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ORIGINAL PAPER

On the climate and climate change of Sitka, Southeast Alaska

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Abstract Sitka, located in southeastern coastal Alaska, is the only meteorological station in Alaska and northern coastal British Columbia, with a long climatological record, going back to the first half of the nineteenth century. Sitka was the capital of Alaska, when it was part of the Russian Empire, to which Alaska belonged until 1867, when the American government purchased it. In 1827, the Russian established an observatory on Baranof Island, Sitka Harbor, which made 17-hourly observations, later extended to 19 and thereafter to all hours of the day. When analyzing the data, the 12-day time difference between the Russian (Julian) calendar, at which the observations were made, and ours (Gregorian) has to be considered. The climate of Sitka is maritime, with relative warm winter temperatures—there is no month with a mean temperature below freezing—and moderately warm summer temperatures with 4 months above the 10 °C level and plentiful precipitation all-year long. It is the warmest zone of Alaska. Even though there is a substantial break in observations in the late nineteenth century, these are the only observation, which started so early in the nineteenth century. Systematic US-based observations commenced much later normally in connection with the gold rush, whaling in Northern Alaska, and the fur trade, predominantly along the Yukon River. During the 186 years of observations from 1827 to 2013, the best linear fit gave a temperature increase of 1.56 °C for the whole period or 0.86 °C per century, somewhat lower than expected for the relatively high latitudes. The increase was nonlinear, with several multi-decadal variations. However, when comparing the first normal (1831–1860) to the last normal (1981–2010) and assuming a linear trend, a higher value of 1.06 °C per century was calculated. The discrepancy might be explained by nonlinearity and the fact that during the late nineteenth and early twentieth centuries, observations were sporadic. Furthermore, the observed warming is less pronounced than the values found for Interior and especially Arctic Alaska for later time period for which such a comparison was possible (Wendler et al. 2014). Significant correlation values were found with the Pacific Decadal Oscillation (PDO), the North Pacific (NP) Index, El Nino 3.4, and the 18.4 years nodal tide; the latter was previously reported in an excellent investigation by T. Royer (1993).

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1 Background

Historical observed meteorological data in Alaska go back for a relatively short time; especially as before 1867, Alaska did not belong to the USA but was part of the Russian Empire. Russian–America, as it was called, had its capital in Sitka (57° 0.3′ N, 135° 19′ W), located on the Baranof Island in South-east Alaska. In Fig. 1, a map of the area is presented.

In 1827, the Russians started making systematic meteorological observation at that station. The temperature was measured in degree Reaumur (0° for freezing point and 80° for the boiling point), and the data were published in Russian and French annually in the Bulletin Scientifique, L'Academie Imperial des Sciences, Saint Petersbourg. After 1867, when Alaska became a territory of the USA, there was a break in the observations, and from thereon, temperature measurements were made in degree Fahrenheit.

The Russians built a special observatory in Sitka in 1842, to carry out these observations, which is shown in Fig. 2.

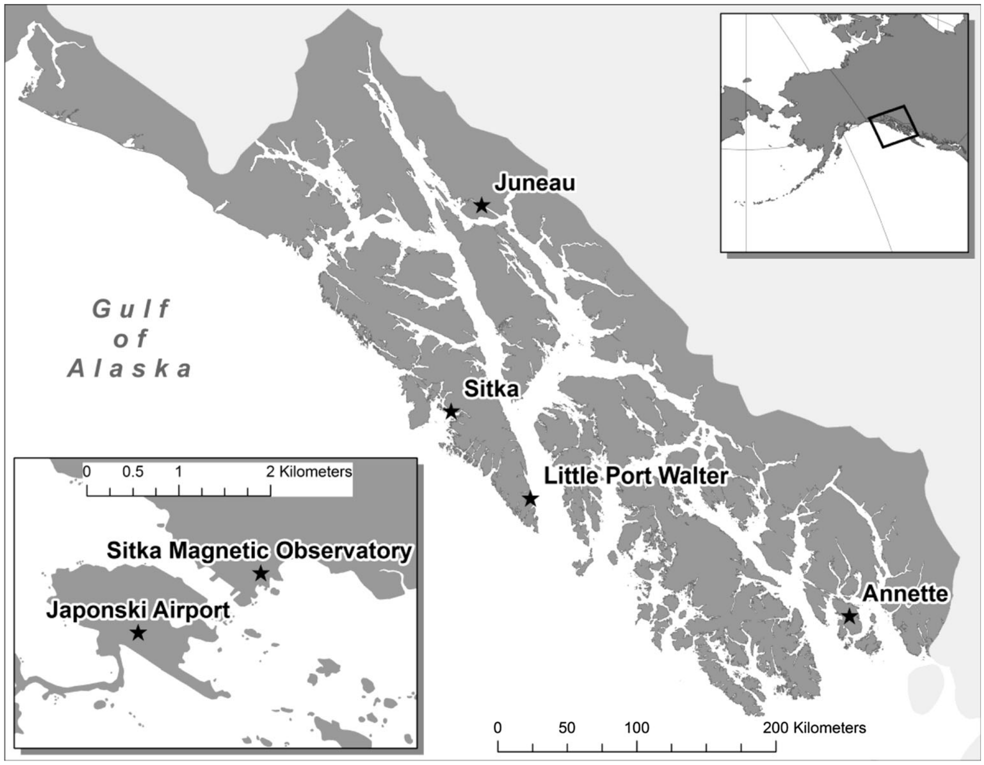

Fig. 1 Map of southeast Alaska with an enlargement of the Sitka area, showing the two observational places

There were two additional stations in Alaska, where the Russians carried out meteorological measurements, namely Iliuliuk (53° 52.6′ N, 166° 31.6′ W) on Unalaska Island (Aleutian Chain) and Ikogmut Mission (61° 47′ N, 161° 14′ W), close to the mouth of the Yukon River, in the proximity of today's Bethel. These two stations had a dual purpose: (1) to spread the Russian Orthodox religion and (2) being headquarters for fur trade. Concerning the latter one, sea otters were especially valuable as were silver fox skins. However, for these two stations, the meteorological measurements were of relatively short duration; hence, they are of little value for climatology studies.

Fig. 2 Russian observatory at Baranof Island, at which the Russian meteorologists carried out the observations produced from a sketch by Frederick Whymper, 1865

A summary of the early climatic observations in Alaska is given by C. Patterson (1879a) in the "Pacific Coast Pilot, Coasts and Island Stations of Alaska," which discusses in great detail all early meteorological measurements. Further, Abbe (1906) published the first Atlas of Climate of Alaska, remarkable as it was based on a relatively short time period. Less than two decades later, Day (1922), the meteorologist in charge for Alaska by the Weather Bureau, at that time part of the US Department of Agriculture, published the climatological data of Alaska by section for the time period up to 1921.

In this paper, we discuss the climate and the observed climate change based on this single station, Sitka, as it is only station in Alaska with such a long data record. Systematic US-sponsored measurements started much later around the end on the nineteenth century mostly in connection with the Alaskan Gold Rush. Data of these stations were only used sporadically to fill gaps in missing data of twentieth century of Sitka. Further, it should be pointed out that the Sitka dataset was previously used by Royer (1993).

2 Climate of Sitka

Southeast Alaska is the warmest climate zone of Alaska (Searby 1968; Shulski and Wendler 2007) and the only region where the mean monthly temperatures stay above the freezing point year-round. It is a mid-latitude maritime climate (Cfb) according to Köppen's classification (Köppen 1884, Köppen and Geiger 1940). "C" indicates that it is a temperate climate with no monthly mean below the freezing point, the second letter "f" refers to precipitation and indicates that significant precipitation is observed in all seasons, while the third letter "b" indicates the degree of summer heat. The warmest month of the year is below 22 °C, but there have to be at least 4 months with temperature above 10 ° C for this classification; for Sitka, it was exactly 4 months.

The mean annual temperature of Sitka for the last climate normal (1981–2010) was calculated as 7.4 °C. The coldest month is January with a mean temperature of 2.4 °C and an average low just above freezing with 0.2 °C. August is the warmest month with a mean monthly value of 14.0 °C and a mean daily maximum 16.6 °C (see Fig. 3). The maximum of August is rather typical for a maritime climate, as the ocean lags in warming up in summer when compared to a more inland station, where the highest temperature is normally observed in July. The annual variation between the warmest and coldest months is relatively small with 11.6 °C. There are only 5.1 days, on average, per year when the maximum temperature rises above 21.1 °C (70 °F). On the other side of the spectrum, there are only 10 days annually, when the maximum temperature of the day does not rise above the freezing point.

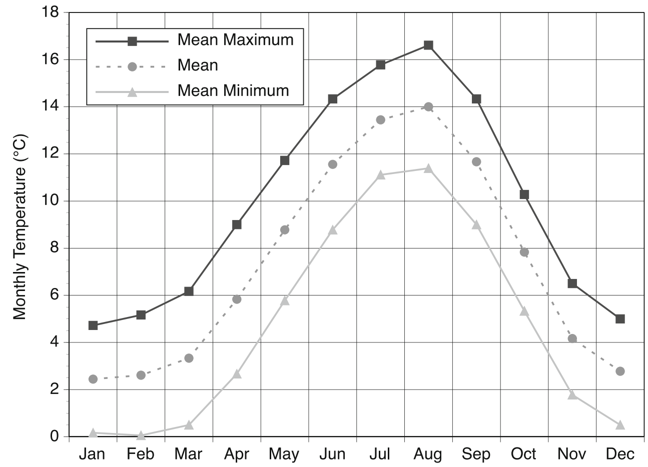

Fig. 3 Mean monthly temperature for Sitka for the last climate normal (1981–2010), as well as mean monthly maxima and minima for this time period

Using Eurasian data, (Conrad 1944) calculated a so-called "continentality index" C, where C is defined by

$$C = 1.7\partial T/sin\alpha - 20.4$$

with ∂T (°C) being the difference in the mean temperature between the warmest and coldest months and α is the latitude. On this scale, the maritime climate of Tromsö on the western coast of Norway registers zero while the continental climate of Verkhoyansk (Interior Siberia), where the coldest temperature on the Northern Hemisphere was measured, rates 100. Applying this empirical formula, a value of 4 could be calculated for Sitka. This strongly maritime climate is rather typical for the area. There are two additional first-order meteorological stations along the coast, to the North, Juneau (58° 22″ N, 134° 35″ W) and to the South, Annette (55° 02′ N, 131° 34′ W). For the last climate normal, they recorded mean annual temperatures of 9.5 and 11.1 °C, respectively, with mean annual differences between the coldest and warmest months of 16.3 and 12.9 °C. Calculating the "continentality," values of 3 and 1 were obtained, even slightly more maritime than Sitka. This compares to Interior of Alaska (Wendler and Shulski 2009), where a value of 70 was found for Fairbanks. Here, the winters are cold, while the summers are relatively warm for the high latitudes. At Ft. Yukon, a few miles North of the Arctic Circle, the highest temperature ever measured in Alaska was recorded in June 1915 at 37.8 °C (100 °F). The highest temperature ever measured at Sitka was a modest 31.1 °C reported on 30 July 1976, while the coldest temperature occurred on 9 January 1953 at −17.8 °C, which compares to the absolute minimum for Alaska of −60.0 °C, observed in Tanana in January 1915, situated also in the continental climate zone of Interior Alaska. Finally, it should be pointed out that different formulations of the continentality index exist, as can be seen from early work (Gorczinski 1920; Johansson 1926; Conrad 1946, 1950).

The precipitation amount is high in southeast Alaska. Little Port Walter (56° 23′ N, 234° 38′ W) holds the record for Alaska with a mean of 5751 mm annually. Here, local uplift enhances the amount. Sitka reports 2205-mm precipitation, much less, but still a very substantial amount when compared to the continental climate of the Interior (e.g., Fairbanks 278 mm) or Arctic Alaska (e.g., Barrow 107 mm). There is a strong annual course in the precipitation, with the maximum observed in fall, when the ocean is still relatively warm while the landmass has been substantially cooled. The fall storms bring a large amount of moisture, and a maximum of precipitation is observed in October (mean value 329 mm) followed by September (298 mm) and November (248 mm). As the thermal contrast between the ocean and landmass decreases, so does the precipitation, and in June, the minimum is reached at 73 mm. More details can be seen from Fig. 4, from which can be also seen that maxima monthly values of the 30-year period can be about twice as large as the normal. There are, on average, 235 days with precipitation of at least 0.01″ (0.25 mm), and in August, 24.4 days of the month report on average rain.

The annual snowfall is, on average, 820 mm; more than half of this occurs in the two winter months of January and February. As there is no month in which the mean temperature is below the freezing point, snow cover, when established, does not last long.

As could be expected from the high amount of precipitation, the amount of cloudiness is high with a mean annual value of 68 %. The maximum occurs in late summer/early autumn (August 77 %, September 74 %, October 73 %), while the minimum occurs in January with a still substantial value of 57 %. Monthly values are presented in Table 1. The atmospheric pressure has a mean annual variation of 15.4 hPa, with

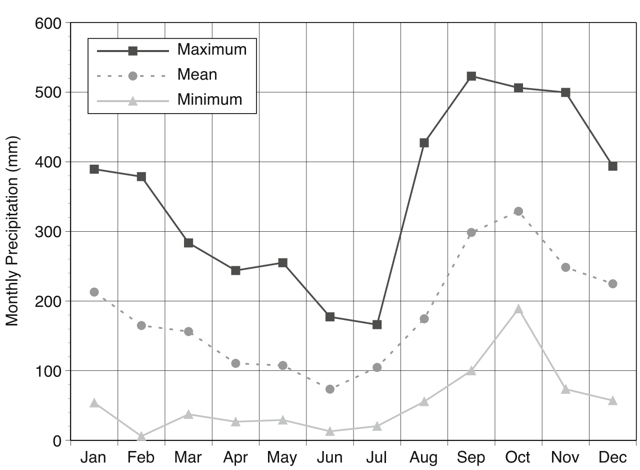

Fig. 4 Mean monthly and lowest and highest monthly value of precipitation for the last climate normal (1981–2010) for Sitka

the maximum is in July (1017.7 hPa) and a minimum in November (1002.3 hPa). It is, as expected, very close to the annual variation of Annette, a first-order station in the same climate region, both in absolute values and annual course. The mean monthly values are presented in Table 1.

Looking at the annual course of the wind speed, the maximum is observed in November and December, during the months of minimum atmospheric pressure with 4.3 m/s, an expected result, while the minimum occurred in August (2.7 m/s), the month with the highest temperature. The mean annual wind speed could be calculated as 3.7 m/s (see Table 1).

When analyzing a station record for changes in its climate, one has to be careful that it is not affected by other factors, e.g., (1) the heat island effect of a growing city, (2) station relocation, and (3) measurements routines.

1. Concerning heat island effects of a growing city with time in Alaska (e.g., Magee et al. 1999), this specific element is of little importance for Sitka, as the population has not grown substantially and is at present roughly 9000 inhabitants.
2. The original observing location of Sitka Magnetic was terminated in 1989, and the observational site was moved some 2 km to the southwest at Sitka Airport. However, for the time period from 1976 to 1989, both stations were operating, which allows a careful comparison. In Fig. 5, such a comparison has been carried out for the above time period and temperature.
3. One has to be careful insofar that the temperature for the 40-year period from 1827 to 1867 was measured as 5.1°Reaumur (6.2 °C), as the incorrect assumption that these early measurements were carried out in the now commonly used scale of degrees centigrade would add 1.1 °C to the observed warming to the nearly two centuries of observations. Further, the difference in the calendar (12 days) between the Russian and ours, as well as the conversion from degree Reaumur into Fahrenheit, was already carried out by Patterson (1879b).

It can be seen that the temperatures correlate excellently (r=0.99), but that the Sitka Magnetic was, on average, 0.9 °C colder than Sitka Airport.

When calculating the mean daily temperature, the maximum plus the minimum temperatures, divided by 2, is used in modern times. The Russian observations were carried out for hourly 17 h from 6:00 to 21:00 h (1828–1831), later 19 h from 4:00–21:00 h (1832–1848) and than 24 h (1849–1867). The average of these observations was taken to calculate the daily mean. By doing this, some cold night hours were omitted, especially, in the very early observations of only 17 h, and hence, too

Table 1 Mean climatic values of the last climatic normal (1981–2010) for Sitka, Alaska

Month	Temperature (°C)			Precipitation (mm)		SLP (hPa)	Wind speed (m/s)	Cloudiness (%)
Jan	4.7	2.4	0.2	213	241	1006.9	4.2	57
Feb	5.2	2.6	0.1	165	203	1007.1	3.9	66
Mar	6.2	3.3	0.5	156	124	1006.1	4.0	64
Apr	9.0	5.8	2.7	110	23	1008.7	3.7	64
May	11.7	8.8	5.8	107	0	1014.9	3.3	64
Jun	14.3	11.6	8.8	73	0	1015.6	3.1	74
Jul	15.8	13.4	11.1	105	0	1017.7	2.8	71
Aug	16.6	14.0	11.4	174	0	1015.9	2.7	77
Sep	14.3	11.7	9.0	298	0	1012.2	3.2	74
Oct	10.3	7.8	5.3	329	8	1006.4	4.0	73
Nov	6.5	4.2	1.8	248	119	1002.3	4.3	68
Dec	5.0	2.8	0.5	225	102	1003.9	4.3	69
Annual	10.0	7.4	4.8	2205	820	1009.8	3.7	68

high average daily temperatures were calculated. We found that the calculated mean annual temperature was 0.50 °C too high for the 17-h observations, and 0.32 °C too high for the 19-hourly observations. The difference between the (max+min) / 2 and the mean of the 24 h was only 0.04 °C, the latter being warmer, and here, no corrections were carried out. As expected, there is a fairly strong annual course in these differences, as the nights are long in winter and short in summer, where, therefore, the maximum effect is to be expected, which can be seen from Fig. 6.

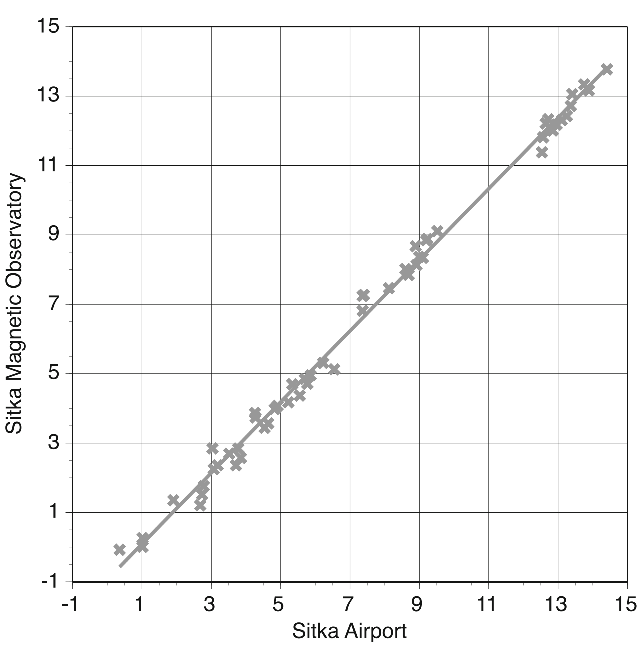

Fig. 5 Comparison of the temperatures (°C) of Sitka Magnetic, the original site of observations, and Sitka Airport, where, presently, the observations are carried out based on seasonal data points, 1976–1989

3 Observed climate change

The Arctic frequently experienced climate change larger than those observed in lower latitudes (Walsh and Chapman 1990; Serreze and Barry 2006; Wendler 2006). After carrying out the above-discussed corrections, a time series of the mean annual temperature could be constructed, which is presented in Fig. 7. As pointed out previously, there is a substantial data gap at the end of the nineteenth century, which we were unable to fill, as there were no southeastern Alaskan or Western British Columbian stations available for this time period. The best linear fit over the whole total time period gave a warming of 1.62 °C over the 186 years or 0.86 °C per century.

The graph shows that the first half of the nineteenth century was cold, for the following time period, the general trends are difficult to determine due to frequently missing data, but years with higher temperatures were occasionally observed. The 1920s brought high temperatures, the same phenomenon

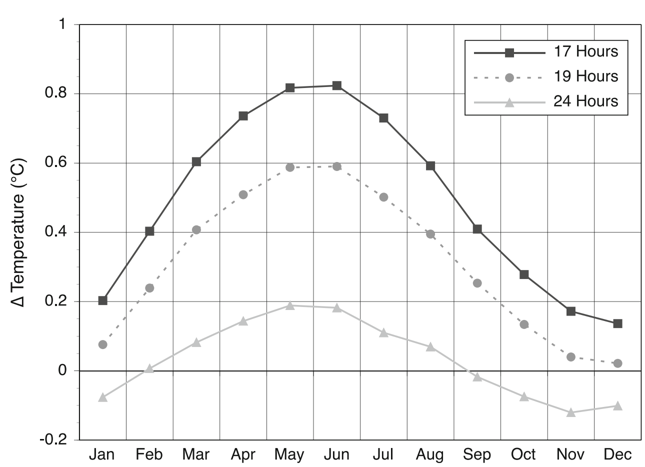

Fig. 6 Annual course of the differences in temperature when calculating the temperatures on the base of the means of 17, 19, and 24 h, when compared to (max+min) / 2

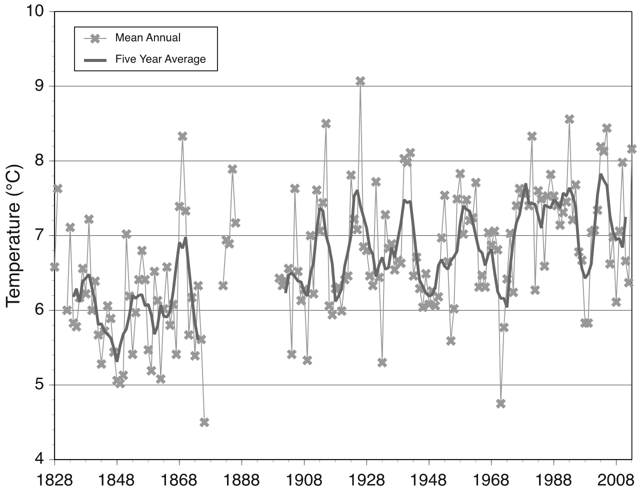

Fig. 7 Time series of mean annual temperature for Sitka, Alaska, as well as the 5-year running average

Winkler (2009) made corrections to the long-term temperature series of Hohenpeißenberg, which goes back to 1781. It is the most famous long-term temperature series in Germany, as the location is not affected by urbanization. This secular rise of the zero point can be of the order of 0.5–1.0 °C. We were not able to locate the old thermometer nor do we know which type was used. We know only that the Russians used a thermometer measuring in degree Reaumur, while the Americans, after the purchase of Alaska in 1867, used thermometers calibrated in degree Fahrenheit. Such effect, if it existed, should result in a more warming than values calculated above. It might be assumed that the American observations were free of such effect, as systematic observation started only at the very end of the nineteenth century, by which time, this has been recognized and thermometers were mostly free of this effect.

being observed in other parts of Alaska (Wendler and Shulski 2009, Wendler et al. 2010). In the following years, the temperature varied widely but was relatively cool. In 1975, a strong warming was observed in connection with the change of sign of the Pacific Decadal Oscillation, which changed from dominantly negative to dominantly positive values. Mantua et al. (1997) were the first to show the strong influence of the phase of the Pacific Decadal Oscillation (PDO) on the climate of Alaska by examining the relationship between climate variability and salmon production in Alaska and the US Pacific Northwest. Monthly anomalies in the sea surface temperature (SST) field of the NP, poleward of 20° N, constitute the basis of the PDO index. Other studies of the PDO, with emphasis on its effect on Alaska, were carried out by Papineau (2001) and Hartmann and Wendler (2005). The latter studies showed clearly that in 1975/1976, when the PDO value changed from dominantly negative to dominantly positive values, a sudden temperature increase across Alaska was observed. At the start of the twenty-first century, the PDO became negative and the temperatures decreased again, which could be seen for most of Alaska with the exception of Arctic Alaska and led to an increase in the sea ice in the Bering Sea, as the intensity of the Aleutian Low decreased, advecting less warm air from the south into Alaska (e.g., Wendler et al. 2014).

The calculated temperature increase of Fig. 7 is 0.86 °C per century. The confidence in this value is somewhat compromised by several periods of missing data. Hence, we also calculated the linear trend between the first normal of 1831–1860 and for the last normal of 1981–2010, as complete climatological datasets are available for both time periods. Taking the midpoints of these two climate normals, a slightly higher value of 1.06 °C per century was found.

Ancient thermometers can suffer from a secular rise of the zero point (Mitchell 1953). In a substantial publication,

4 Correlations of temperature with atmospheric indices

We correlated the annual temperature of Sitka with the PDO for the time period from 1900 to 2012. The results are shown in Fig. 8. It can be seen that the correlation coefficient is 0.6233, resulting in a variance of 0.39, or with other words, 39 % of the observed temperature change can be explained by the changing PDO values. The value is significant at the 95 % confidence level.

Wilson et al. (2006) carried out a study on the temperatures for the Gulf of Alaska based on tree rings, going back 1300 years. Looking at climatic indices, he found also the best correlation with the PDO (r=0.53, var. = 0.28), again significant for this longer time period at the 95 % confidence level. Further, Royer (1989) investigated the upper ocean temperature variability in the Northeast Pacific Ocean.

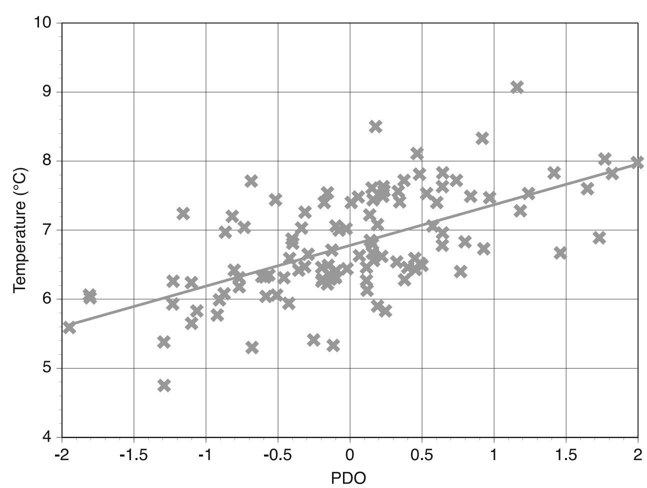

Fig. 8 Correlation between Sitka's mean annual temperature and the PDO index for the time period 1900–2013

Since the beginning of the twentieth century, monthly values of the PDO are available (Zhang et al 1997, Mantua et al. 1997) and we were able to correlate seasonal temperatures with the PDO. Spring had the highest correlation coefficient (r=0.704, var. = 0.50), followed by winter (r=0.648, var. = 0.42), while for summer (r=0.546, var. = 0.30) and autumn (r=0.507, var. = 0.26), lower values were found. This is understandable, as at these times of the year, local heating plays a more significant role. All values are significant at the 95 % confidence level.

We correlated Sitka's temperatures also with other climatological indices. The second highest correlation (r=−0.627, var. = 0.39) was found with the North Pacific (NP) index, which is based on the area-weighted sea-level pressure (SLP) over 30–65° N and 160° E–140° W. As the SLP and temperature are related, this is not a surprising result. The El Nino 3.4 and the PDO are also related, the PDO being the deviation of the SST temperature of the Pacific Ocean North of 20° N, while the El Nino is related to the tropical SST (5° N–5° S). In Fig. 9, the relationship between the mean annual temperatures at Sitka and the El Nino 3.4 is shown. As expected, not only the PDO shows a higher correlation coefficient, but also the El Nino 3.4 is still correlated on the 90 % confidence level.

Looking for cycles, we carried out a Fourier transform on the temperatures (not shown). Besides the normal and always observed annual variation, the solar cycle with 11 years was not statistically significant. However, Royer (1993) and McKinnell and Crawford (2007) observed previously the 18.6-year lunar nodal cycle.

5 Air–water temperature comparison

Water temperatures were obtained off Sitka from buoy measurements from 1987 to 2014. While this period is too short for climate change investigations, the comparison gives some interesting insights. The water temperature is higher than the air temperature at Sitka for 8 months of the year, with maximal differences of 4.1 °C in November and December, when the land has cooled far down, while the water temperature has remained relatively warm. For the following 3 months, the temperature difference stays fairly constant with a mean value of 3.1 °C (Fig. 10).

In April, with the sun above the horizon for more than 12 h a day, the air temperature starts to increase strongly, and for the following 4 months, Sitka's air temperature is higher than the water temperature of the adjacent ocean. The temperature

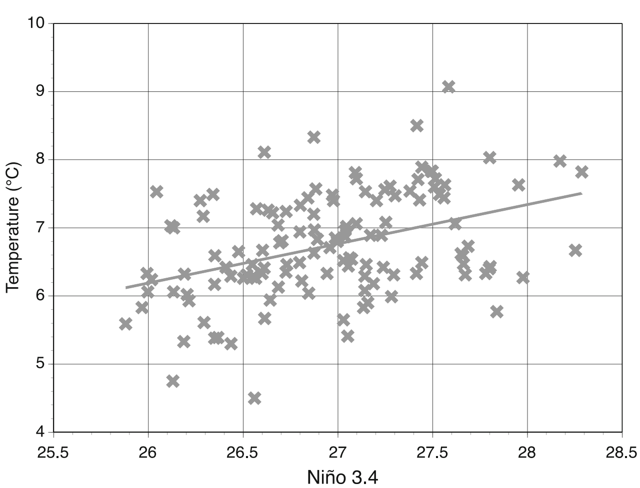

Fig. 9 Correlation between annual values of the El Nino 3.4 and the mean annual temperatures at Sitka, Alaska, from 1870 to 2013

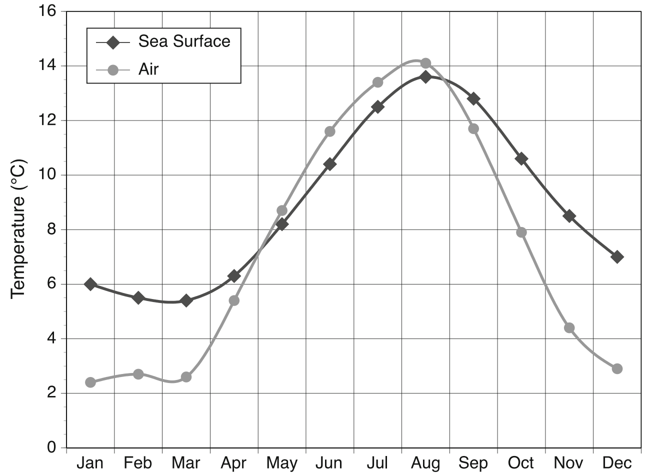

Fig. 10 Mean monthly air temperature of Sitka and water temperature of Sitka for the time period 1987–2014

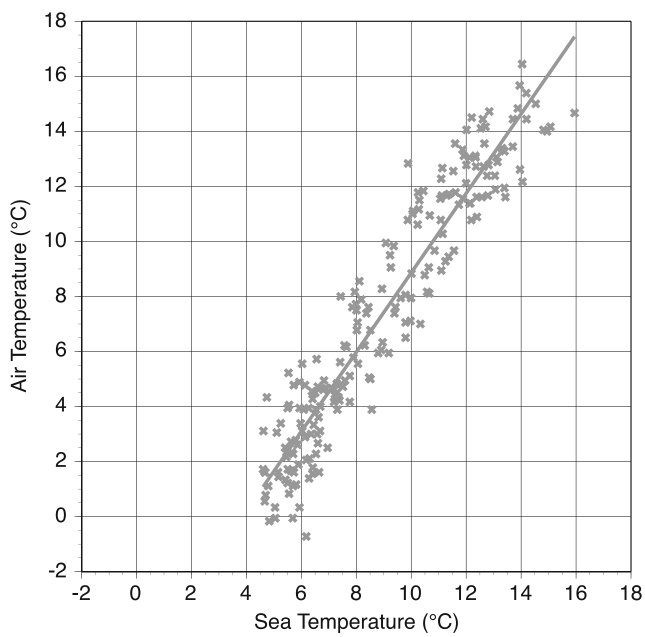

Fig. 11 Monthly values of Sitka's air temperature plotted against the water temperature off Sitka for the time period 1987–2014. To obtain the best relationship, the air temperatures were lagged by 1 month

difference is relatively modest with 0.8 °C as the average for the 4 months. The mean annual water temperature is 1.6 °C higher than the air temperature of Sitka, an effect of advection of warm water. The time period is too short for meaningful dependencies; however, the correlation factor between PDO and water temperature for the 18 years was calculated at 0.428. Further, the graph shows that a temperature above 13 °C is necessary for the land to be warmer than the sea surface. In Fig. 11, we plotted the air and sea surface temperatures against each other with a lag of 1 month for the air temperature. A very good correlation was found (var. = 0.90).

6 Discussion and conclusion

In a very recent and highly interesting paper, Johnstone and Mantua (2014) analyzed the temperature variability and change for coastal California, Oregon, and Washington. While the area is to the south of Sitka, it lies in the same climatic area of the Northeast Pacific Coast. They found a temperature increase of about 1 °C since 1900, similar to our values. As in our case, they find a strong temperature dependence on the PDO, which responds to regional atmospheric dynamics. They furthermore demonstrate that the observed temperature increase can be explained without anthropogenic greenhouse forcing. Using several independent data sources, they demonstrated that the century-long warming can be primarily attributed to changes in atmospheric circulation. We were, with our much more limited dataset, unable to demonstrate this.

Acknowledgments We are thankful to T. Royer for temperature data as well as very useful discussions about the historic Sitka climatology. B. Moore and M. Shulski helped in various ways, for which we thank them. Further, we acknowledge Robert McCoy, Director of the Geophysical Institute, who financially supported this investigation, with State Funds directed to the Alaska Climate Research Center. Finally, we thank the two reviewers unknown to us, who pointed out some shortcomings in the manuscript, which improved this study.

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