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RETROSPECTIVE ANALYSIS OF SEA SURFACE TEMPERATURE IN THE NORTHERN BERING AND CHUKCHI SEAS

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Contents

Retrospective analysis of sea surface temperature in the northern Bering and Chukchi seas

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Abstract. Sea surface temperature (SST) data from the Chukchi and northern Bering seas beginning in the 1920s are analyzed to investigate low-frequency variability. Although surface air temperatures at Nome, AK, and adjacent weather stations show a shift in the late 1930s and a strong warming signal after 1977, spatial variability and sparse oceanic sampling make it impossible to draw robust conclusions regarding low-frequency temporal variability in SST. Given the data at hand, however, there is no conclusive evidence for decadal-scale or regime-shift variability in SST in the northern Bering/Chukchi Sea region during the 20th century, and the data can be considered to be a single climatology. The warmest SSTs ever measured in eastern Bering Strait were obtained in 2004 during a RUSALCA cruise, and the warmest temperatures measured in western Bering Strait were observed in 2006, providing evidence that we are seeing a distinct warm period in the current decade relative to the 20th century. A cruise from 1880 shows SSTs consistent with the 20th-century climatology.

1. Introduction

Major changes in the Arctic environment have occurred over recent decades. These changes include changes in sea ice extent (e.g., Nghiem *et al.*, 2007; Stroeve *et al.*, 2008), oceanography (Polyakov *et al.*, 2007; 2003) and ecosystems (Grebmeier *et al.*, 2006). It is important to document 20th-century baseline conditions in the Pacific Arctic so that we can understand how things are changing. This study evaluates available sea surface temperature (SST) records in the Northern Bering Sea and the Chukchi Sea to assess how conditions have changed within the last decade and to provide a baseline for the future.

Many studies have focused on variability in the Arctic over larger spatial scales (e.g., Polyakov *et al.*, 2007; Steele *et al.*, 2008). Changing sea ice extent has been the most dramatic example of the effects of global warming on the Arctic and many studies have evaluated the causes of sea ice variability (e.g., Maslanik *et al.*, 2007; Nghiem *et al.*, 2007). Steele *et al.* (2008) evaluate trends in SST in various regions of the Arctic. They find no strong trends in the Bering and Chukchi Seas before the late 1990s. Steele *et al.* (2008) averaged over relatively large regions over which differing processes are regionally important. We examined changes in SST over the northern Bering Sea and the Chukchi shelves especially surrounding the North Pacific 1976 regime shift. Unfortunately, there are major data gaps in the 20th century SST records; but our purpose is to summarize what is available.

Spatial patterns of summertime SST are addressed using all available ocean temperature data. An emphasis on temporal variability at smaller spatial scales in Bering Strait is possible due to the higher density of data collected over the years. The flow through Bering Strait is the only connection between the Pacific and the Arctic. This flow has been shown to influence ice melt (Paquette and Bourke, 1981) and stratification (Shimada *et al.*, 2001; Steele *et al.*, 2004; Woodgate *et al.*, 2005a) in the Arctic. Much recent work with year-round moorings has been accomplished in Bering Strait (i.e., Roach *et al.*, 1995; Woodgate *et al.*, 2005b; 2006). Our aim is to put these recent measurements into a historical context.

2. Data

2.1 Atmospheric

To evaluate the large-scale atmospheric temperatures, monthly mean surface air temperature data from Nome and Kotzebue, AK, and Providenja and Mys Uelen, Russia, were downloaded from the National Climatic Data Center (`http://www.ncdc.noaa.gov/oa/ncdc.html`). These four temperature records are significantly correlated with each other. Because the Nome temperature record is the longest (1907–2006), we use those data. A monthly climatology for Nome surface air temperature was constructed by averaging all data from each month.

2.2 Oceanic

Ocean temperature data from the World Ocean Database (WOD05) (Johnson *et al.*, 2006) were downloaded from the Ocean and Weather Data Navigator (`http://dapper.pmel.noaa.gov/dchart/`) for the region 175°E–160°W, 62°–72°N. After removing profiles positioned over land, as well as outliers and empty stations, the total dataset consisted of 18,698 profiles. The majority of these profiles (14,831) were collected during the summer months (July, August, September), so we restrict our analysis to those 3 months. After removing those profiles that had no data in the top 10 m, the resulting dataset consisted of 14,384 profiles spread relatively evenly between the 3 months (Fig. 1). While the earliest profiles in the dataset were collected in 1855, the dataset includes only 32 profiles prior to 1925. Because many of the profiles do not have data right at the surface, SST is defined here as the mean temperature over the upper 10 m. The scattered profile data were gridded to a regular grid using objective mapping as in Kessler and McCreary (1993) with mapping scales of 0.5° in both latitude and longitude.

Additional temperature data not included in WOD05 were obtained from the Russian-American Long-term Census of the Arctic (RUSALCA) program for August 2004, 2005, and 2006, and September 2007. In particular, we discuss transects across Bering Strait. In addition, a transect across Bering Strait taken on 5 September 1880 (but not included in WOD05) is discussed (Dall, 1882).

3. Atmospheric Surface Air Temperature Time Series

Climatological surface air temperatures ranged from –15.0°C in January to 10.4°C in July. Not surprisingly, variability was greatest in winter months (January standard deviation = 4.8°C) and lowest in the summer months

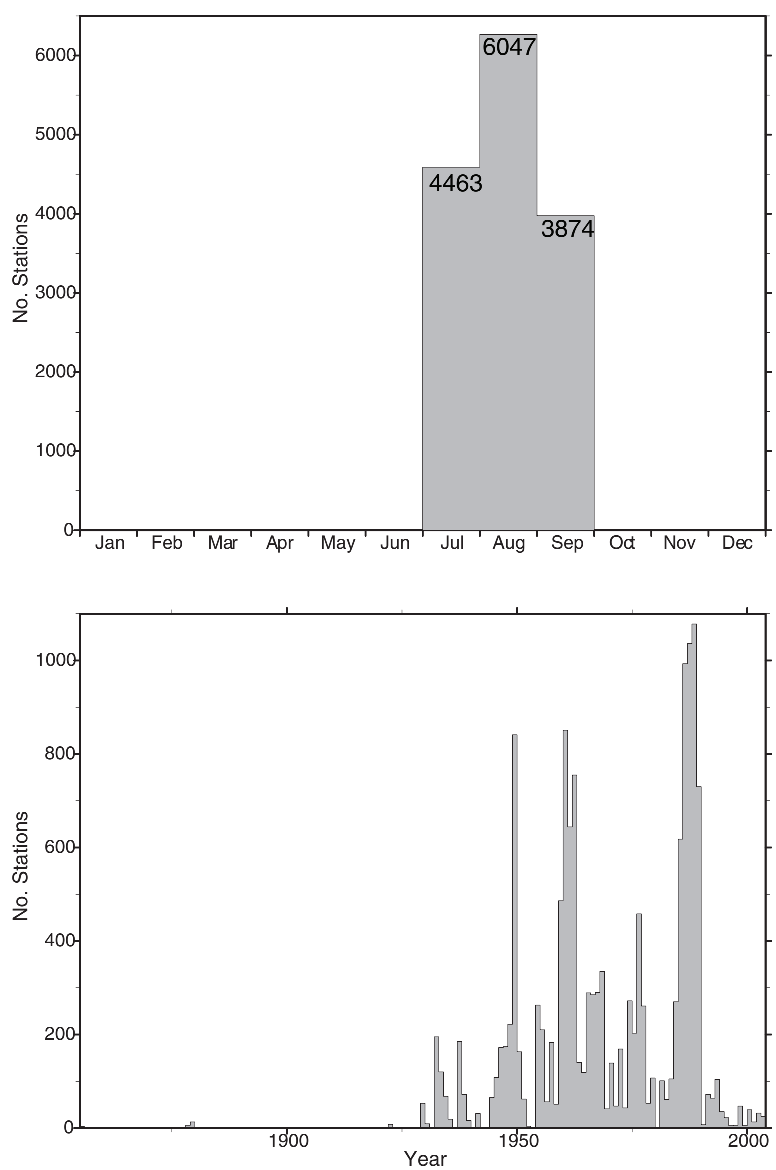

Figure 1: Histogram showing temporal distribution of ocean temperature profiles.

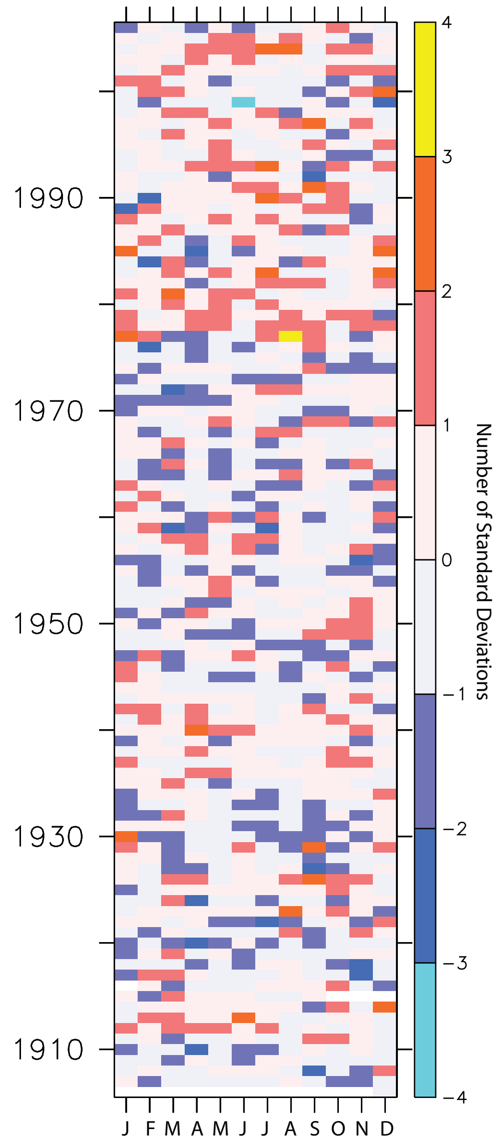

Figure 2: Nome surface air temperature anomalies normalized by monthly standard deviation. Anomalies calculated with respect to monthly climatology.

(July standard deviation = 1.4°C). After removing the climatology and normalizing by the monthly standard deviation, Nome temperatures exhibit anomalously high temperatures from 1977 to present (Fig. 2). This "regime shift" has been widely studied and has been attributed to a deepening Aleutian Low (Overland *et al.*, 1999) and reduced SLP in the Arctic (Savelieva *et al.*, 2000).

A short period from the late 1930s to the early 1940s also exhibits anomalously high air temperatures. A composite time series of Arctic surface air temperatures covering the entire Arctic showed that high-latitude temperature was higher in the late 1920s through the early 1940s than in recent decades (Polyakov *et al.*, 2003). However, when only the region surrounding the Northern Bering and Chukchi seas (Nome, Kotzebue, Providenja, and Mys Uelen) is analyzed, this earlier warm period is not as strong or as persistent as the recent (post-1977) warm period. At Nome, anomalously warm temperatures in the 1930s–1940s occurred primarily in the spring and fall (April and October), while summer anomalies were <1 standard deviation from the mean (Fig. 2); this event is considered to relate to El Niño conditions. The post-1977 event extends over decades, showing warm anomalies greater than one standard deviation throughout the year.

4. Spatial Patterns of SST (10-m average temperature)

Objective maps of all data in each summer month illustrate the spatial patterns of SST (Fig. 3). Here we plot only July data, but patterns are similar in August and September. Norton Sound exhibits the warmest temperatures in our study region. SST in Norton Sound (165–161°W, 63–64.5°N) average 9.0°C, 12.0°C and 8.6°C in July, August, and September, respectively. The warm SSTs in Norton Sound are likely due to the shallow depths and the riverine input that stratifies surface waters.

Surface temperatures in Bering Strait reflect the three water masses that flow through the strait (Coachman *et al.*, 1975). Alaskan Coastal Water is relatively warm and flows through the eastern channel of Bering Strait continuing northeastward along the Alaskan coast. Anadyr Water, colder than Alaskan Coastal Water, flows from the Gulf of Anadyr, through Anadyr Strait west of St. Lawrence Island, and through the western channel of Bering Strait. Bering Shelf Water in the middle of the strait is generally formed as a mixture of Anadyr Water and Alaskan Coastal Water.

These patterns (warmer in the east, colder in the west) continue into the southern Chukchi Sea, reflecting the continuation of the Alaskan Coastal Current along the coast of Alaska (Coachman *et al.*, 1975). The coastal current bifurcates near Point Hope with transport to the northwest along the Hope sea valley in addition to northward transport to the east of Herald Shoal (Ahlnäs and Garrison, 1984; Coachman *et al.*, 1975; Overland and Roach, 1987). This bifurcation is reflected in a tongue of warmer water extending offshore from the Alaskan coast near Point Hope (Fig. 3). These flow patterns have been shown to influence the melt-back patterns of sea ice (Paquette and Bourke, 1981). The colder water over Herald Shoal results from a Taylor column that traps ice and cold water above the shoal and results in later ice melt than in the surrounding water (Martin and Drucker, 1997).

Cold temperatures along the northern Siberian coast are associated with the Siberian Coastal Current (Weingartner *et al.*, 1999). This region is influenced by winds, Siberian river outflows, and ice melt. The Siberian Coastal Current usually converges with the northward flow through Bering

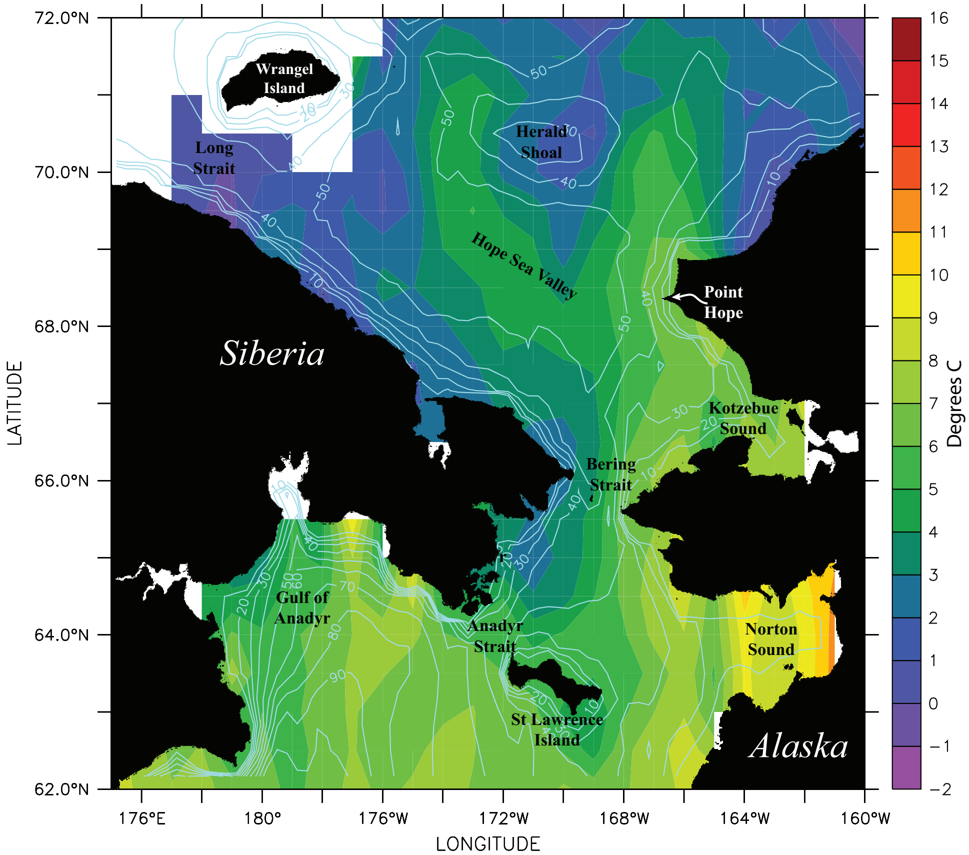

Figure 3: Objective map of SST (°C) using all available July data. Bathymetry (m) is overlaid (light blue contours).

Strait and is deflected offshore. Some indication of the offshore deflection in the cold SSTs offshore of the 50-m isobath near ~70°N is evident (Fig. 3). The Siberian Coastal Current occasionally flows southward through Bering Strait, especially in fall and early winter when northerly winds are strong (Weingartner *et al.*, 1999).

5. Spatial and Temporal Variability in SST

Unfortunately, insufficient SST data exist to determine whether significant shifts in regional oceanographic conditions occurred at the same time as the shifts in Nome surface air temperatures. To characterize the changes in SST patterns surrounding the 1977 regime shift, we divide the dataset into pre- and post-1977 periods (1977 is included in the latter period). We use all WOD05 data to form composites of the two periods and look for differences. These differences are not statistically significant but do provide suggestions of where, and by how much, conditions may have changed. Coherent spatial patterns lend confidence to these results.

5.1 July

In July, north of Bering Strait, SSTs on the eastern side of the basin were warmer after 1977 by up to 4°C (Fig. 4). Warmer temperatures were also apparent crossing the Chukchi Sea in a northwesterly direction from Point Hope, reflecting the previously mentioned bifurcation of the Alaskan Coastal Current. The July post-1977 SST map was heavily dominated by data from 1986–1989, while the pre-1977 data were more distributed over many decades. During the mid-1980s, the Yukon River discharge at Eagle, AK, was above average for June and July (`http://nwis.waterdata.usgs.gov/ak/nwis/nwisman/?site_no=15356000&agency_cd=USGS`). The resulting increased stratification of the Alaskan Coastal Current may have contributed to the warmer temperatures during that time period.

Unfortunately, after 1976, no July data exist south of Wrangel Island (along the north Siberian Coast west of ∼178°W). However, the data east of 178°W on the north Siberian Coast and through the west side of Bering Strait indicate cooler SSTs (by 2–3°C) after 1977. Again, the post-1977 map is heavily dominated by 1986–1989 data. The cooler waters on the western side of Bering Strait could be due to an enhanced Siberian Coastal Current with increased southward intrusions through Bering Strait. This conjecture is supported by evidence that annual mean transport through Bering Strait in 1987 and 1988 was much lower than average (Roach *et al.*, 1995). The cooler temperatures in the western side of Bering Strait could also be due to changes in the properties of the Anadyr Water that flows northward through Anadyr Strait and into Bering Strait. There is some indication of colder SSTs in the Gulf of Anadyr (Fig. 4).

5.2 August

The warming of the Alaskan Coastal Water apparent in July is not as clear in August (Fig. 5). This may be due to much more limited data in August in the Alaskan Coastal Current region after 1977.

Norton Sound is warmer in August in the latter period than prior to 1977. The Norton Sound data is well distributed over the years. Hamazaki *et al.* (2005) found that Norton Sound benthic biomass increased after 1976. Whether these ecosystem changes might be related to changes in temperature is unclear.

The region along the northern Siberian coast that showed some indication of cooling in July exhibits warming in August. Again, limited data exist in the post-1977 period, so the warming signal is heavily influenced by only a few years of data.

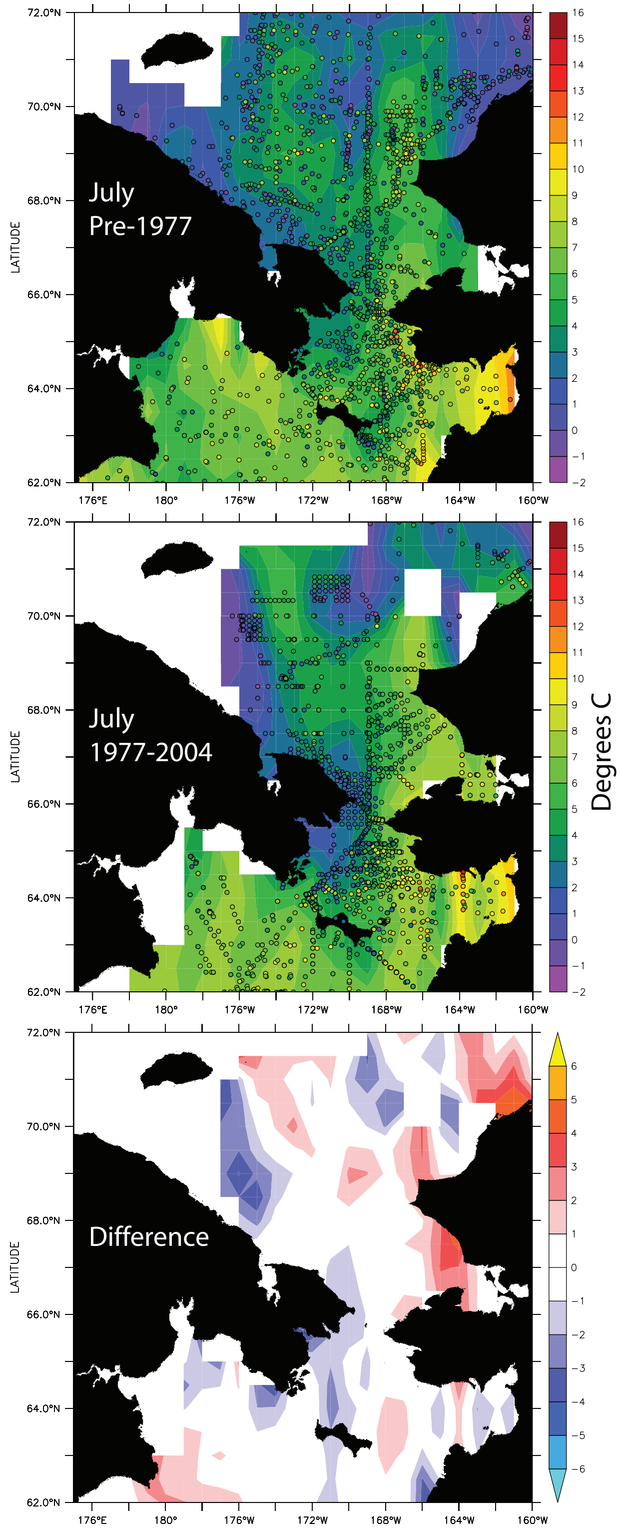

Figure 4: Objective maps of July SST pre-1977 (top), 1977–2004 (middle) and difference (middle–top). Data used to create the objective maps are overlaid as circles.

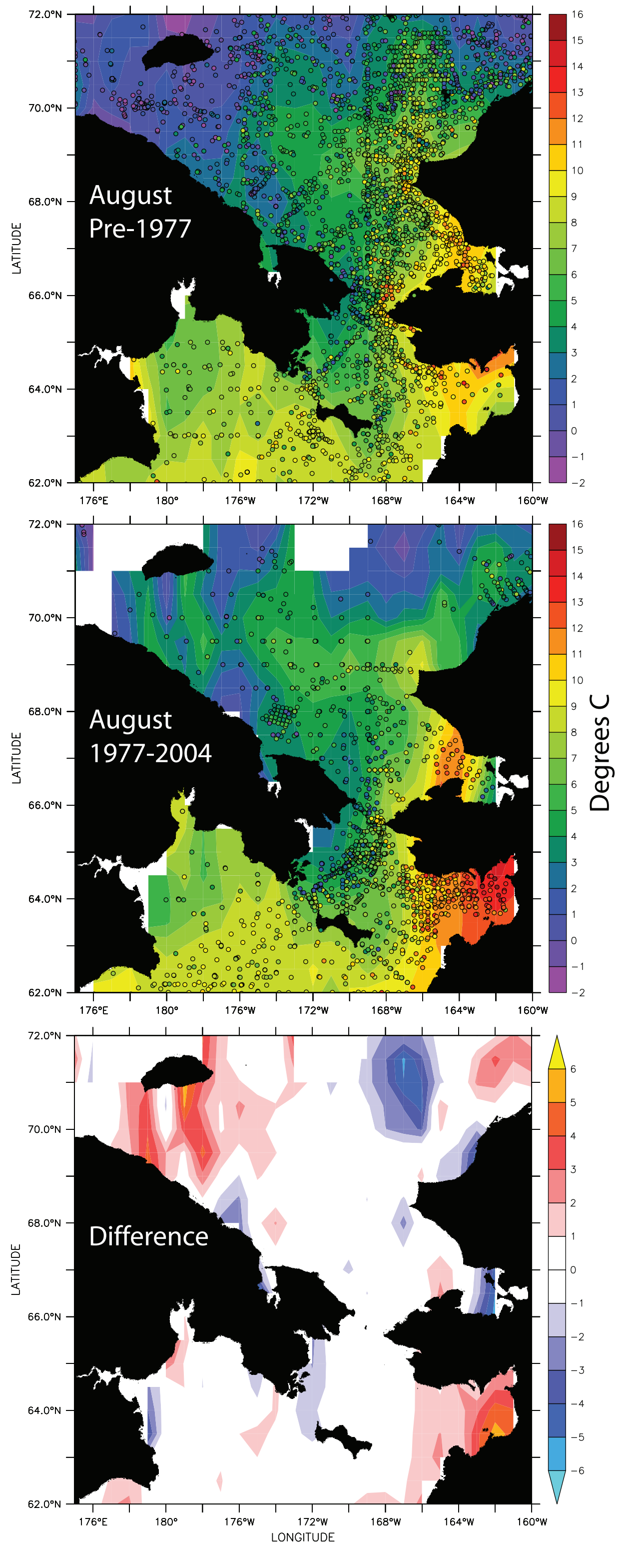

Figure 5: As in Figure 4, for August.

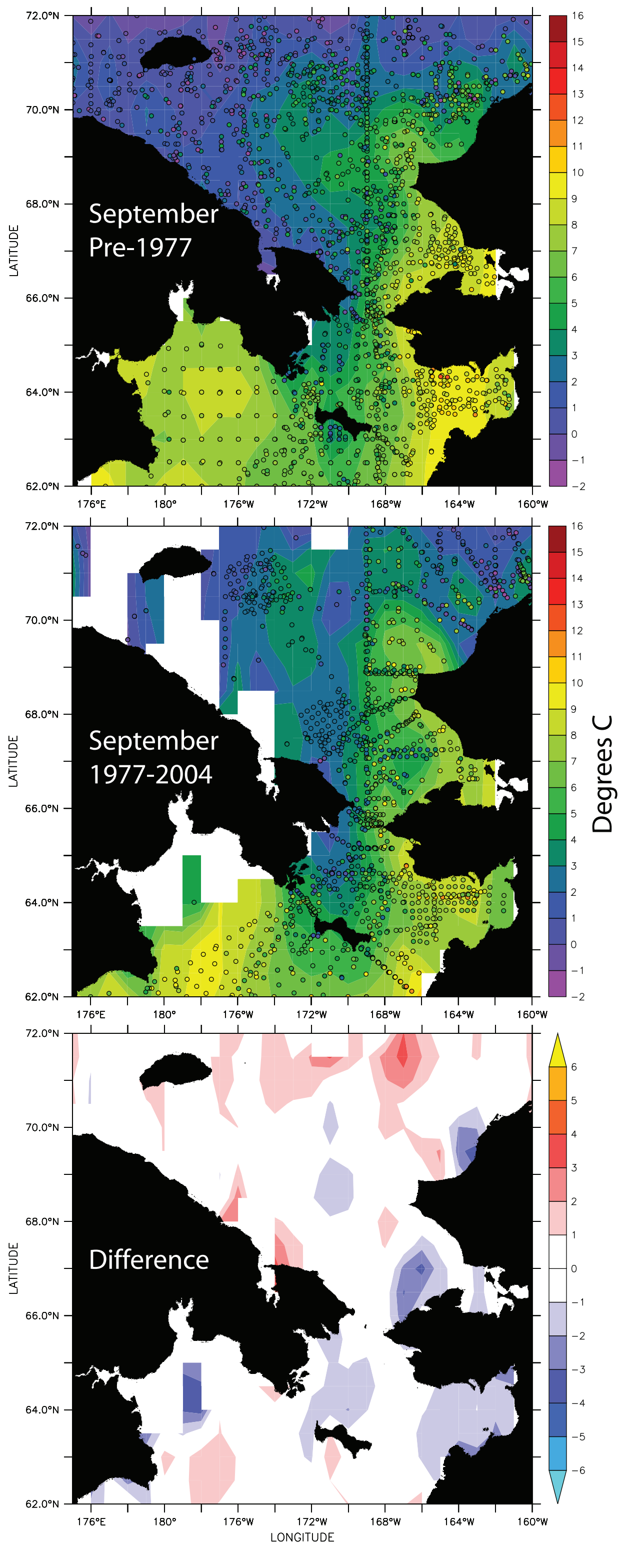

Figure 6: As in Figure 4, for September.

5.3 September

Warming across the northern part of the region in September (Fig. 6) may be due to changes in sea-ice extent. According to the Hadley Centre Sea Ice dataset (Rayner *et al.*, 2003), the northern edge of our region exhibited >30% sea ice coverage during July–September prior to 1977. In the years 1977–2004, summer sea ice coverage in the region averaged 5–10%. Less sea ice over the summer would allow more heat to be absorbed by the surface waters.

Norton Sound and Kotzebue Sound both exhibit cooler conditions after 1976 (Fig. 6). Post-1977 Norton Sound data were dominated by 1985 data while Kotzebue Sound was dominated by 1986 data. Cooling in Norton and Kotzebue Sounds may indicate less transport of Alaskan Coastal Water in September. However, August and September Yukon River discharge were higher than average in 1985 and 1986. Nome air temperature data (Fig. 2) show that September 1986 and 1987 were slightly cooler than average.

6. Temporal Variability in Bering Strait

The results discussed above have to be considered with caution, as the sampling in this region has not been temporally or spatially consistent. The most consistently sampled part of the region is Bering Strait. Here, we focus on Bering Strait, comparing historical WOD05 data with more recent transects.

Using all data in the WOD05 database, the properties of the eastern (168.5–168°W, 65.5–66°N) and western (169.5–169°W, 65.75–66.25°N) sides of Bering Strait can be examined. Surface temperatures (10-m average) average greater than 7°C in the eastern part of the strait and less than 4°C in the western part of the strait in July–September (Table 1). The range of temperature observations in eastern Bering Strait is large. The coldest surface temperatures recorded in the eastern part of the pass were less than 1°C in early July 1985 while the warmest temperatures were greater than 12°C in August 1968. Part of that range is due to the lateral extent of the warm Alaskan Coastal Current. The colder temperatures tend to be those measured farther west. On the western side of the strait, the temperature range is smaller. The coldest temperature recorded was –0.6°C in late September 1957, while the warmest surface temperature recorded was almost 7.0°C in August 1962. Examination of available Bering Strait data shows no significant trends over the 20th century (Fig. 7). Thus, we cannot reject the null hypothesis that the data are sampled from a single population (i.e., no regime shifts). However, due to the temporal sparseness of data, the possible existence of low-frequency variability or trends cannot be ruled out.

In recent years (2004–2007), the Russian-American Long-term Census of the Arctic (RUSALCA) program (`http://www.arctic.noaa.gov/aro/russian-american/`) sampled across Bering Strait. These data are not in-

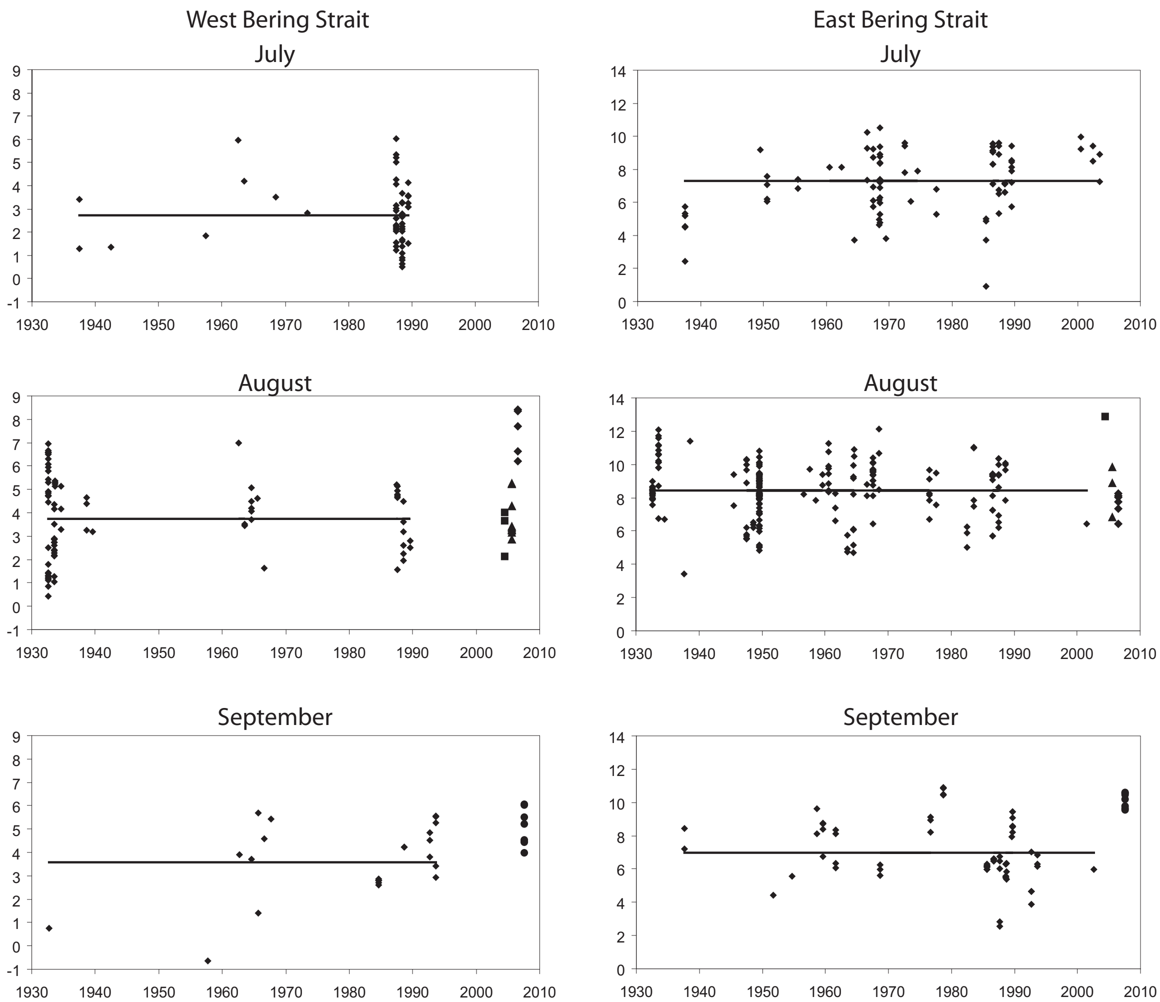

Figure 7: Time series showing SST (°C) for all available data in the western Bering Strait (169.5–169°W, 65.75–66.25°N) on the left and the eastern Bering Strait (168.5–168°W, 65.5–66°N) on the right. Historical data from WOD05 represented by small diamonds; RUSALCA data represented by squares (August 2004), triangles (August 2005), large diamonds (August 2006) and circles (September 2007).

cluded in the WOD05 database, nor in the statistics reported in Table 1. In August 2004, only one cast was sampled in the eastern region defined above. The 10-m average temperature on that cast was 12.9°C, warmer than any previous measurements in the database (Fig. 7). This is consistent with summer bottom temperatures from a mooring in the eastern Bering Strait. Woodgate *et al.* (2006) show bottom temperatures at mooring A4 that were ~2°C warmer in 2004 than measured the three previous years at that site. The three RUSALCA casts in the western region of the strait were within the range of variability seen in the historical data (Fig. 7).

In 2005, temperatures in both the eastern and the western regions were near average. In 2006, the casts on the western side of the Strait were warmer than the previous observed temperature range, while the eastern side of the Strait was near (or slightly below) the mean of previous observations. The

Table 1: Comparison of sea surface temperature on the eastern and western sides of Bering Strait.

	Western side of Strait (169.5–169°W, 65.75–66.25°N)				Eastern side of Strait (168.5–168°W, 65.50–66.00°N)			
	Mean	**St. Dev.**	**Range**	**No. of casts**	**Mean**	**St. Dev.**	**Range**	**No. of casts**
July	2.7	1.3	0.5–6.0	53	7.3	1.9	0.9–10.5	89
August	3.7	1.7	0.4–7.0	81	8.4	1.6	3.4–12.1	220
September	3.6	1.6	–0.6–5.7	24	7.0	1.8	2.5–10.9	69

warmest 10-m average temperature recorded in August 2006 in the western region of Bering Strait was 8.4°C, ∼1.4°C higher than the previous observed high temperature.

The 2007 RUSALCA cruise was completed in early September. Temperatures ranged from 4.0–6.0°C in the western strait and 9.6–10.6°C in the eastern strait. These temperatures are at the warm end (but not outside) of previously observed range of temperatures in the east. In the west, the warmest temperatures observed in 2007 were ∼0.3°C warmer than previously observed (prior to 2006).

A transect across Bering Strait taken 5 September 1880 (and not included in the WOD05 database) shows surface temperatures of 2.6–2.8°C on the western and 8.3–8.9°C on the eastern side of the strait (Fig. 8) (Dall, 1882). These temperatures are lower than average on the eastern side and higher than average on the western side compared to the 20th century climatology but within one standard deviation of the mean (Table 1), and thus are not inconsistent with the 20th century SST climatology.

7. Discussion and Summary

We have addressed regional changes for the northern Bering and Chukchi Seas around the 1976 regime shift, and 20th century time series in the vicinity of Bering Strait.

While surface air temperatures show a strong warming signal after 1977, high variability in this region and sparse oceanic sampling make it impossible to draw robust conclusions regarding low-frequency variability in SST. Sampling has not been consistent spatially or temporally. Thus, observed changes in SST surrounding the 1977 regime shift have to be interpreted with caution. Some observed changes were relatively strong and spatially consistent, suggesting real changes. In July, the region influenced by the Alaskan Coastal Current was warmer after 1977, while the region over Herald Shoal was colder. This pattern did not carry into August and September. Norton Sound data shows post-1977 warming in August, while both Norton and Kotzebue Sounds exhibit cooling in September. The lack of similar patterns in the 3 months may be due to real intraseasonal variability in oceanic conditions possibly due to seasonality of Yukon River discharge (July discharge is significantly greater than August or September discharge). However, it could be purely due to insufficient data.

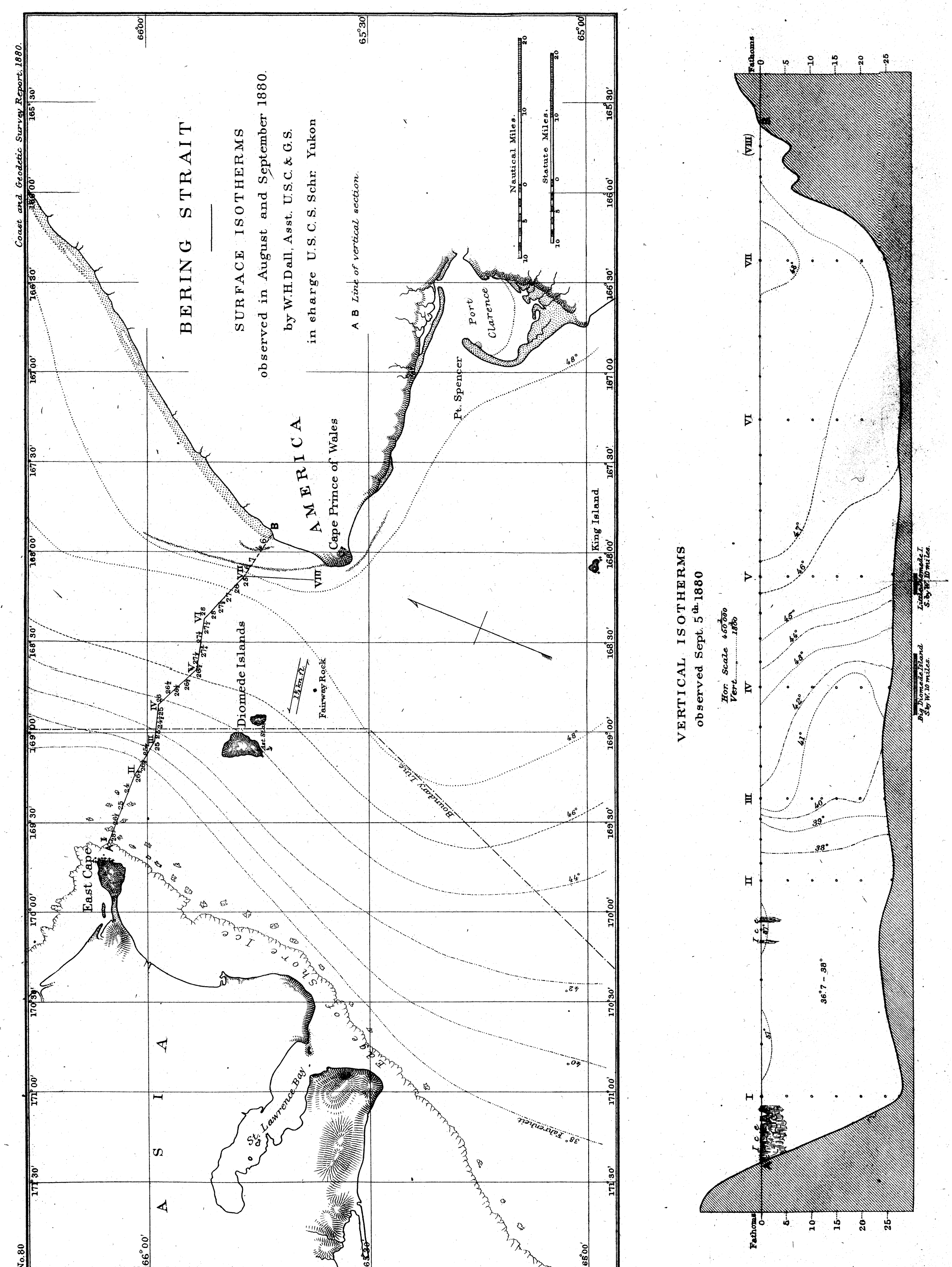

Figure 8: Temperature transect (°F) across Bering Strait taken in September 1880 (bottom) along with location of transect (top). From Dall (1882).

Given the data at hand, we cannot conclude that the northern Bering/ Chukchi Sea region shows decadal-scale or regime-shift variability in SST compared to the hypothesis that all measurements for the 20th century come from a single population. However, we also cannot say conclusively that no decadal or longer timescale variability existed. The warmest temperatures ever measured in the eastern Bering Strait were measured in 2004 and the warmest temperatures measured in western Bering Strait were observed in 2006, providing evidence that we may be seeing a warm period in the 21st century superimposed on substantial interannual variability. Model results suggest that the influence from the anthropogenically forced trend in SST will be as large as the natural variability in North Pacific SST by 2030–2050 (Overland and Wang, 2007). Thus, we would expect to see additional temperature measurements outside of the range observed thus far. In contrast, data from the end of the little ice age (1880) is not inconsistent with the 20th-century climatology.

To have a baseline for comparison of potential future changes in the northern Bering and Chukchi Seas, it was important to assemble all previous data and assess how far the previous record can be characterized, given data gaps. Sampling from a single population is as far as we can reasonably go in identifying the 20th-century climate structure for the Bering Strait region. The paper points out the importance of obtaining every scrap of historical data; even single measurements in single years help to determine the range of interannual variability. These data are golden for climate analyses. Further, the importance of continuing regular observations, consistent in location and month for every year, is self evident.

8. Acknowledgments

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