METEOROLOGICAL FORCING OF SEA ICE VARIABILITY IN THE SOUTHERN BEAUFORT SEA

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ABSTRACT

Arctic climate processes are, in general, poorly understood. One of the complexities in understanding how the arctic will respond to global scale climate variability and change is the role which snow and sea ice play in controlling energy and mass fluxes across the ocean-sea ice-atmosphere (OSA) interface. The snow/sea ice system is significant at a range of time and space scales on how the atmosphere and ocean are coupled throughout the annual cycle. Feedback mechanisms complicate these processes and the timing of particular events can have significant impacts in both the ecological and geophysical characteristics of the system.

The Canadian Arctic Shelf Exchange Study (CASES) is a Canadian led international research program that will examine the relationship between sea ice variability and carbon fluxes between the Mackenzie Shelf/Cape Bathurst Polynya and the Canada Basin. In this paper we provide an overview of the CASES experiment including plans for a 365-day icebreaker based sampling program to begin in September 2003. We then present results from a historical analysis, which was conducted to provide context to the field sampling program. We present results from ocean, sea ice and meteorological coupling over the period 1978 to 2001 within the CASES study region.

Results show that the sea ice average areal extent and spatial distribution have been decreasing at an alarming rate in the southern Beaufort Sea since 1978. The meteorological forcing of this reduction is evaluated through analysis of NCEP reanalysis data in periods where prolonged negative and positive anomalies in sea ice concentration persist. The results illustrate that sea ice dynamics and thermodynamics can be influenced by subtle atmospheric and pressure pattern differences between the North Pacific and the Southern Beaufort Sea. We conclude the paper with a discussion of the importance of sea ice mass balance and areal extent reduction relative to carbon fluxes on and across the Beaufort Shelf.

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1. INTRODUCTION

The extent and thickness of Arctic sea ice vary considerably from year to year and over decadal time scales. Assessing the effects of present variability in sea ice cover on Arctic marine ecosystems and regional climate requires a substantial improvement in our understanding of the links between freshwater and sea ice, sea ice and climate, and sea ice and biogeochemical fluxes. The need for data is particularly strong for the shallow coastal shelf regions (30% of the Arctic basin) where variability in the extent, thickness and duration of sea ice is most pronounced and where Arctic marine food webs are most vulnerable to change.

The environmental, socio-economic and geopolitical consequences of an eventual sustained reduction of Arctic sea ice are bound to be tremendous: marine Arctic ecosystems will be displaced, a new ocean will open to exploitation, climate warming may accelerate, global ocean circulation may be modified, and traditional use will change. Given our Arctic responsibilities and as one of the first countries to be affected, Canada should lead the increasing international effort to study the Arctic Ocean. Toward that goal, the CASES Research Network was conditionally funded in March 2001 by the Natural Sciences and Engineering Research Council of Canada (NSERC) to conduct the Canadian Arctic Shelf Exchange Study (CASES), an international effort under Canadian leadership to understand the biogeochemical and ecological consequences of sea ice variability and change on the Mackenzie Shelf.

A central aim of the CASES field program is to study the fall and winter pre-conditioning of the Mackenzie Shelf/Amundsen Gulf ecosystem by the minimum fall and winter discharge of the Mackenzie River, and its spring and summer development in response to the intense freshet and the variable ice break-up. Because the area cannot be reached from southern ports until August when the ice retreats, the only possible way to achieve this is by over-wintering a research icebreaker in the area.

In preparation for this over-wintering, a preliminary expedition was conducted in September-October 2002 to moor current meters and sediment traps, deploy drifting buoys, and carry out ship-based biogeochemical sampling. The main thrust of CASES is a one-year over-wintering of a class-1200 Canadian Research

Icebreaker in the study area, starting in September 2003. During this annual cycle, the ship and landfast ice camps will support the year-round sampling of the ocean-sea ice-atmosphere interface and associate shelf ecosystem. Ship-based sampling will be conducted along a series of across shelf sampling transects adjusted seasonally with the expansion-reduction of the open water (navigable) area. Satellite remote sensing coverage of the area will be extensive with real-time data received on the ship to assist field operations.

In preparation for the CASES investigation we examined historical satellite passive microwave sea ice concentration data to estimate the average trends in ice concentration, formation, ablation and spatial pattern. We evaluated the sea ice variables using meteorological forcing estimated from the NCEP reanalysis data. Through this analysis we intend to develop a picture of the past 22 years of sea ice and meteorological forcing in the CASES study region (Southern Beaufort Sea), thus providing a historical context for the research results which will be forthcoming from the CASES research network.

At this AMS meeting our aim is to provide an overview of the results from this paper in this 'extended' abstract form. The complete version of the paper will be submitted to the Journal of Geophysical Research (Oceans) in the spring of 2003. In this extended abstract we present average meteorological and sea ice and conditions within Amundsen Gulf, Mackenzie Shelf and Beaufort Sea (hereafter referred to as the 'CASES region') over the period 1979 to 2000. We then present a brief review of some of the trends in the coupling between meteorological forcing of the sea ice using the framework of anomaly analysis. Only a summary of the pertinent methods is provided in an effort to respect page limits.

2. METHODS

The CASES region consists of Cape Bathurst Polynya, Mackenzie Estuary/Shelf, and the offshore southern Beaufort Sea. In this analysis we consider the annual average sea ice concentration and selected atmospheric variables within an area considered to influence this region. A brief summary of pertinent methods required to address our stated objectives follow.

2.1 *Meteorological Methods*

The historical atmospheric analysis used daily NCEP (National Centers for Environmental Prediction) gridded atmospheric fields between 1978 to 2001 that included surface air temperature (2 m), sea level pressure (SLP), winds (10 m), relative humidity (2 m), precipitable water, 500 hPa geopotential heights and 1000-500 hPa thickness. The study area was encompassed by 60°N to 90°N latitude and 180°W to 70°W longitude (Figure 1) to note large-scale atmospheric patterns associated with local CASES area synoptic conditions.

The data were averaged in several ways to depict overall mean, annual and monthly atmospheric conditions. The overall mean atmospheric fields spanning all available years were calculated for each variable to inspect overall climatological conditions as well as individual annual means to illustrate inter-annual variations. The data were also monthly-averaged by grouping it into 13 months (Julian Months) each consisting of 4 Julian Weeks (28 days), except Julian Month 13 that contains one extra day (last day of the year). Leap year days are added into the Julian Week containing that day. Monthly data were averaged in two ways; 1) monthly means spanning all years to illustrate overall seasonal trends, and 2) monthly averages for each individual year to inspect intra-annual variations.

Supplementary atmospheric surface data consisted of the Meteorological Service of Canada (MSC) station climate data between 1971-2000 for determining "climate normals" for stations within the CASES study region (Inuvik, Tuktoyaktuk, Holman, Sachs Harbor, Paulatuk, Cape Parry and Komakuk – see Figure 1). These data consisted of air temperature (2 m), precipitation and snow depth, and days with various weather occurrences. Surface wind data (wind roses) and other adverse weather statistics for each station were provided by the Prairie Aviation and Arctic Weather Centre (PAAWC).

2.2 *SSM/I Methods*

Sea ice concentrations were provided by the EOS Distributed Active Archive Center (DAAC) at the National Snow and Ice Data Center (NSIDC), University of Colorado, Boulder, CO. The data were derived from Nimbus-7 Scanning Multi channel Microwave Radiometer (SMMR) and DMSP-F8, -F11 and -F13 Special Sensor Microwave/Imager (SSM/I) daily brightness temperatures at a grid cell size of 25 x 25 km. The sea ice concentrations were generated by the Oceans and Ice Branch, Laboratory for Hydrospheric Processes at NASA's Goddard Space Flight Center (GSFC), using SMMR brightness temperatures that were processed at NASA GSFC and SSM/I brightness temperatures processed at the NSIDC. The data set covers the period January 1979 through December 2000.

The data are distributed by NSIDC as daily composites from which we computed weekly averages. The Year Week and Year Month schemes, described above, were also used to structure the sea ice data into a consistent time series. Spatially, the data set depicted the NOW polynya area in a 32 by 32 array, with each pixel having a nominal spatial resolution of 25 km^2. Each pixel within the array was coded to either land or ice concentration (in percent). Weekly averages resulted in 936 of these images (52weeks*22 yrs). These data were co-registered into a single three dimensional array with coordinates defined as (i,j, and t). Computations varied depending on the particular objective being addressed:

We computed a 22-year weekly averaged dataset. This resulted in an average ice concentration for a week (e.g., week n), which was computed as the average of the 22 years of that week. The product of the data manipulation was a data set of 52 weekly averages. We extracted a subset of these data for visual presentation and an animation of the weekly average ice concentrations was produced (view at http://www.umanitoba.ca/ceos/publications). To estimate the average timing of formation and decay within the polynya we produced a data set by defining the first date at which the concentration of sea ice reached a threshold. The formation images were created by assigning the value of the first week of the year in which a pixel reached or exceeded an ice concentration value of 70%. The range of weeks searched was limited to week 35 of a given year through to week 8 of the following year (this ensured that we selected only the 70% ice formation point and not the corresponding decay point). The decay images were created by assigning the value of the first week of the year in which a pixel had an ice concentration value less than or equal to 30%. The range of weeks searched was limited to week 9 to 34 of each particular year. The search of the last year of the data set was truncated at week 52, since there were no data available for the following year.

We computed a 22-year time series using the weekly anomalies from the full data record. The methods of computation were identical for both the monthly and weekly anomalies. The 22-year average ice concentration for each week (month) of the year was calculated for each pixel in the weekly (monthly) SSM/I images. This resulted in 52 (13) images (one for each week (month) of the year) in which each pixel (i,j) is the 22 year average ice concentration at pixel location (i,j) for a given week (month) of the year. Each of these 18-year weekly (monthly) average images was subtracted on a pixel-by-pixel basis from the corresponding weekly (monthly) image for a given year. This operation was performed for each year in the data set. This yielded 22*52=1144 (22*13 = 286) images that showed the deviation in ice concentration from the weekly (monthly) 22-year average of a given year. This results in a dataset which show how different a particular week (month) is from the 'normal' expected for that week (month). In this context normal is defined as the average for all of the particular weeks (months) in the 18-year data record. We do not interpret sea ice concentration anomalies smaller than about ± 5% since this level is likely within the noise of the ice concentration retrieval algorithm.

We then computed a time series slope surface for the CASES study region using the 1144 weekly anomaly fields. For each pixel (i,j) in the weekly deviation images, a time series was constructed which consisted of pixel (i,j) ordered by time. Since the size of an SSM/I subset was 85 * 85 pixels, the analysis created 7225 time series in total. These time series showed the weekly deviation from the 22-year average over all weeks for all years. A least squares linear regression line was then fit through each time series and the probabilities associated with the confidence intervals for the slope were computed. A final image was constructed in which the value of each pixel of the image represented the slope of the time series at each of the 7225 pixel locations within the CASES study region. We note here that the seasonal periodicity is absent in the trend surface because we used the weekly anomaly data. We retained those slopes that met or surpassed the 99 percent confidence level ($p<0.01$). These slopes were then mapped back onto the SSM/I grid to show the spatial pattern of the changes in ice concentration anomalies both as an overall trend and the spatial variability in any observed trend.

3. RESULTS AND DISCUSSION

In what follows we present only those results pertaining to the anomaly analysis of the meteorology and sea ice coupling. Complete results are available in Barber and Hanesiak, 2003 (to be submitted to JGR oceans)

3.1 *Sea Ice*

Averages in sea ice accretion and ablation were computed (not shown here). The trends in dates of onset of freeze-up and melt were computed and will be described in Barber and Hanesiak, 2003. Anomalies were computed based on the approach described in the methods. The results from the weekly anomaly concentrations were put into an animation format (www.umanitoba.ca/ceos/publications). This animation was used to visually identify two periods of unusually strong positive and negative anomalies in the ice concentration record. The periods chosen were a) May 1 to Oct 3, 1983 (positive) and b) May 1 to July 1, 2000 (positive); c) May 1 to October 3, 1993 (negative) and d) April 1 to November 1, 1998 (negative). We are unable to graphically show the anomaly fields in their entirety but illustrate with an example of the third week of June 1998 (Figure 1).

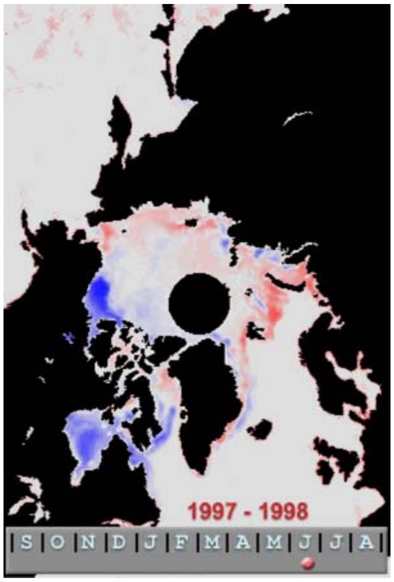

Figure 1. Example of anomaly fields for the second week of June 1998 (negative anomaly case (blue). Note that positive anomalies are in red.

3.2 *Meteorology*

The atmospheric influence on sea ice anomalies is evident from mean sea level pressure (SLP), surface air temperature anomalies and 500 hPa geopotential height anomaly patterns. During positive sea ice anomalies (1983 and 2000), a mean surface ridge resides over the southern Beaufort Sea and southern Nunavut (Figure 2). This ridge pattern develops sooner (a few weeks to more than a month) than the initiation of the ice anomaly, suggesting that the atmosphere is the key mechanism behind the positive ice anomalies. The SLP pattern induces a mean NE to E surface flow (sometimes from the SE).

Corresponding overall mean air temperature anomalies were –1°C to –3°C over the CASES region with a cold source region to the SE (i.e. surface advection was from a cold anomaly source) (Figure 3). In all negative (positive) ice anomaly cases, the source region was found to play an important role in maintaining and prolonging cold air (warm air) temperature anomalies until the atmospheric circulation changed significantly to “kick” the ice regime into a more normal mode. The magnitude of the air temperature anomalies for years that produced positive ice anomalies were much more negative in spring and fall than for summer, suggesting that spring melt and fall freeze-up are the most important seasons for producing the ice anomalies.

During negative sea ice anomalies (1993 and 1998), a mean surface ridge still resides near the CASES region but is shifted toward the east (fig not shown). Again, this ridge pattern develops sooner (a few weeks to more than a month) than the initiation of the ice anomaly. The seasonal SLP pattern induces a mean easterly flow in spring, S to SW flow in summer and fall (or SE flow with a warm source). Corresponding overall mean air temperature anomalies were +1°C to +4°C over the CASES region with a pronounced warm source region to the E and SE in 1998 (i.e. surface advection was from a warm anomaly source). The magnitude of the air temperature anomalies for years that produced negative ice anomalies were much more positive in spring and fall than for summer, suggesting once again that spring melt and fall freeze-up are the most important seasons for producing the ice anomalies. In 1993, the overall mean 500 hPa pattern shows a distinct positive anomaly ridge extending from the northern Archipelago through the CASES region and into the Yukon/Alaska region (fig not shown), whereas, in 1998 strong positive 500 hPa anomalies existed over the Archipelago accompanied by strong negative anomalies in the Bering Sea. The resulting 500 hPa pattern induces a weak NW flow aloft in the CASES region (fig not shown).

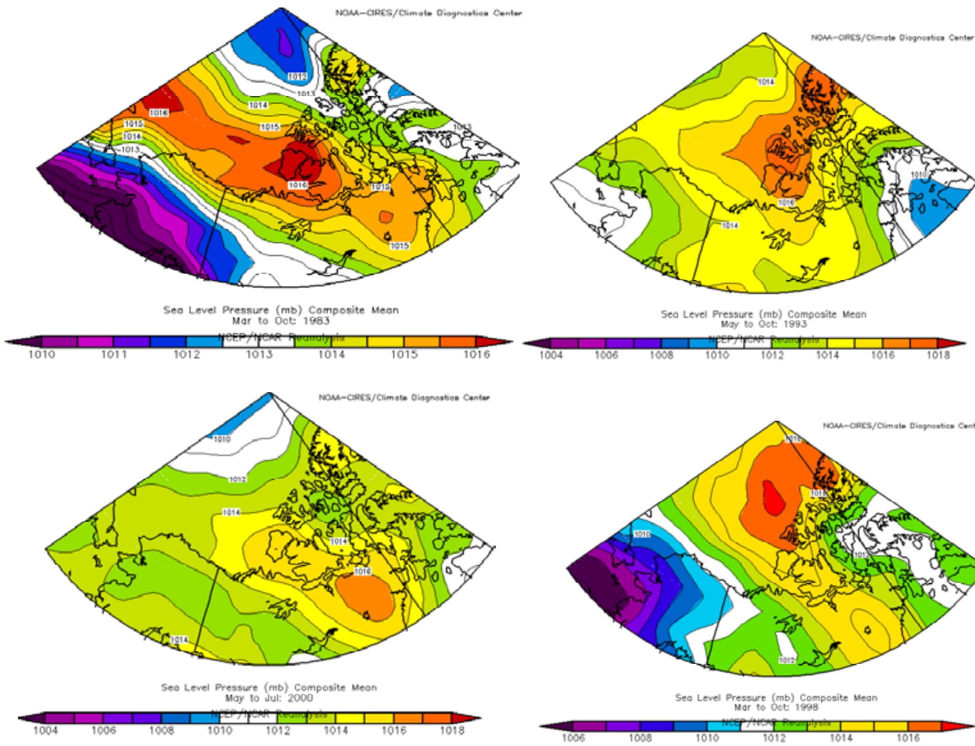

Figure 2. Anomalies of Sea Level Pressure for positive (left) and negative (right) sea ice anomaly patterns.

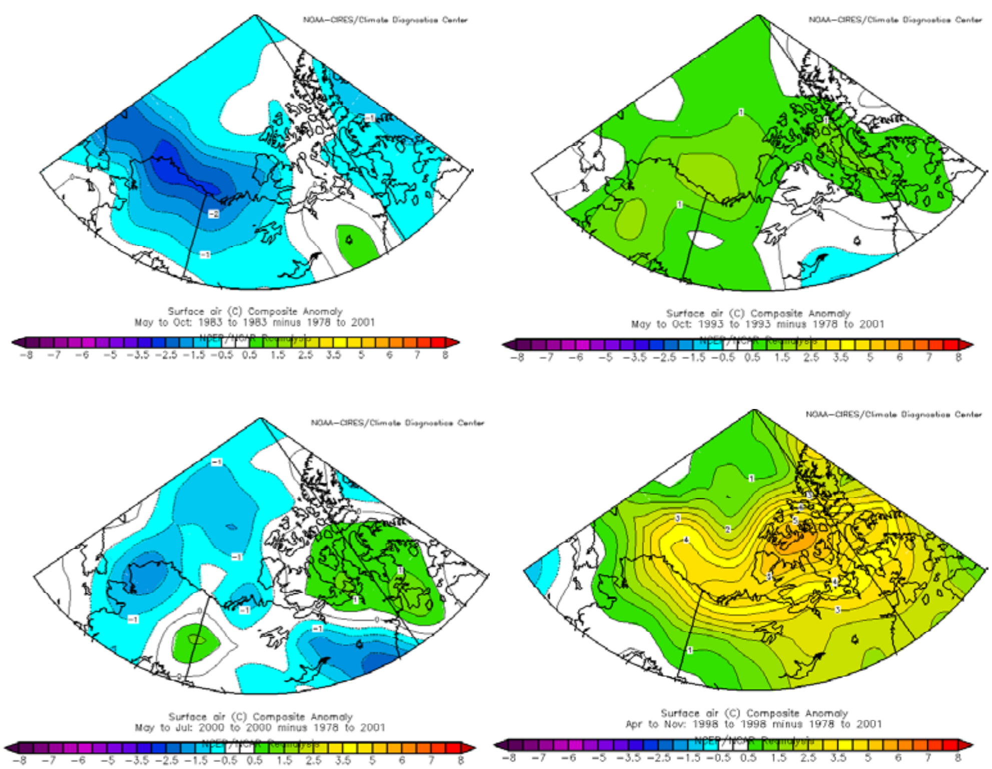

Figure 3. Anomalies of Surface Air Temperature for positive (left) and negative (right) sea ice anomaly patterns.

4. SUMMARY

The results suggest that there are significant and identifiable variations in the hemispheric surface and middle troposphere atmospheric circulation that may drive negative and positive anomalies in the CASES sea ice regime. Interestingly, the results correspond to a "tighter" polar vortex circulation in years with positive CASES ice anomalies, which is analogous to a positive AO index (and positive NAO index). Another interesting fact is that 1982/83 and 1997/98 were strong El Nino years with 1983 being a positive ice anomaly year (positive AO and NAO) and 1998 being a negative ice anomaly year (negative AO and NAO). In addition, 1991-95 saw a prolonged positive El Nino cycle with peaks in 1991/92 and spring of 1993 and a corresponding weak negative AO index in 1993 (between March to October) during a negative ice anomaly year. The year 2000 saw a negative ENSO index and a positive AO index during a positive ice anomaly year. The results suggest that a negative ENSO (or La Nina) and a positive AO/NAO amplifies a positive CASES region ice anomaly, whereas, a positive ENSO (or El Nino) and negative AO/NAO amplifies a negative CASES region ice anomaly. In 1983 (positive ice anomaly), the positive ENSO and positive AO/NAO opposed each other in terms of amplification of sea ice anomalies, however, a strong AO/NAO index appears to have been a greater factor in producing the positive ice anomaly that year. 1997/98 saw the largest negative ice anomaly in the western Arctic ever observed during reliable satellite records, which corresponded to a very strong positive ENSO index and strong negative NAO index (and a weaker negative AO index), hence an amplification of the negative ice anomaly in the CASES region.

Over the period 1979 to 2000 it is interesting to note that the trend in sea ice concentration is towards a reduction (increase in negative ice concentration anomalies). This shows that although the CASES study region is experiencing both negative and positive concentration anomalies there is a statistically significant trend towards increasing negative concentration anomalies (Figure 4). This fact has also been reported in the literature based on the observations of Inuvialuit living in the study region (Barber et al., in review).

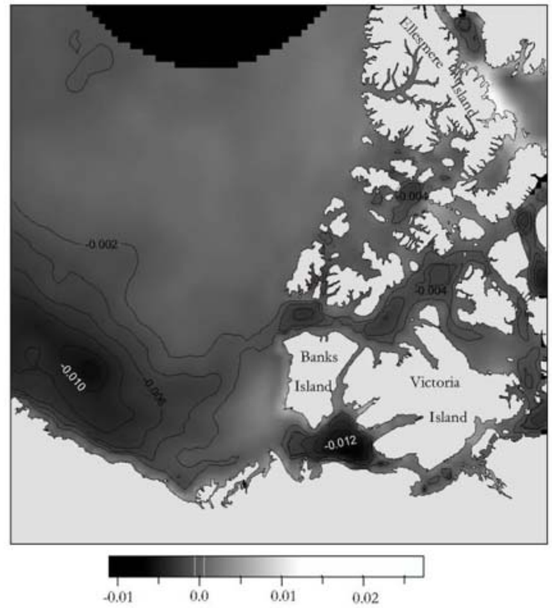

Figure 4. Time series slope surface showing the 22-year NOW trend in ice concentration. The values in the figure are in units of decimal percents and denote the least-squares regression line slope fit through the weekly anomalies of the 22 year record. Due to the large sample size and small variance the slopes are statistically significant if they are larger than about ± 0.001 (± one tenth of one percent). The range of non-significant slopes is denoted in the gray-scale legend.

5. REFERENCES

Barber, D.G., L. Barber, L. Carpenter, D. Cobb and R. DeAbreu. Sea ice variability and climate change – 'two ways of knowing' – identifying future research priorities. *Arctic*, in review.

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