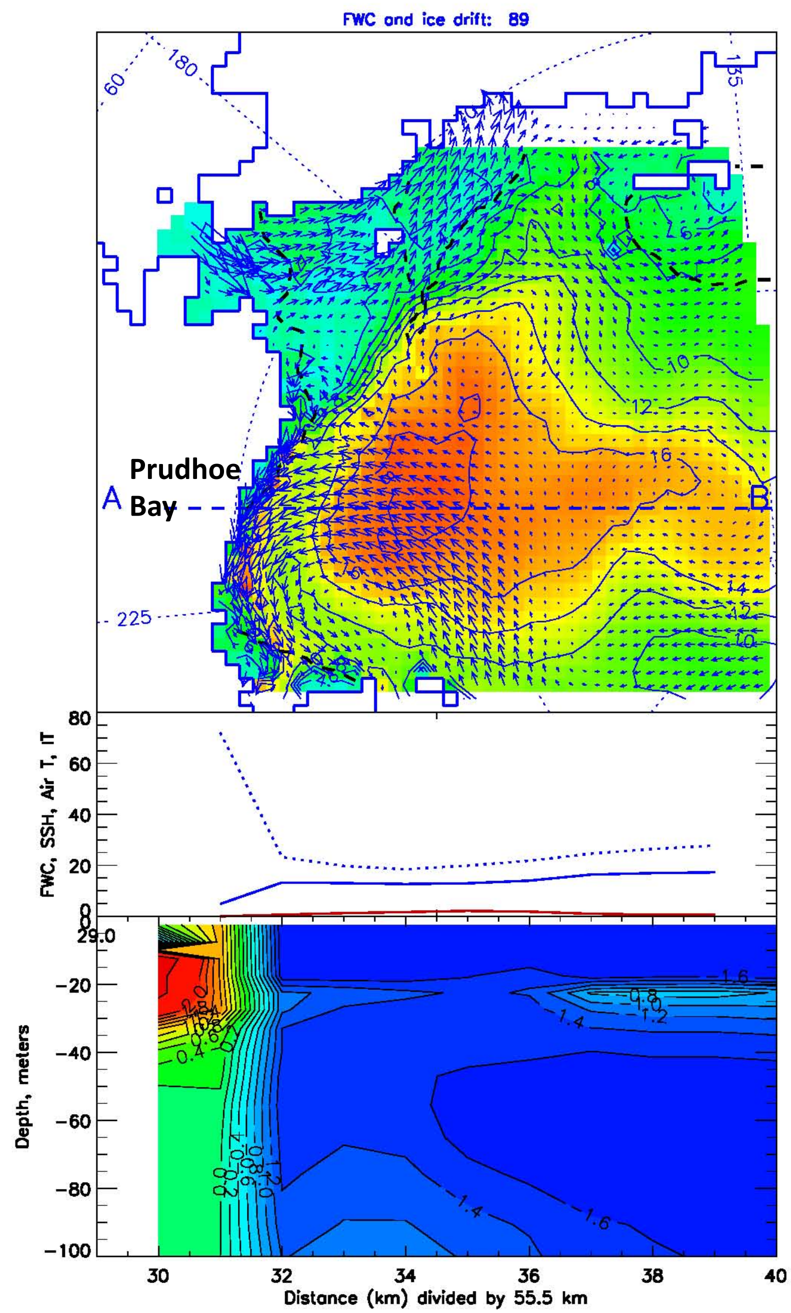
Prudhoe Bay: August 11, 9:00 am

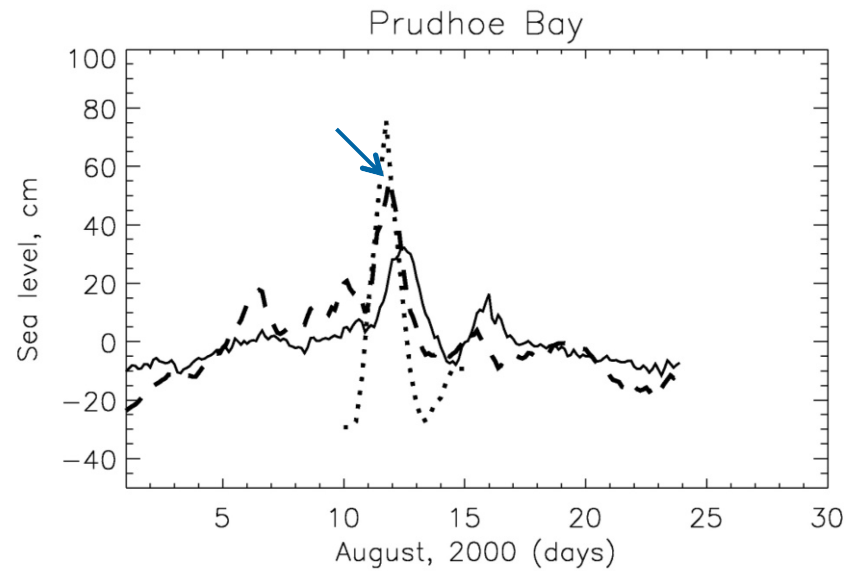




3D model results

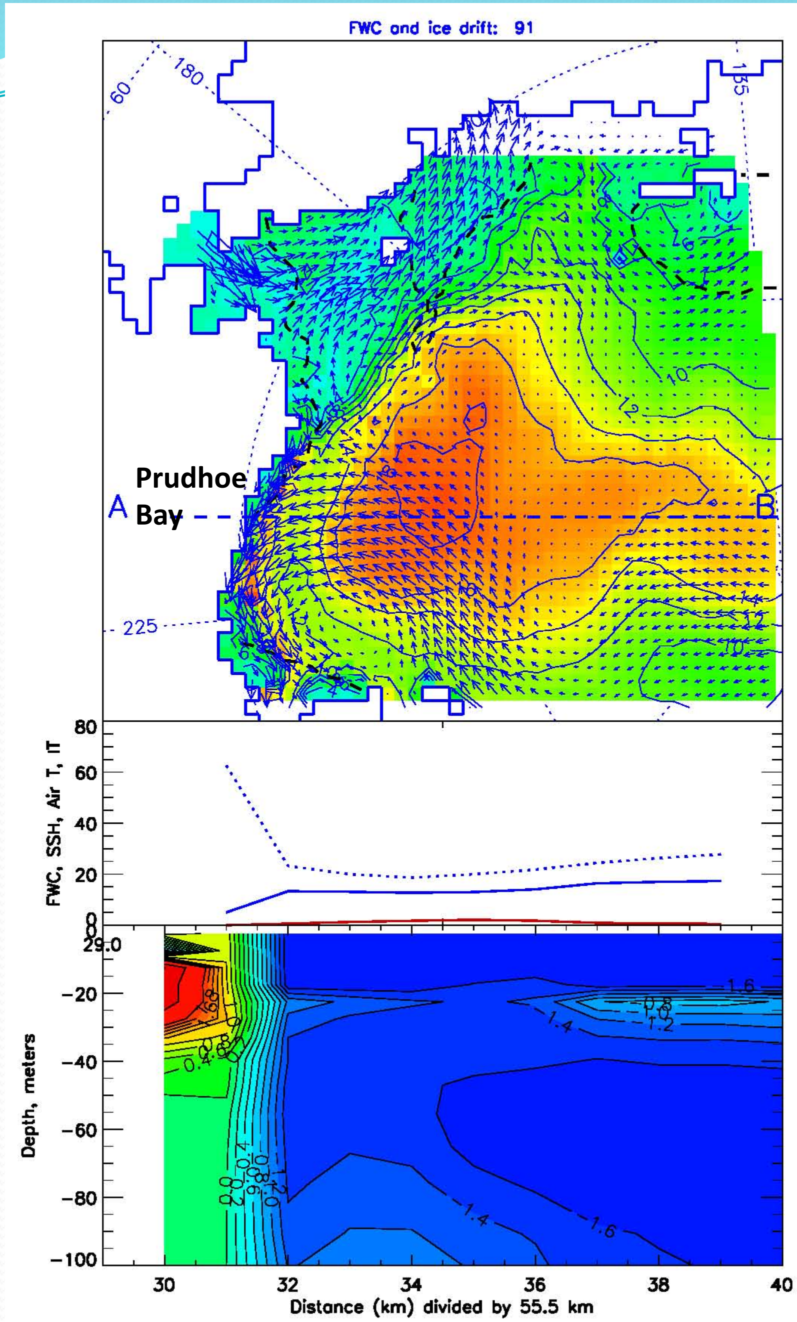
Prudhoe Bay: August 11, 3:00 pm

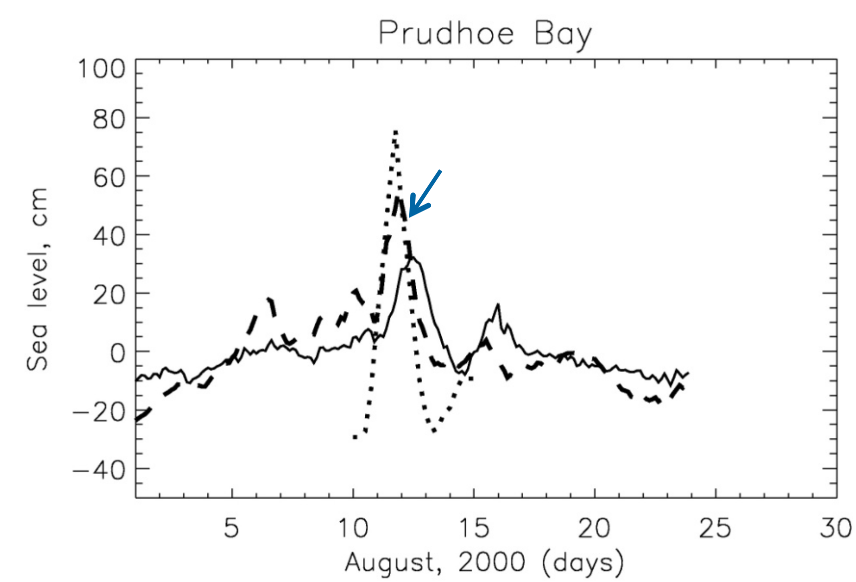




3D model results

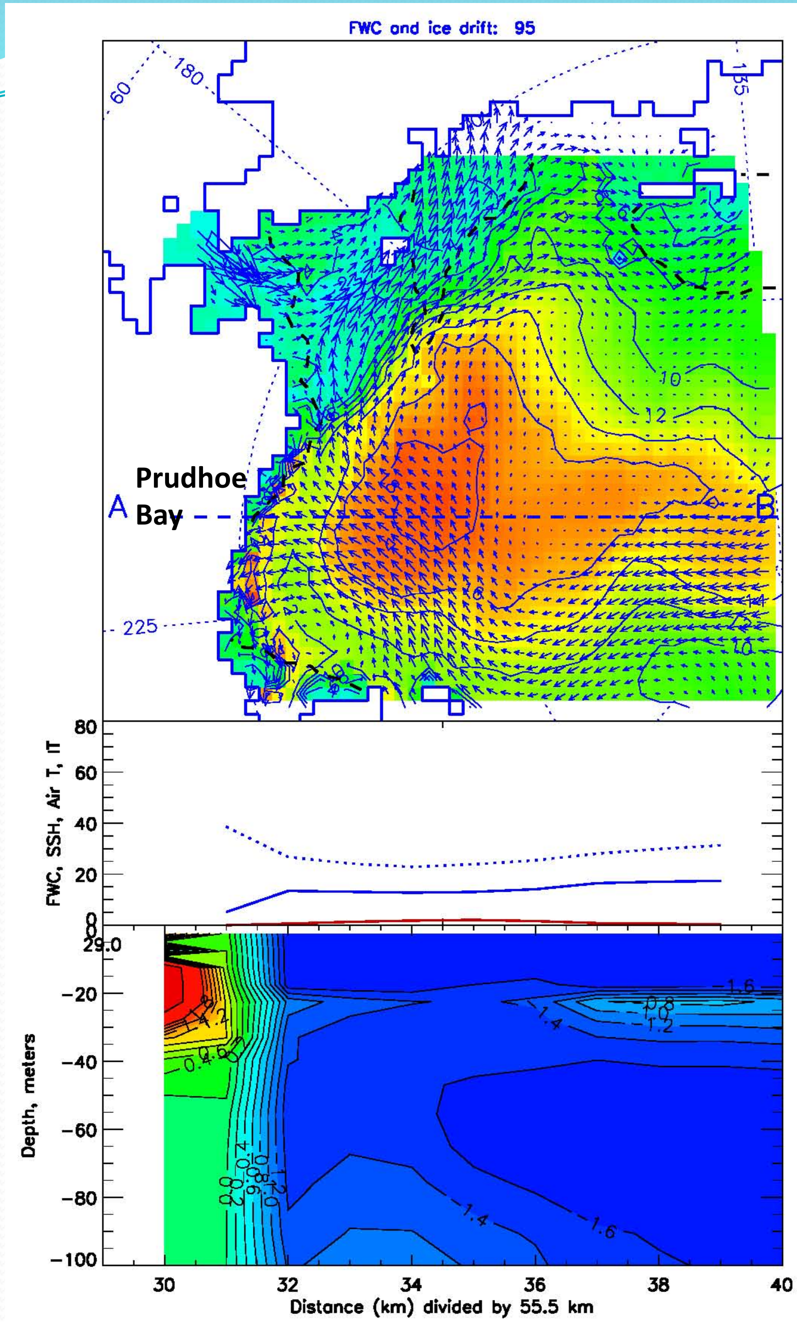
Prudhoe Bay: August 11, 9:00 pm

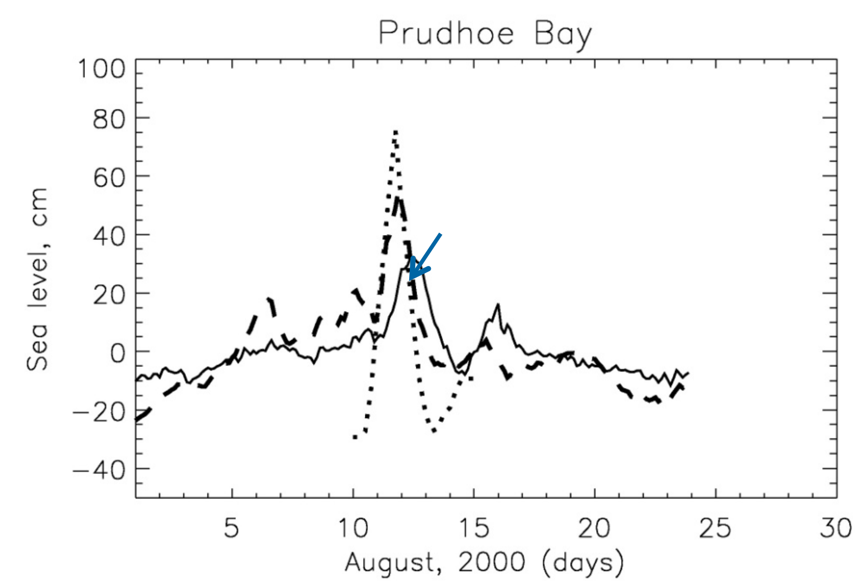




3D model results

Prudhoe Bay: August 12, 9:00 am





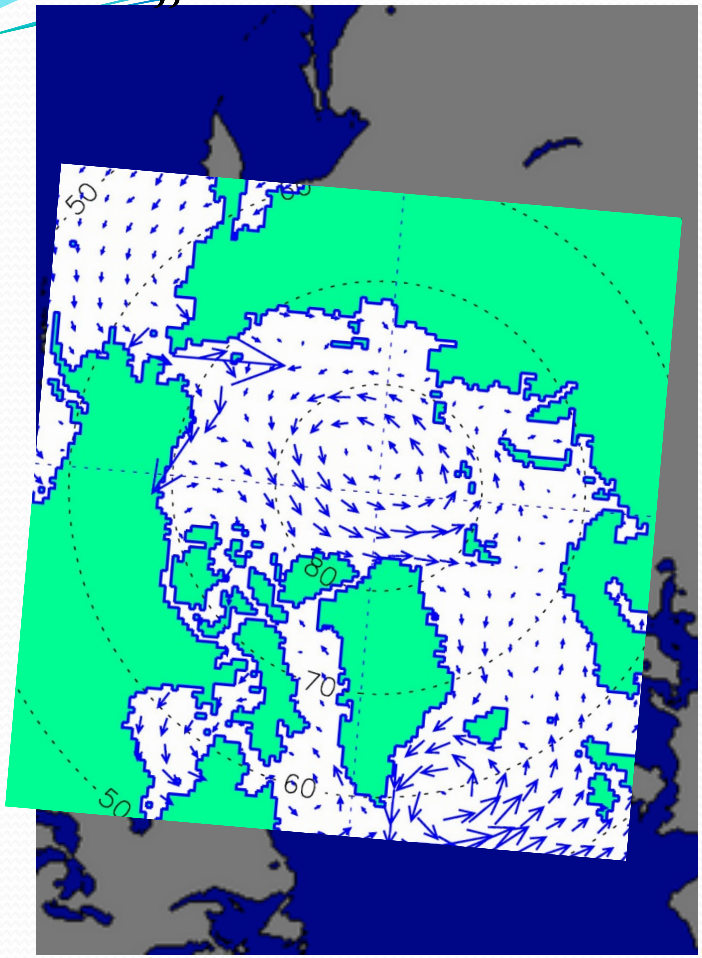
3D model results

Historical observations and future IPCC projections conclude that under conditions of climate change:

- Sea ice is (and will continue) melting and its thickness is reducing;
- Sea level is (and will continue) rising;
- Number of storm surges is (and will continue) increasing.

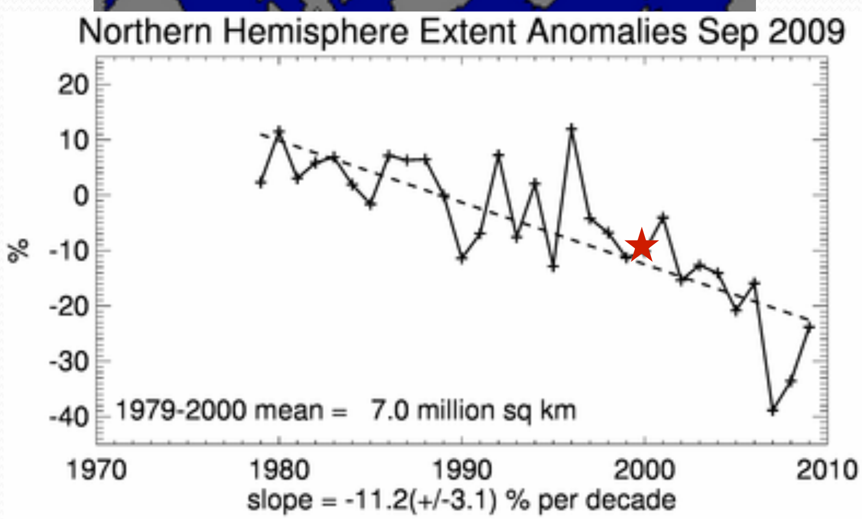
These factors are crucial for coastal processes influencing navigation and key social-economic activities in the region. Following slides illustrate this.

MJJAS drift and currents



September

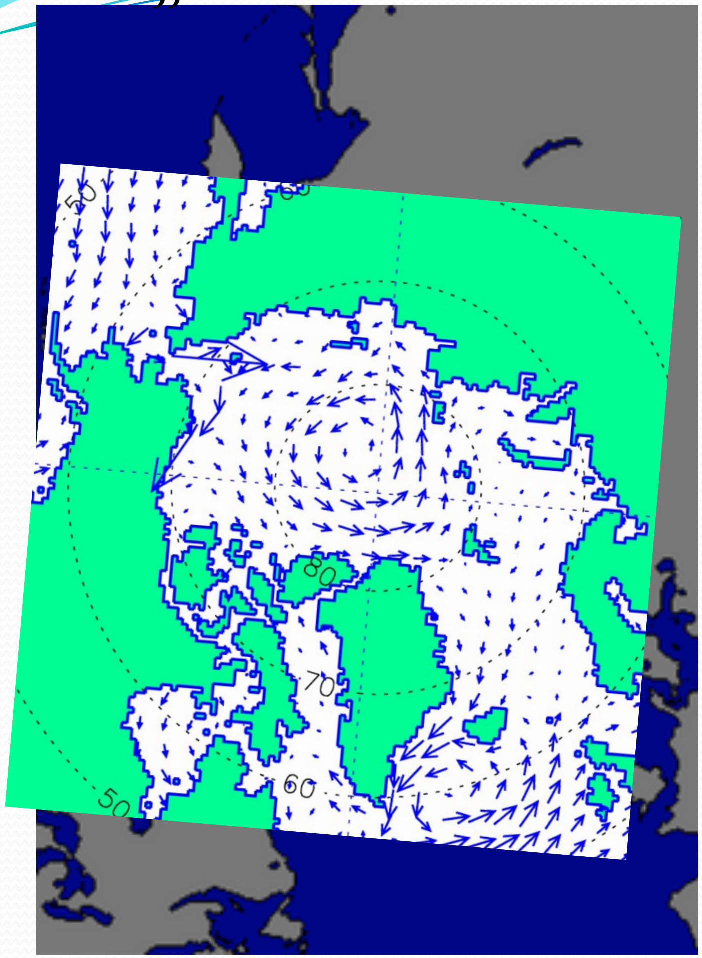
2000

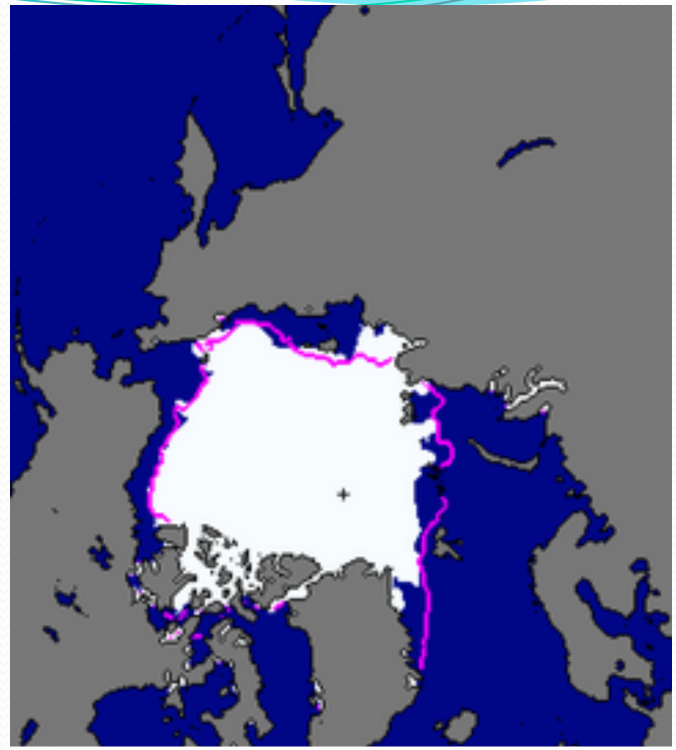


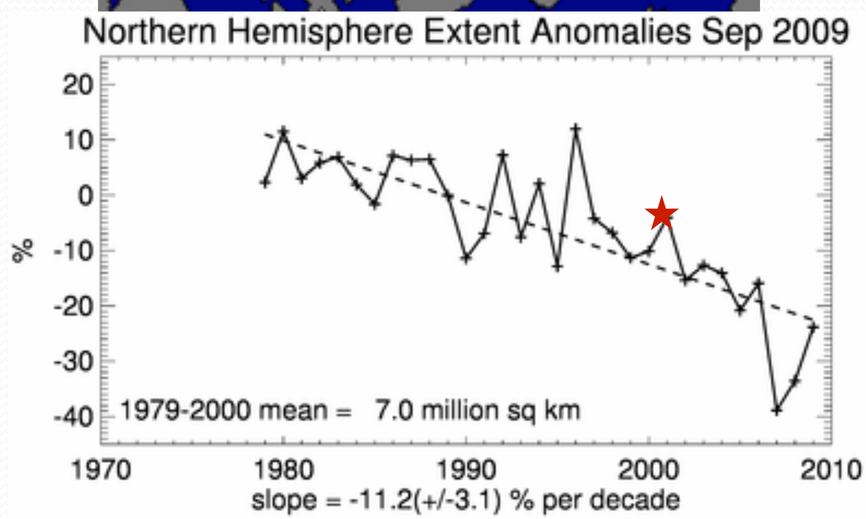
MJJAS drift and currents

September

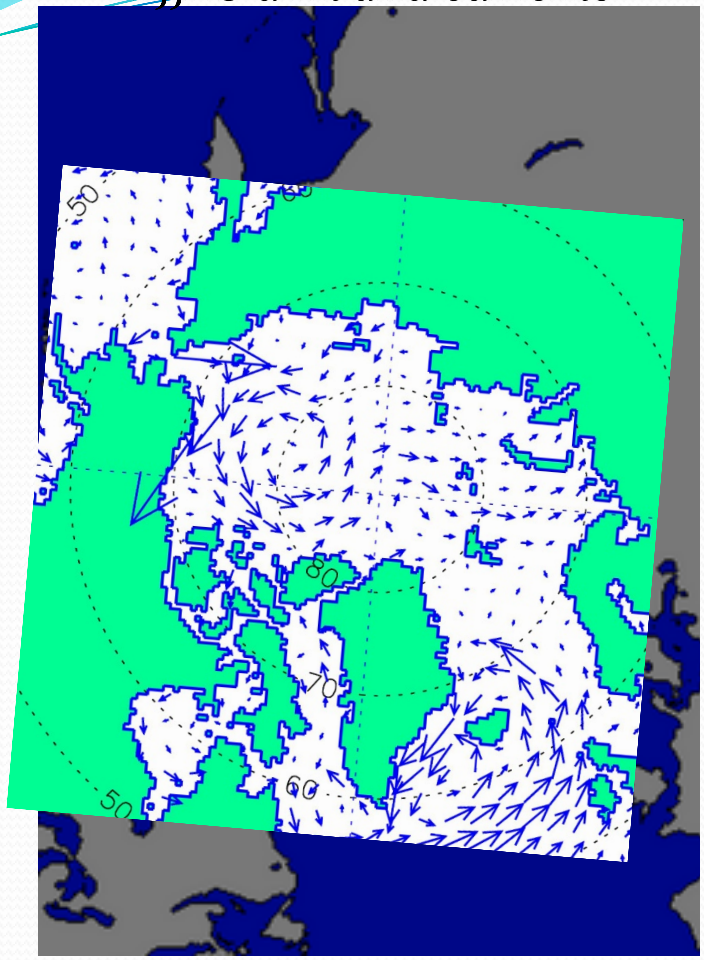
2001





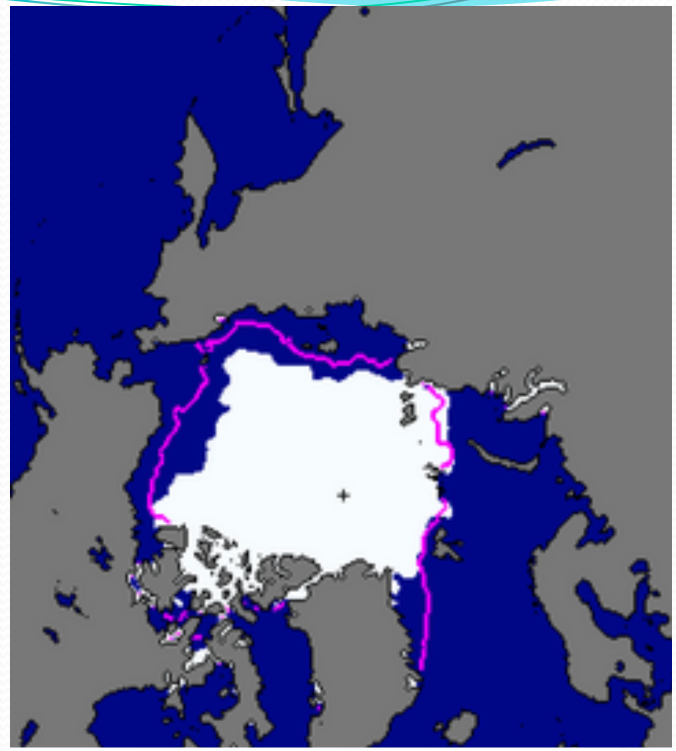


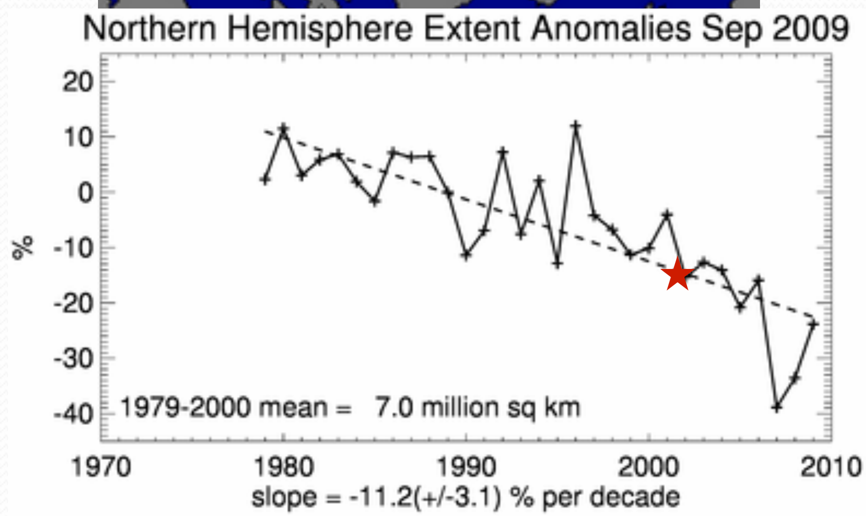
MJJAS drift and currents



September

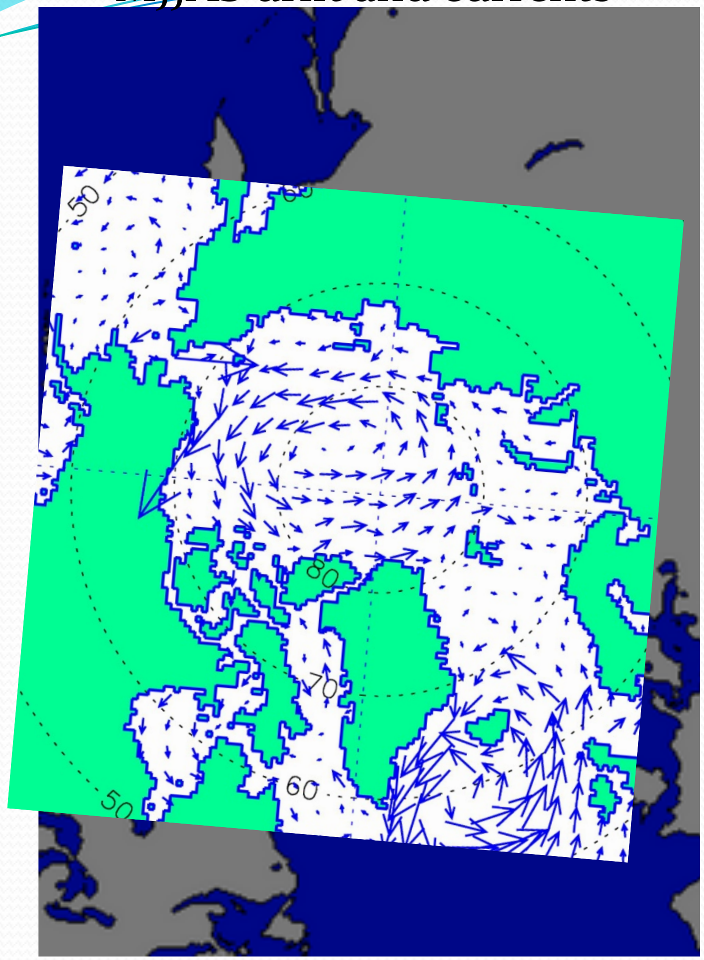
2002



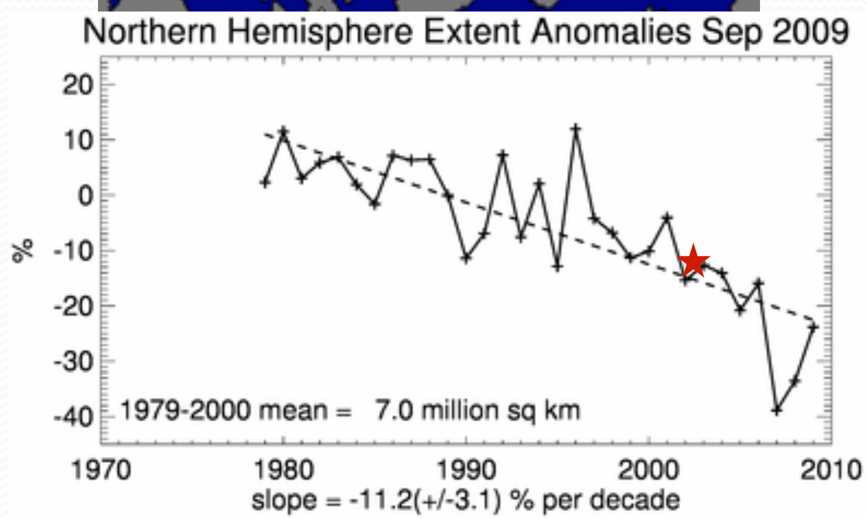


September

MJJAS drift and currents



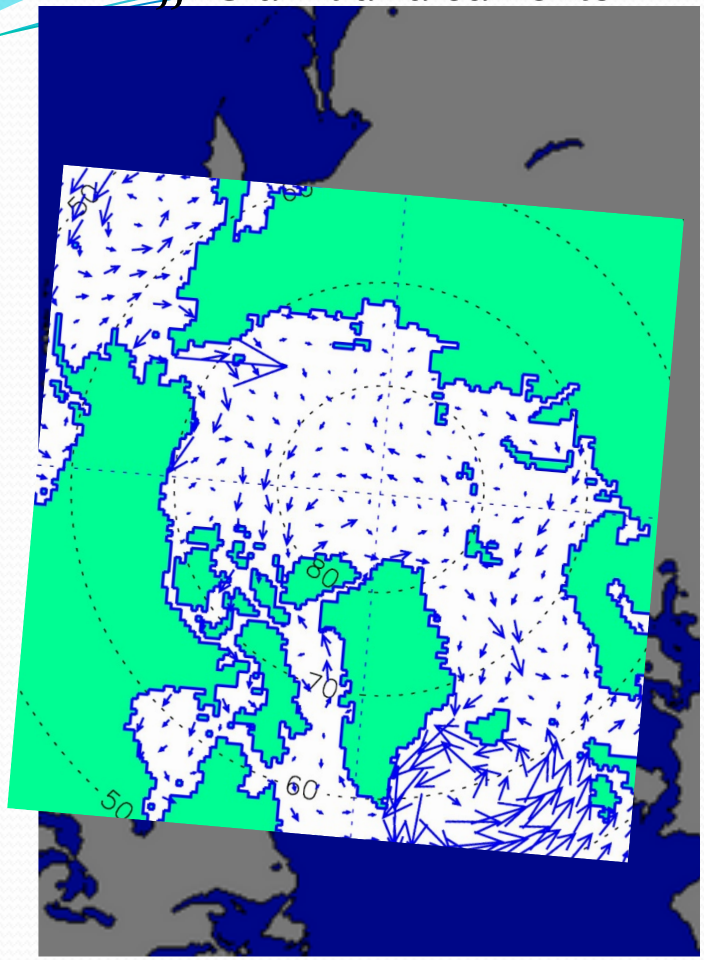
2003

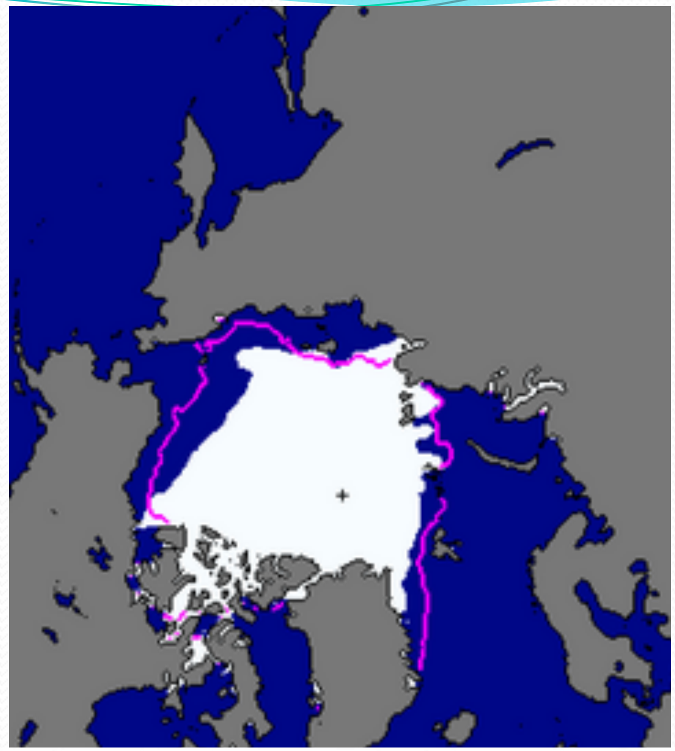


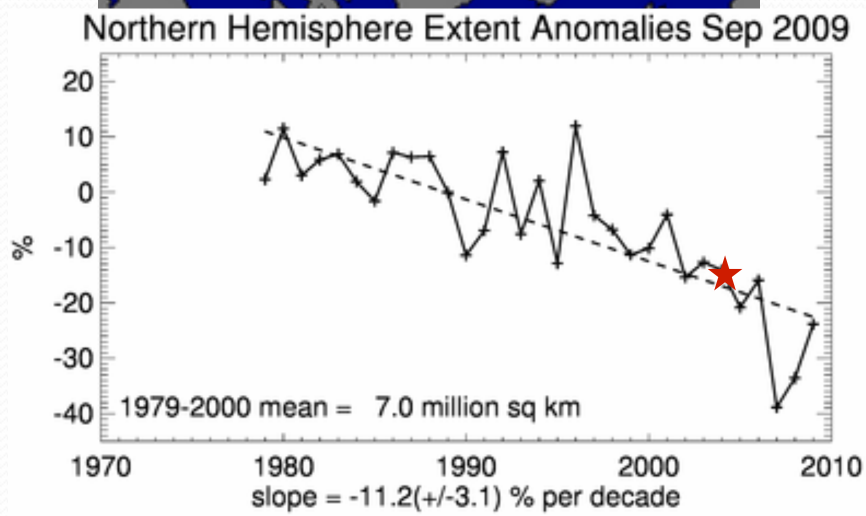
MJJAS drift and currents

September

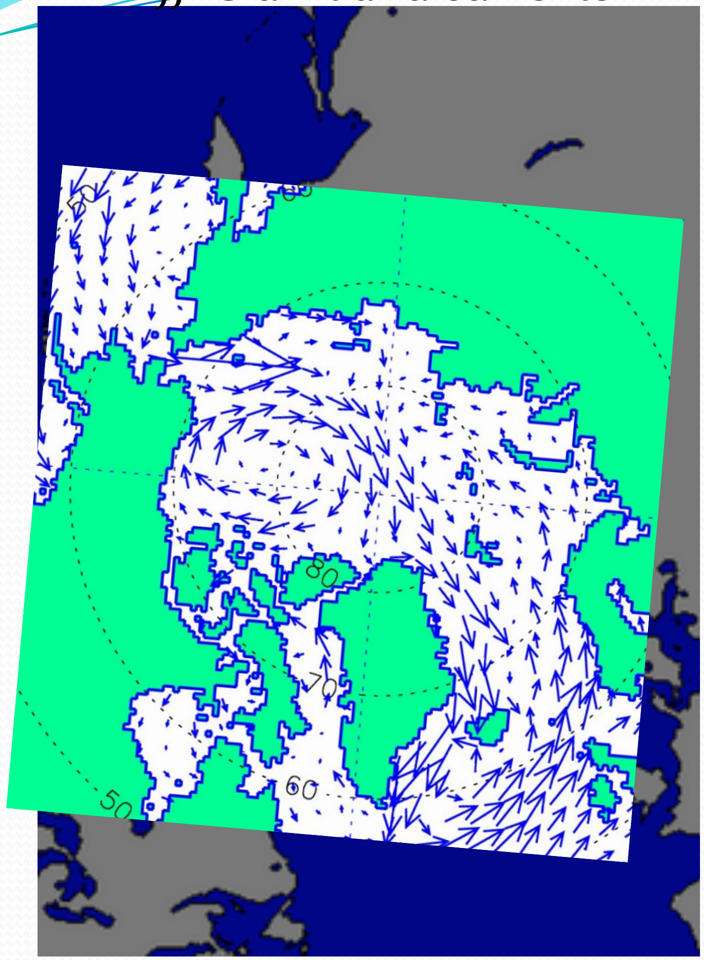
2004





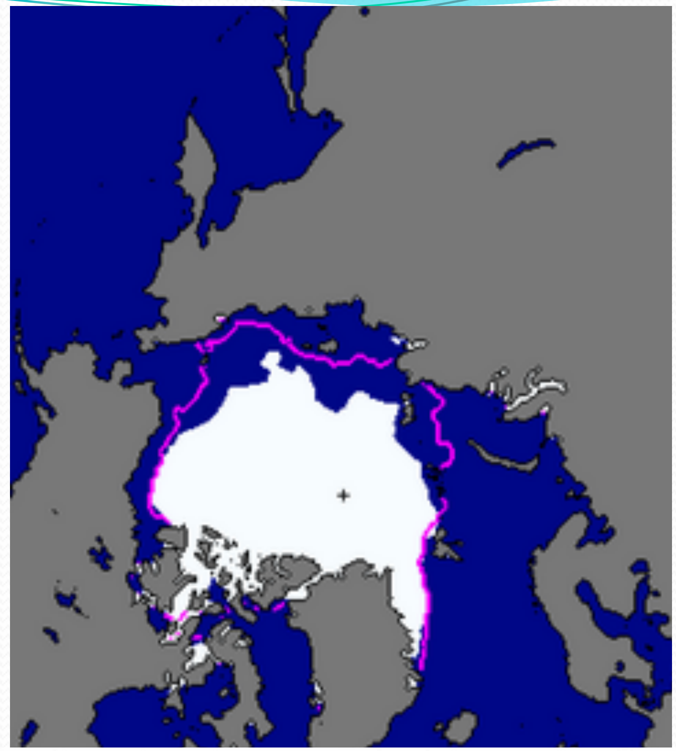


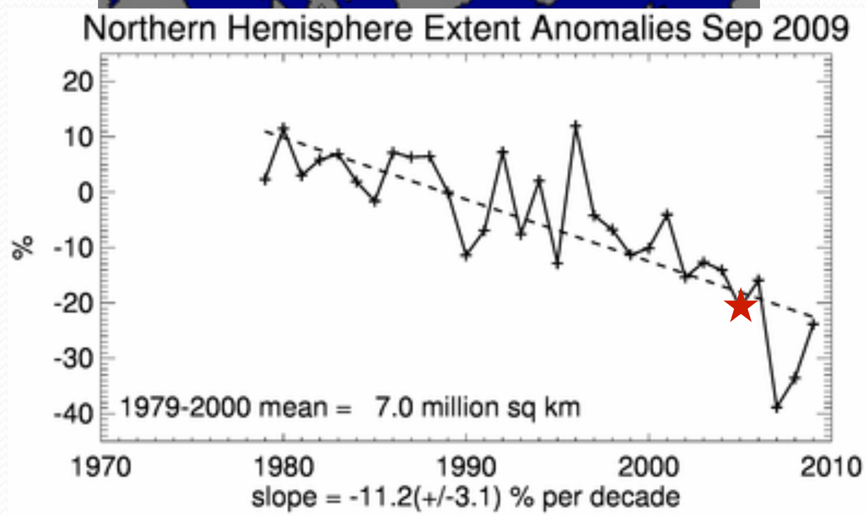
MJJAS drift and currents



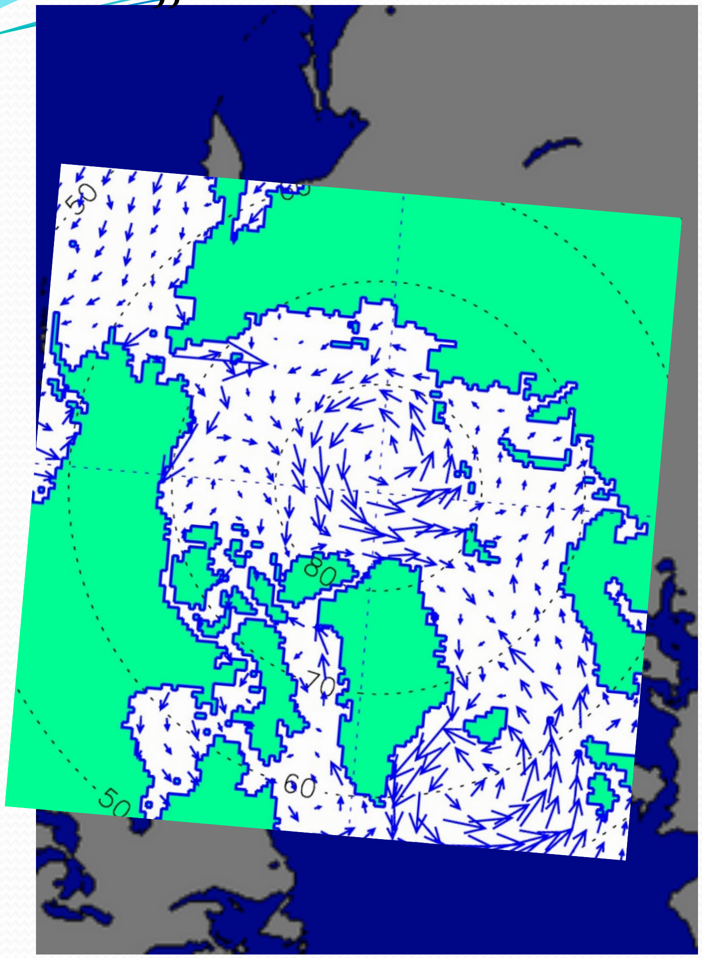
2005

September



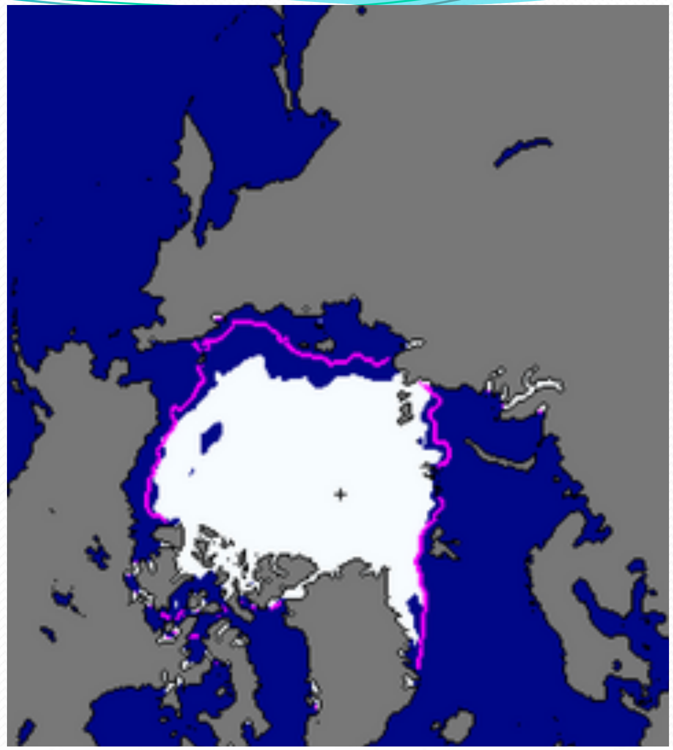


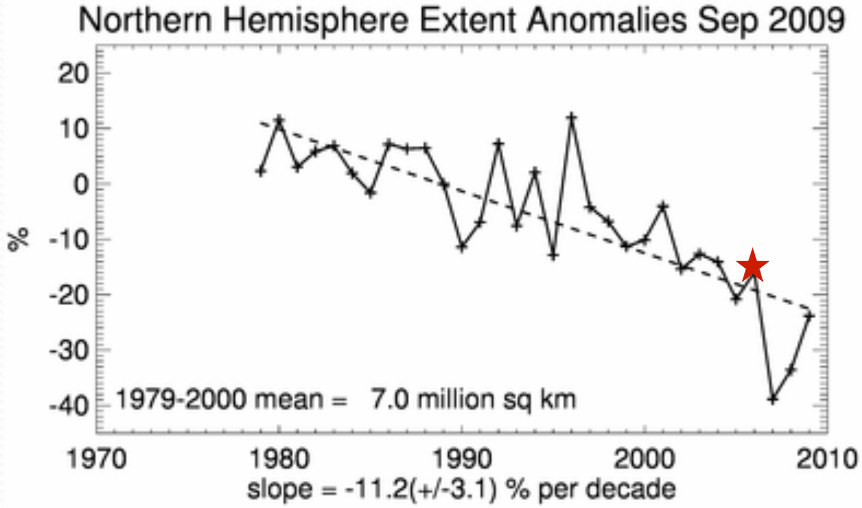
MJJAS drift and currents



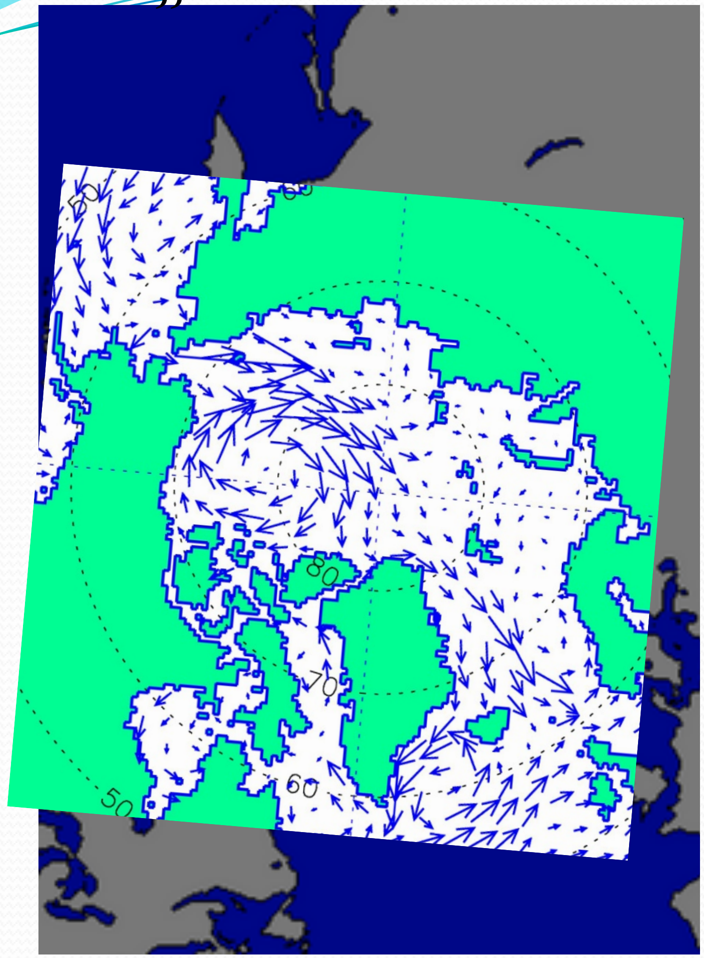
September

2006



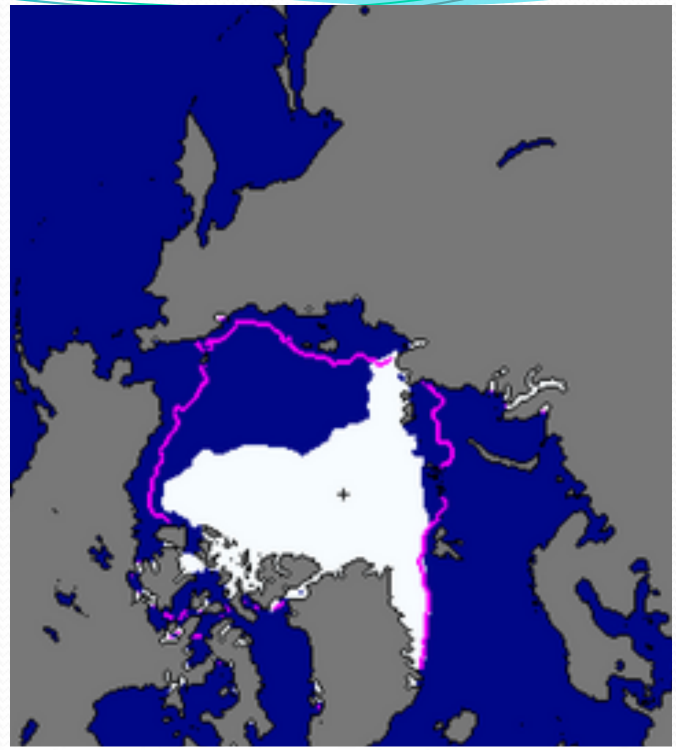


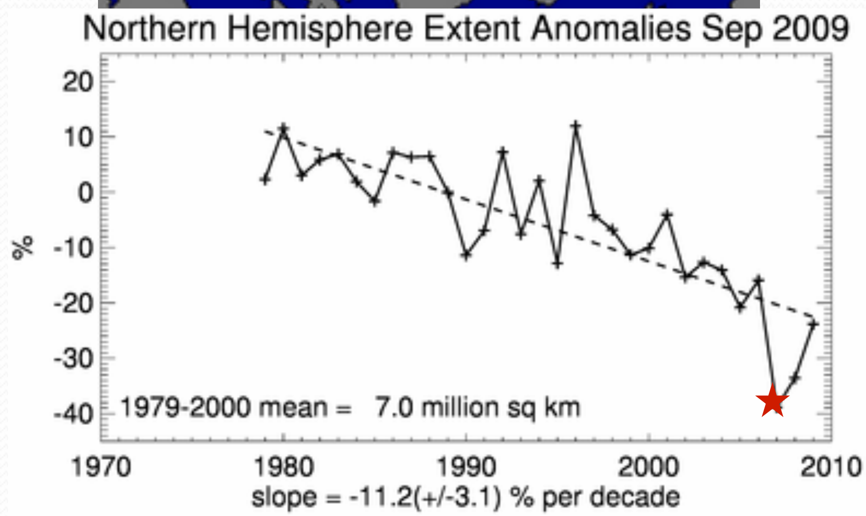
MJJAS drift and currents



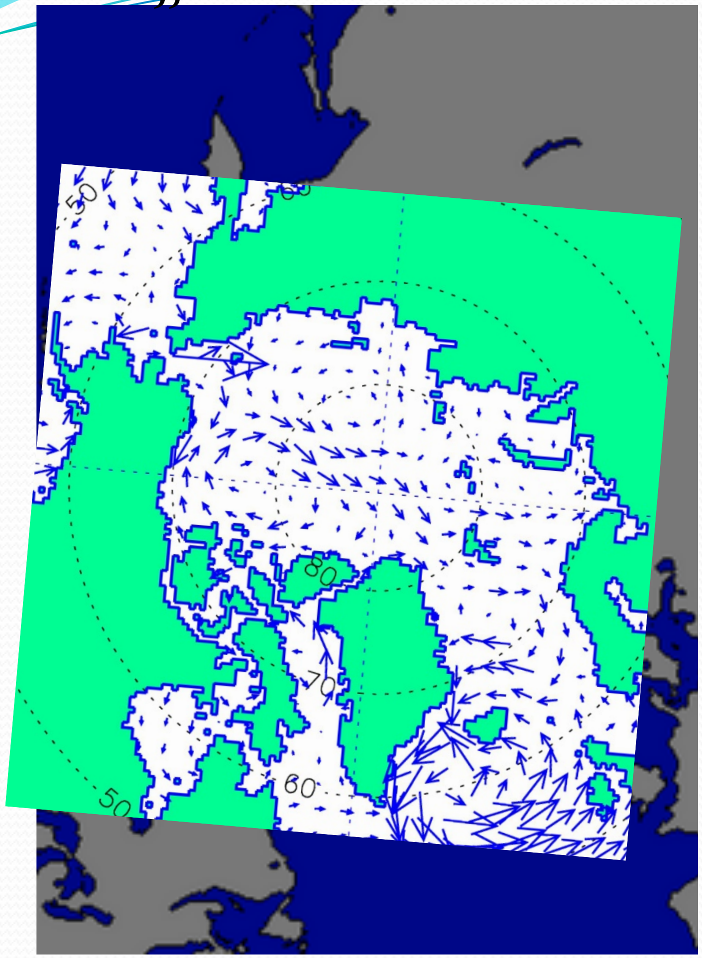
2007

September



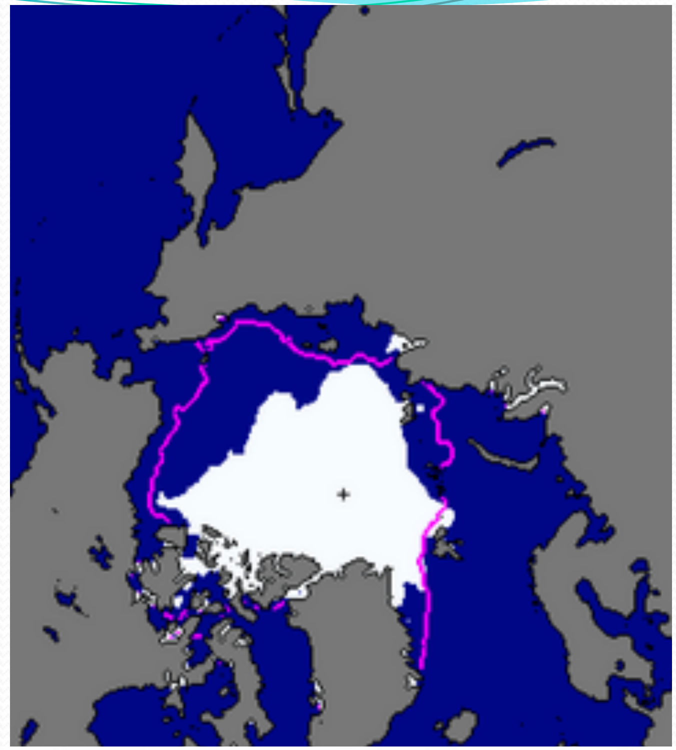


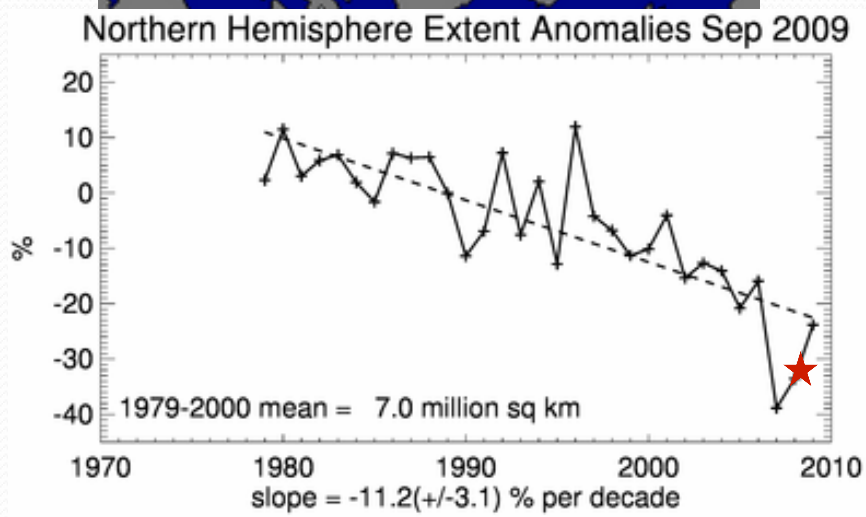
MJJAS drift and currents



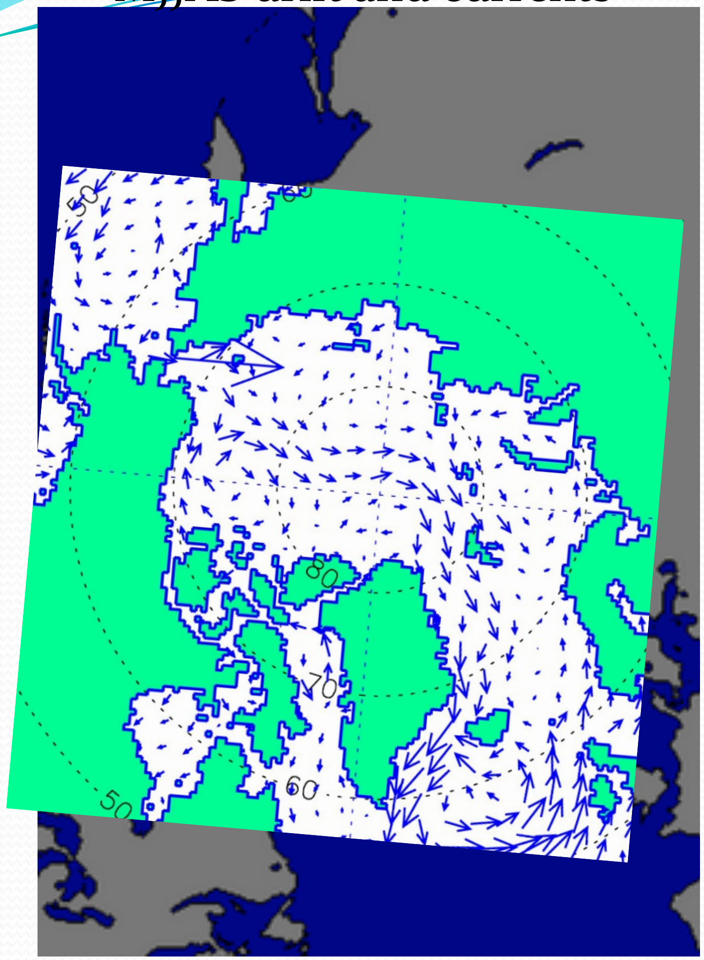
September

2008



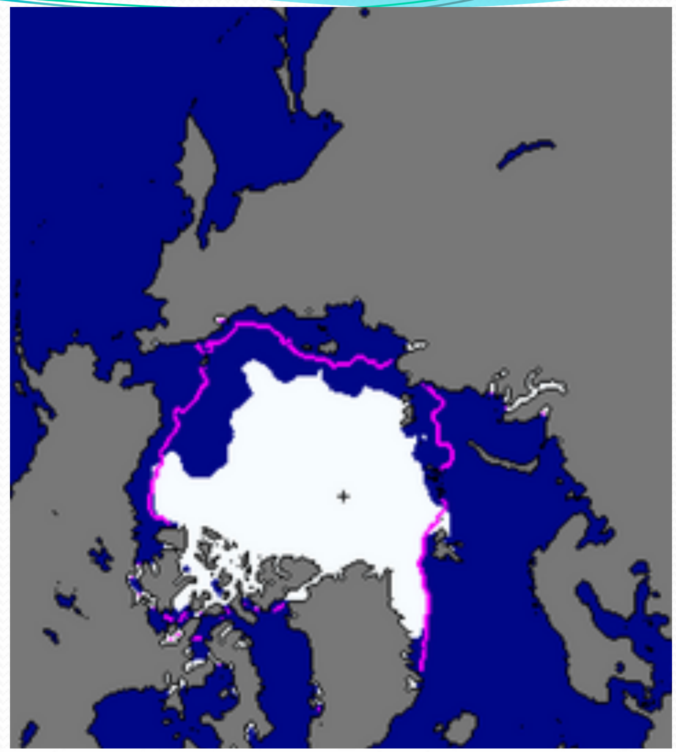


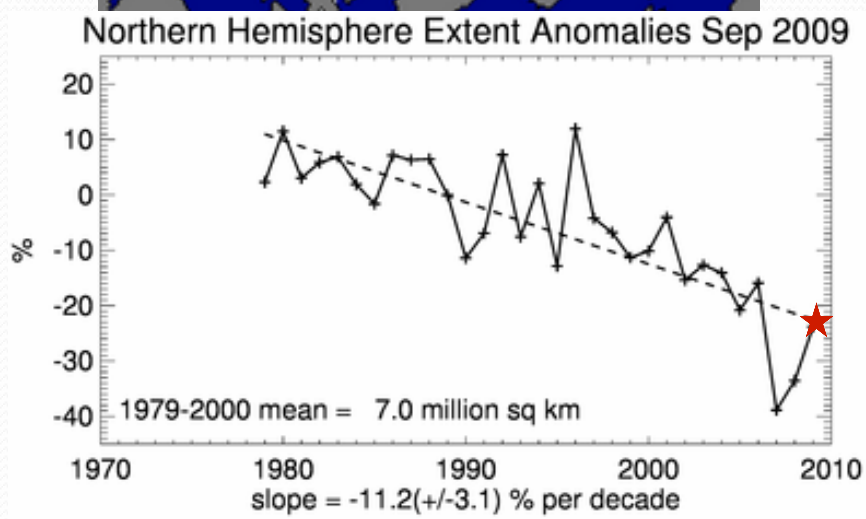
MJJAS drift and currents



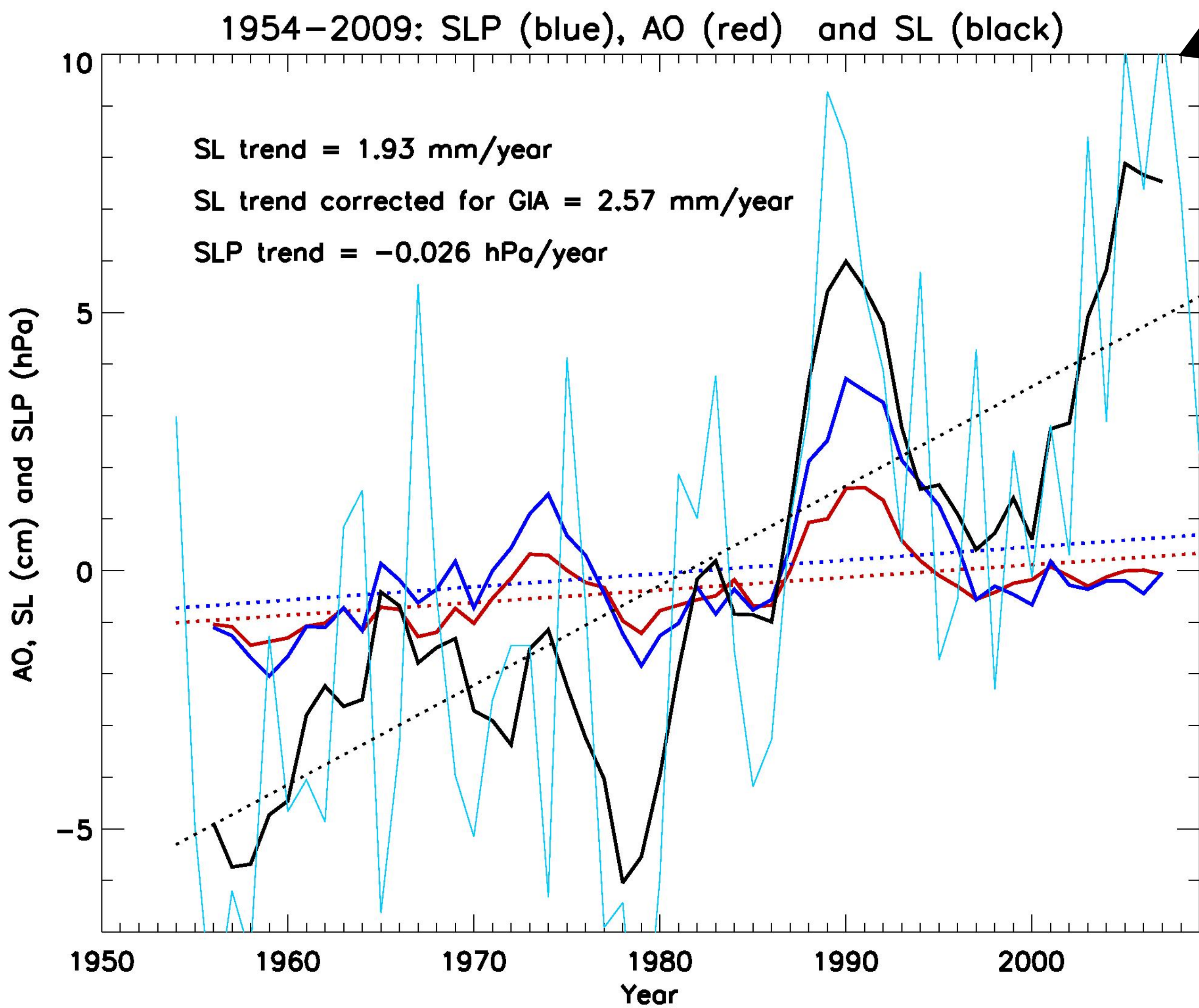
2009

September





Sea Level is rising:



Absolute maximum

Sea level (SL) time series from nine coastal stations in the Siberian Seas, having representative records for the period of 1954–2009 (The sea level data are from I. Ashik, Arctic and Antarctic Research Institute).

Summary

- Critical environmental, socioeconomic, and defense issues have focused the people's attention on the coastal zone.

- This zone is particularly vulnerable in the Arctic, where unprecedented climate changes have already been observed in the context of high natural variability on a range of time scales.

- Key environmental issues affecting human activities on the Alaskan North Slope and Siberian coastal regions include:
  - coastal erosion,
  - recent decline in ice extent and thickness,
  - less stable and predictable shore-fast ice, gouging of shelves and coast by sea ice, pile-up of ice on shore,
  - rise in sea level, and storm hazards.

- One element of the observed climate change is the increased frequency and intensity of extreme events.