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POLYNYA METEOROLOGY:
AN EVALUATION OF NEAR-SHORE, DOWNWIND, AND RETRIEVED PARAMETERS

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1. INTRODUCTION

Climatological data provide the subtext with which we analyze both the pre-conditioning of the polynya environment and subsequent contributions of polynya and lead development to atmospheric variability over and downwind of the open water.

In situ measurements of surface meteorology are recorded across the Arctic by a number of platforms, including coastal weather stations, floating ice camps, and buoys. While numerous, coastal weather stations only capture changes in surface variables over the circumarctic landmass and may be influenced by local topography and proximity to extensive ice caps. Floating ice stations and buoys, however, are generally found in the central Arctic Ocean, providing Lagrangian measurements over a period of months to years. Seasonal to interannual variations in buoy data density associated with either instrument failure or shifting location within the drifting ice pack can leave some areas unsampled and thereby bias measurements both in time and space.

Shipboard measurements of surface meteorology comprise characteristics of both platform types, providing data within an ice-ocean landscape surrounded by, or adjacent to, coastal topography. As such, direct comparisons with either platform will include some amount of environmental and measurement bias. Forecast models, which ingest both coastal and buoy data as well as some satellite-derived parameters, may provide more integrated meteorological values, though at a lower spatial and temporal resolution than either the land-based or shipboard data. However, since polynyas usually lack meteorological buoys, and they occupy an area the size of only a few model grid cells at best, this study is based on comparisons between shipboard data and the long-term, high quality coastal weather stations, thus providing a local and remote measure of polynya influence on the atmosphere. These relationships are viewed in light of recent shifts in hemispheric pressure patterns, and the resultant deviations in sea ice, surface temperature, and wind fields.

2. DATA

To evaluate the connections between Arctic coastal and polynya surface meteorology, weather station data collected along the periphery of four polynyas and one flaw lead were compiled and compared to shipboard measurements (Table 1). The stations chosen for these comparisons represent the closest, available data to the study sites during the sampling periods. Each ice-free area was matched with a minimum of three weather stations, with occasional matches at some distance from the polynya site.

	Station Name	Average Ship-Station Distance (km)	Minimum Ship-Station Distance (km)	Inshore Data Distribution
NEW92	Nord	253.32	121.94	357
	Danmarkshavn	369.38	155.69	40
	Daneborg	635.47	382.46	0
NEW93	Nord	257.78	107.07	313
	Danmarkshavn	388.75	178.65	13
	Daneborg	647.47	370.25	0
NOW98	Alert	687.98	413.91	0
	Carey Island	138.36	17.64	8181
	Eureka	439.74	269.64	0
	Grise Fjord	242.41	119.19	2623
	Cape Herschel	214.11	6.00	4832
SLIP99	Nome	747.82	324.60	0
	Savoonga	688.67	78.87	55
	Gambell	704.46	73.25	71
	Provideniya	778.47	152.35	30
NOW99	Thule	170.41	46.34	1163
	Nanisivik	550.61	320.20	0
	Resolute	634.61	384.38	0
BFL00	Barrow	176.32	4.09	1538
	Nuiqsut	295.91	114.84	357
	Wainwright	276.06	43.61	967
	Umiat	356.73	211.06	0

Table 1. Coastal weather stations used in comparative climatologies. Inshore data distribution refers to the number of ship-based data points that were collected within 200 km of each corresponding weather station.

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	Station Name	Average SAT Difference	Std Dev of SAT Difference	Average SLP Difference	Std Dev of SLP Difference	Average RH Difference	Std Dev of RH Difference	Average Wind Speed Difference	Std Dev of Wind Speed Difference
NEW92	Nord	-1.96	2.48	-0.26	1.52	11.93	12.48	-0.08	3.01
	Danmarkshavn	-3.38	2.90	-2.98	1.44	17.23	14.04	0.11	3.15
	Daneborg	-4.08	2.89	-3.36	2.22	14.16	15.51	0.22	3.18
NEW93	Nord	-3.75	3.11	-1.55	3.82	19.81	12.68	-1.57	5.16
	Danmarkshavn	-2.91	2.47	-1.80	1.95	12.21	12.25	0.07	3.24
	Daneborg	-3.41	2.76	-0.53	3.21	16.49	13.15	-1.79	4.67
NOW98	Alert	2.36	5.57	-6.42	5.26	3.37	14.48	3.21	4.20
	Carey Island	-0.73	1.94	-3.38	1.93	-1.29	9.68	-0.27	4.33
	Eureka	-1.21	5.07	-4.90	4.12	16.16	12.86	1.44	4.71
	Grise Fjord	-0.55	2.41	-4.53	2.60	7.50	14.14	4.50	3.72
	Cape Herschel	1.20	2.82	N/A	N/A	14.87	12.41	3.36	4.08
SLIP99	Nome	6.65	6.39	-3.22	9.25	7.11	14.01	4.19	5.89
	Savoonga	6.32	2.53	N/A	N/A	4.80	8.80	2.49	6.32
	Gambell	4.12	3.00	N/A	N/A	8.72	11.70	-0.44	6.21
	Provideniya	3.10	3.71	N/A	N/A	8.56	13.03	2.45	5.75
NOW99	Thule	-0.40	2.50	-1.71	2.18	19.83	13.44	1.09	3.89
	Nanisivik	4.42	1.75	-2.32	4.29	4.70	9.79	0.07	4.76
	Resolute	1.42	2.22	0.89	7.12	3.00	9.02	-2.48	5.53
BFL00	Barrow	-1.24	2.29	-0.03	1.53	4.38	8.77	-0.11	2.98
	Nuiqsut	-1.81	3.14	-0.99	2.13	9.34	13.36	0.90	3.12
	Wainwright	-1.89	2.27	2.03	2.04	4.82	8.66	-0.23	3.42
	Umiat	-4.23	3.62	N/A	N/A	13.57	14.71	2.14	3.31

Table 2. Synopsis of cruise-averaged ship – weather station differences for common meteorological variables. Units are in °C for Surface Air Temperatures (SAT), hPa for Sea Level Pressures (SLP), % for Relative Humidity (RH), and m•s^{-1} for wind speeds.

The St. Lawrence Island Polynya (SLIP), for instance, which forms in the northern Bering Sea, is located in the lee of the island, where two weather stations are maintained. Other station matches for this polynya had to be gathered from neighboring coastlines, namely Siberia and Alaska, at a distance of over 100 km from the shipboard measurements. In the Northeast Water Polynya (NEW) experiments, the ship remained offshore, at times 120-380 km away from the distant fjords where Nørd, Danmarkshavn, and Daneborg weather stations are located. And while Cape Herschel and Carey Island reported surface meteorology data along the North Water (NOW) Polynya boundaries, other stations used in this comparison are situated throughout the western Canadian Archipelago -- Eureka, Alert, and Grise Fjord. Such spatial separations were sometimes purposeful, as in the selection of Umiat at the base of the Brooks Range, near the Anaktuvuk Pass in Alaska. These data were gathered primarily for wind comparisons, to isolate any down-sloping events along the North Slope, and to observe whether these winds influenced coastal wind time series.

3. RESULTS

3.1 Surface Wind Speed

Discrepancies between the coastal and polynya measurements were most noticeable in the wind vector time series. Although the actual magnitude of wind difference was quite small – generally < ± 2 m•s^{-1} – between the coast and the adjacent polynya, wind directions were very sensitive to topographic effects. For example, measurements collected at Gambell and Savoonga on St. Lawrence Island, though shadowed from certain wind directions by Sevuokuk (187m) and Kookooligit (614m) Mountains, recorded the fastest average wind speed in the down-slope direction of these two features. At each site, however, the wind directions suitable for polynya development along the southern coast – NE at Gambell and E at Savoonga – dominate the wind time series. Similar occurrences of shadowing and funneling of winds, either by surrounding mountains or the sloping topography of fjords, were present in most other coastal station data collected for this study. Only those meteorological towers at Wainwright, Barrow, and Atqasuk on the North Slope of Alaska and Nørd on Cape Nordostrundingen (NEW) were unobstructed by terrain.

In general, the mean wind speed over polynyas and leads either fell within or exceeded the range of coastal mean wind speeds. Over the North Water (NOW) in 1998, winds averaged higher speeds than in the sheltered locales of nearby weather stations. The NOW-area 1999 data, which used different weather stations for comparison, occupied the mid-range of wind speeds measured at Thule, Nanisivik, and Resolute; though measurements were closest in character to winds measured at Nanisivik, where differences between the two data sets averaged only 0.07 $m \cdot s^{-1}$ (essentially no difference, Table 2). Similar agreements in shipboard and station wind speed were found in the Northeast Water during the 1992 expedition, when winds were light and variable. In 1993, however, wind speeds over NEW increased slightly, and directions were focused more along the north-south axis.

High wind speeds displayed both a seasonal and synoptic dependence, favoring early spring and late fall months for sustained high winds, and 3-4 day increases in wind speed during storm passages. The polynya accounting for the most occurrences of winds greater than 10 $m \cdot s^{-1}$ was SLIP, which also occupied the position of largest fetch. No directional dependence was apparent in this distribution, receiving equally strong forcing from all quadrants. Coastal data recorded their share of intense wind forcing events, as well. High-speed winds blowing in down-slope directions from topography suggest katabatic flow off of nearby ice caps, particularly in the Greenland and St. Lawrence Island coastal data.

3.2. Surface Air Temperature

Although topographic influences and down-sloping may account for a small fraction of the land-sea air temperature difference, it is mostly the disparity in heat capacities of soil, snow, ice, and ocean that produce the near-uniform negative temperature gradient with respect to land in summer (Table 2). Over the polynya, cooler surface air temperatures prevail, with a smaller diurnal range than those measured at neighboring coastal sites. Whereas increases in solar radiation over summer melted snow and warmed the soil on bare land, most of the insolation within the polynya was expended on ice melt, further moderating polynya temperatures to within a few degrees of 0°C.

North Water data from 1998 and 1999 capture a seasonal cycle in warming, beginning with an increase in land temperatures in response to the growing number of daylight hours, reducing the land-sea temperature difference fostered over the preceding winter. In June and July, once the snow has melted and the land surface is exposed, coastal weather station surface air temperatures exceed those measured over the polynya. Then, as the length of daylight decreases with progression into fall months, polynya air temperatures are warmed by heat released from the oceanic surface layer, whereas heat lost from the coastal margins quickly dissipates in August.

While both NEW cruises depict the mid-to-late summer scenario of ocean-moderated air temperatures, data from spring and fall transition months at SLIP and Barrow Flaw Lead (BFL) feature synoptic influence. Only SLIP air temperatures were consistently warmer than coastal measurements, likely due to the advection of warm sub-polar air by large-scale southerly flow and convective heat release from the shallow Bering Sea under intense wind forcing. Also, at this time of year (April 13 – May 10) under extensive cloud, coastal weather stations had not yet received adequate radiation to melt local snow cover. At the beginning of Barrow Flaw Lead sampling (August 8), however, the Beaufort Sea had received significant insolation over summer, inducing wide-scale melt and creating a large open water area. Surface air temperatures during August resemble those of the Northeast Water, while in September the polynya adopts a high amplitude diurnal signal of several degrees. Although these daily fluctuations are still smaller than those measured at coastal weather stations, their appearance suggests that under minimal cloud and ice conditions, Arctic air surface temperatures assume the behavior of those over sub-polar ice-free oceans.

This shift towards mid-latitude conditions in the absence of ice raises questions about the prolonged effect of air temperature increases on the cryosphere. Not only do rising surface air temperatures affect ice melt, but also ice reformation, which is important to polynyas through their dependence on ice bridges for the reduction of extraneous flow-through. Air temperature has been identified as the major controlling factor in the formation of the Odden ice tongue just south of the Northeast Water Polynya. During the winters of 1992 and 1993, a weak or no Odden was visible in passive and active satellite imagery collected over the region from 8° W to 5°E and 73° to 77°N (Schuchman et al., 1998). The absence of this ice feature could ultimately result in depressed convection rates due to the lack of brine, which is released during the formation of new ice, of which the Odden is entirely composed.

3.3 Relative Humidity

Although relative humidity is not often measured at coastal weather stations, dew-point and dry-bulb temperatures are, and it is from those data and the Clausius-Clapeyron equation that the majority of these time series are constructed. In comparisons with station data, it is apparent that high relative humidities are not restricted to the polynya boundary, but also moisten the neighboring coastline. Polynya values, however, are often greater than 80% with numerous reports of 100%, thereby exceeding the average coastal measurements by as much as 20% (Table 2). Only Carey Island, which is located within the North Water polynya, averaged higher relative humidities than the polynya itself, and only by a small percentage, 1.2%, which is probably not significant. As in measurements of surface air temperatures, the Barrow Flaw Lead shows a diurnal signal in relative humidity as well as a slight drying of the polynya air column towards the end of the cruise, in early September.

4. DISCUSSION and CONCLUSIONS

While multi-decadal meteorological time series analyzed by Rigor et al. (2000) and Polyakov et al. (2003) suggest that the Arctic is becoming warmer and moister coincident with the shift to a positive Arctic Oscillation / North Atlantic Oscillation phase and an increase in CO_2 concentrations, measurements at polynyas and coastal weather stations indicate surface air temperatures remained close to 0° C from mid-summer into fall. The monthly-averaged polynya air temperatures, as compared to similar values from weather station data from Polyakov et al. (2002), indicate that the high heat capacity of open water areas moderate the range of air temperatures found within the polynya. During summer when land is exposed, air temperatures measured at the coasts exceed those over ice-free waters by as much as 10°C; however, the most pronounced land-sea differences are observed during spring months (and to a lesser extent, fall), when land-based sites are covered with ice and snow.

Another moderating effect of ice-free areas is the high relative humidity present with respect to neighboring land sites. This readily available moisture source also provides convective energy for formation of cloud layers at many atmospheric levels downwind of the polynya or lead. Cloud analyses support this hypothesis through the shift in reporting from single cloud layers to multiple cloud layers at the end of each summer season, increasing in frequency with polynya fetch. However, much of the water content within these clouds is rapidly transformed to ice, accounting for the large effective cloud radii and the relatively low liquid water contents retrieved from lidar-radar in this region.

While air temperature and relative humidity can vary greatly over the land-sea boundary, sea level pressure changes little, even over distances of 300 km from the ship. Those small pressure changes generally favor lower pressure over the polynya than the surrounding coast, perhaps due to the convective heat rise over these open water areas. Some storm activity is also present within the sea level pressure time series, particularly in transition month data.

Storm passages were also present in the surface wind data, which catalogued a number of wind speeds greater than 10 $m•s^{-1}$, again, most often during transition month cruises, such as the springtime studies of the SLIP. At coastal sites, intense wind forcing included katabatic events, which flowed down-slope from neighboring ice caps with occasional speeds of > 20 $m•s^{-1}$. Average wind speeds, however, were below the global average of 7-10 $m•s^{-1}$, due to weakened summertime pressure gradients over the Arctic. In winter, when the full effects of the positive phase Arctic Oscillation are exhibited, it is likely that wind speeds increase, perhaps opening latent heat polynyas not yet documented.

The main conclusion of this study is that the polynyas do indeed modify the surface meteorology of the overlying atmosphere. The degree of modification is largely determined by the local geographic and orographic characteristics of each polynya, and the season, although there are some modifications, such as reduced amplitudes of summertime diurnal air temperature fluctuations compared to those measured at coastal sites, that appear to be common to all. The length scales of many of the Arctic polynyas as such that they are not well-resolved in weather forecast and climate models. The use of measurements from nearby weather stations, some of which are not very close, to represent conditions over the polynyas, is subject to large uncertainties. These conclusions further underscore the need for better understanding of the mechanisms of polynya generation and maintenance, and emphasize the uncertainties implicit in forecasts of the response of the Arctic to changes in the climate system.

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