The influence of mesoscale land–sea breeze circulation on local wind climatology in the Svalbard fjords of Kongsfjorden and Hornsund

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Abstract
We analyse data series (1992–2013) of wind measurements from meteorological stations in Ny-Ålesund and Hornsund on Svalbard and then have them compared to surface layer winds from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis. We find significant discrepancies between the local wind direction and directions of wind compatible with the analysis of large-scale pressure fields. We argue that one of the most important factors controlling wind directions in the Svalbard fjords is the difference in temperature between the neighbouring glaciers and surface sea temperatures of open waters warmed by the west Spitsbergen current. This creates atmospheric circulation patterns similar to the land breeze in temperate climates. We show that the frequency of simultaneous breeze-type circulation events on the northern and southern fjords of Spitsbergen is highly correlated with sea–land temperature difference on monthly timescales. A Monte Carlo analysis of breeze probabilities rejects the null hypothesis of independent breeze events in both fjords. This result shows that breeze events are not independent where two fjords placed at opposite ends of Spitsbergen’s west coast are concerned, and we also posit that the breeze occurrence is largely controlled by the synoptic situation. Such large-scale wind phenomena should have an impact on air–sea heat fluxes to the east of Spitsbergen.

KEYWORDS
Arctic, climatology, fjords, wind

1 | INTRODUCTION
Svalbard is a Norwegian archipelago in the Arctic Ocean located between 74°N and 81°N and 10–28°E. The climate of Svalbard is principally a result of its close proximity to the North Atlantic Current which keeps the surrounding waters of Greenland Sea open from the west. It has a subpolar climate along the west coast and a polar one on the east coast. There has been a steady increase in the amount of literature on Svalbard’s meteorology (Esau...
et al., 2012) even if many aspects are not fully understood. For example, it has already been established that measurements of surface wind direction and speed at coastal Arctic stations are often not representative for the neighbouring regions. Winds over the Greenland Sea and Arctic Ocean occur most frequently with a northern direction which cannot be confirmed by measurements on Svalbard stations (Pilgjuj et al., 2019). An important paper on the wind climate of the Hornsund station in Svalbard (Marsz et al., 2013) states that the “Hornsund station is characterized by a special wind regime. [...] This is caused by a strong influence of local conditions.” The situation is similar to other fjord-based stations in Svalbard. For example, the north and south wind directions dominate at the Kaffjöyra station (Przybylak et al., 2018; Kejna and Sobota, 2019). The climatology compiled by Hanssen-Bauer et al. (1990) shows that for Kongsfjorden, surface winds usually blow along the axis of the fjord. Esau and Repina (2012) provide a review of literature on the climate wind of Kongsfjorden. However, not only does wind direction channelling influence the local wind climatology, but other influences, like fen and fall (katabatic) winds, are also important (Repina, 2018). Using an eddy-resolving model, Esau and Repina (2012) showed that thermal land–sea breeze circulation is more important in Ny-Alesund (Kongsfjorden) than katabatic winds. While air temperature is strongly influenced by the mesoscale atmospheric circulation (Łupikasza and Niedźwiedź, 2019), horizontal temperature gradient has quite an impact on this circulation. In this study, we compare the wind climate of two different Svalbard fjords. Our hypothesis is that local winds in fjords of western Spitsbergen are influenced by the breeze-type mesoscale circulation caused by the difference in temperature between the land areas to the east (mostly glaciers) and much warmer waters of the West Spitsbergen Current. In the presented work, the phenomenon we observed is called land–sea breeze circulation. This postulated mesoscale land–sea breeze circulation, driven by the difference in temperature between the Norwegian Sea and inland glaciers, has a seasonal timescale unlike the “classic” local diurnal breeze observed solely in the month of July at Isfjorden, Svalbard (Grønås and Sandvik, 1998).

2 | METHODS

The two fjords comprising the focus of this study are Kongsfjorden and Hornsund (Figure 1). Both fjords are found on the western coast of Spitsbergen, the main island of the Svalbard archipelago. Kongsfjorden, in the north of Spitsbergen, has its main axis at northwest–southeast (head of fjord azimuth at approximately 120° direction), while the main axis of Hornsund, a larger fjord in the south of the island, has a more zonal position (head of fjord azimuth at approximately 90°). The fjords are separated by a latitude of 2° (their latitudes are...
approximately 79°N and 77°N, respectively). Both fjords are seasonally frozen but adjacent to all-year ice-free ocean waters except for episodic additions of sea-ice from the Barents Sea, mostly during the spring (Piskozub, 2017). We analyse measurements of wind at 10-m height and 6-hr time resolution from stations located in the fjords: 31,138 datapoints from April 1993 to December 2013 from the AWIPEV station, the joint French–German Arctic Research Base—the German Alfred Wegener Institute for Polar and Marine Research (AWI) and the French Polar Institute Paul Emile Victor (IPEV), in Kongsfjorden (Maturilli et al., 2013); and 30,595 datapoints from December 1992 to December 2013 from the Polish Polar Station in Hornsund, comparing them to 10 m winds from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) 2.5 × 2.5°, 6-hourly, reanalysis (Kalnay et al., 1996). The measuring stations from which the data comes are World Meteorological Organization (WMO) network stations, while devices used for measurements are WMO-standard compliant. Automatic stations have been used in recent years. The 6-hourly local wind data are the result of temporal 10-min averaged measurements that also accord with WMO standards. We chose the low-resolution NCEP/NCAR reanalysis to represent the large-scale circulation for two reasons. First, its low resolution minimizes the effect of contamination of a large-scale wind field with assimilated local data influenced by the very phenomena here being studied, thus allowing us to use it as a large-scale circulation. The second reason is that a high-resolution model could resolve the very orographic and thermal mesoscale phenomena being studied.

**FIGURE 2** Local wind rose for (a) Ny-Ålesund station for the years 1992–2013, (b) for Hornsund station for the years 1993–2013 and large-scale wind rose (from NCEP/NCAR reanalysis) interpolated, (c) for the position of the Ny-Ålesund station for the years 1992–2013, (d) Hornsund station for the years 1993–2013
instead of representing a large-scale circulation. For similar reasons, we decided not to use the recently compiled calendar of Svalbard circulation (Niedźwiedź, 2013), given its possible circularity as the calendar was based on synoptic maps covering the entire northern part of the North Atlantic. We are using both sources (local data and reanalysis) together to check our hypothesis that local winds in fjords of western Spitsbergen are influenced by

**FIGURE 3** Ny-Ålesund station local wind roses for each of the 30° sectors of large-scale wind direction. Data from the years 1992–2013.
breeze-type mesoscale circulation caused by the temperature difference between the land areas to the east (mostly glaciers) and much warmer waters of the West Spitsbergen Current.

We used the most recent sea surface temperature (SST) climatology, merging in situ and satellite data, created for the WMO recommended base period 1981–2010 (Xue et al., 2011), a $1 \times 1^\circ$ update of an earlier SST
climatology (Xue et al., 2003, http://origin.cpc.ncep.noaa.gov/products/people/yxue/sstclim). There are no long-term temperature data from inland Spitsbergen even though recently data from a 12-month campaign, September 2010–August 2011, partly overlapping with the SST climatology period, have become available (Przybylak et al., 2014). The campaign involved setting out 30 meteorological stations in remote parts of Svalbard, mostly on, or next to, Spitsbergen glaciers. The locations of these stations are described in detail (positions and map) in the article by Przybylak et al. (2014). We decided to use the 12-month data as a proxy climatology based on the much larger seasonal (rather than interannual) temperature variability in Spitsbergen on the monthly scale.

3 | RESULTS

Figure 2a,b shows the observational wind roses, respectively, for Ny-Ålesund (Kongsfjorden) and Hornsund (Cisek et al., 2017a). We present the wind roses in the typical form preferred by meteorologists, with feather length representing frequency at which the wind blows from a given direction (this is important as some recent papers have preferred the inverse, oceanographic convention). Figure 2c,d shows the surface wind directions from NCEP/NCAR reanalysis, interpolated for the position of the stations. The interpolated value at a meteorological station is based on linear interpolation of the values at neighbouring grid points in each of the two dimensions (Figure 1). The observational wind roses show that in both fjords, wind channelling along the fjord axis is the most important process controlling the local wind direction. Local wind frequencies are qualitatively different from large-scale winds calculated in the reanalysis, concentrating along the fjord axis.

The independence of local winds from large-scale winds is visible, even better, in Figures 3 and 4. They show the wind roses of observed local winds for reanalysis of large-scale winds from a given sector for Ny-Ålesund and Hornsund, respectively. The large-scale winds are divided into 12 sectors, each of 30°. An interesting fact is the domination of local easterly winds, independent of the large-scale wind direction. However, it is difficult to explain all the observed features with wind channelling alone. In particular, local winds with direction inverse to that of large-scale winds cannot be explained by orography. We have noted 385 such events in Ny-Ålesund and 394 in Hornsund. According to modelling results (Wells et al., 2008), wind direction may change by 180° but only in the vortex (due to the Coriolis force) behind a blocking range perpendicular to the large-scale wind direction. No such objects exist at the eastern ends of the two fjords studied, and Hornsund fjord in particular is at present divided from the Barents Sea in the east by only 6 km of glacier and may become an actual sound in this century (Ziaja and Ostafin, 2015).

However, local wind blowing against the direction of large-scale wind in coastal locations is often caused by land–sea breeze circulation, with scales of 2 to 2,000 km (Miller et al., 2003). At the time of large-scale westerly
circulation, Spitsbergen's local easterlies have the characteristics of breeze due to the horizontal thermal gradient between open water and the Svalbard glaciers, as shown by Esau and Repina (2012) in the case of Kongsfjorden. We have noted 11,190 such events for Ny-Ålesund and 14,207 for Hornsund. Such situation happened simultaneously in both fjords 8,105 times. The phenomenon of land–sea breeze circulation in this area, unlike the breeze occurring in the lower latitudes, is not related to the time of day and its character is usually a land breeze in the temperate latitudes (at night the air over land is colder than over water). In the studied area, the temperature over the open water ocean in comparison to that over land and glaciers is considered, and the first is always higher. An inverse situation with westerly local winds and easterly large-scale winds is fairly uncommon (respectively 6,141 and 4,897 events including 2,486 simultaneous events in both fjords). Local westerly winds occur more often at low velocity. It is usually turbulence at the mountain, where the wind direction is influenced by orography.

On average, 70.5% of Ny-Ålesund land–sea breeze circulation events had a concurrent event in Hornsund, while only 55.4% of Hornsund land–sea breeze circulation events had a concurrent Ny-Ålesund event. Figure 5 shows the probabilities of land–sea breeze circulation events in Ny-Ålesund and Hornsund, as well as simultaneous events for each month of the year. It is visible that land–sea breeze circulation is least probable during summer. Because the temperatures of surface waters in the non-freezing West Spitsbergen Current waters west of the fjords are never higher than approximately 3°C (Walczowski and Piechura, 2011), the difference in temperature between the glaciers in the east and the sea in the west is largely controlled by the surface temperature of glaciers, and therefore it is lowest during summer.

4 | DISCUSSION

If the land–sea breeze circulation events have local causes as suggested by the literature (Marsz et al., 2013), the time series from separated fjords Hornsund and Kongsfjorden should be independent. It is easy to calculate the probability of simultaneous events in the case of independent variables, which is equal to the product of probability for each series. However, the scientific question is more complicated, namely how improbable is the observed number of simultaneous land–sea breeze circulation events if the null hypothesis of the independence of events in both fjords is true. We used a bootstrapping technique (Efron and Tibshirani, 1994) from a Monte Carlo model (code written in ANSI C using the KISS random number generator, cf. Marsaglia and Zaman, 1993) to test the null hypothesis of no correlation between the land–sea breeze circulation events in both fjords by calculating 10,000 random resampled distributions of the land–sea breeze circulation events dates with the observed probabilities for each month of the year. The resultant null hypothesis probability values and standard deviations are shown in Figure 5. The difference in the observed probability of simultaneous land–sea breeze circulation events compared to the null hypothesis probability is between 9 standard deviations (in March) and 16 (in July). Such large values correspond to a rejection of the null hypothesis with probabilities between $p < 10^{-18}$ for March and $p < 10^{-61}$ for July. This result shows that land–sea breeze circulation events are not independent between two fjords placed at opposite ends of Spitsbergen's west coast, indicating that mesoscale thermal-type phenomena are the reason for a large number of land–sea breeze circulation events. Such large-scale wind phenomena should have an influence on air–sea heat fluxes east of Spitsbergen. Also, considering the effect of land–sea breeze circulation on optical properties of the atmosphere, it is appropriate to conclude that this is a mesoscale phenomenon (Cisek et al., 2017b).

In order to check whether large-scale land–sea breeze circulation events are actually driven by the difference in temperature between the glacier covering inland Spitsbergen and the open ocean west of the island, we decided to correlate the simultaneous land–sea breeze circulation event frequencies for each month with the average difference in inland and offshore temperatures for the same months. There is much more data available for sea surface temperatures (SST than for inland Spitsbergen (where the meteorological stations are all coastal ones). However, the in situ data are collected from research vessels mostly in summer, when the land–sea breeze circulation is least frequent and heat fluxes are smallest due to the small difference between air and water temperatures (Piechura et al., 2002). Therefore, they have to be augmented by satellite data. The most recent SST climatology, merging in situ and satellite data, was used. Moreover, the temperature data from 30 stations collected during the 12-month measurement campaign (Przybylak et al., 2014) were applied in the work. We calculated correlations of monthly average temperature differences between the 1-year campaign measurements stations and SST monthly climatology for the $1 \times 1°"pixel"$ closest to the west coast of Spitsbergen (77–78°N, 15–16°E). We chose for the analysis two stations (HT4 and HT9 in Przybylak et al., 2014) on Hans Glacier east of the Hornsund station, two stations (LW1 and LW2) in front and on Waldemar Glacier south of the
Ny-Ålesund station, as well as two stations close to the middle of Spitsbergen: Sveagruve (SVE) in the south-central part of the island at the head of Van Mijenfjorden, and Skotethytta (SKO) near Pyramiden at the foot of the Billefjorden. The stations were chosen for their relevance for the east–west circulation regarding the two stations from which we had wind data, and for the whole of Spitsbergen. We have also downloaded 30-year data from Sveagruva (SVE30) from the eKlima portal of the Norwegian Meteorological Institute for comparison. We found it important to compare the temperature over a larger area of the archipelago, and not just over two stations. This gives a broader picture and shows that differences in temperature occur not only between the water and glacier, but also, and perhaps most importantly, between the ocean and the whole island. This confirms the mesoscale nature of the studied phenomenon.

The monthly differences in temperature between the chosen stations and off-shore SST climatology values are shown in Figure 6. It is visible that the breeze-driven temperature difference is similar to the frequencies of mesoscale land–sea breeze circulation events (Figure 5). The calculated Pearson correlation values between the land–ocean temperature monthly average differences and the frequency of simultaneous land–sea breeze circulation events at both fjords studied (i.e., at both north and south Spitsbergen) are .92 and .93, respectively, for LW1 and LW2 at Waldemar Glacier, .93 for both Hans glacier stations (HT4 and HT9), as well as .94 for Sveagruva (SVE) and .96 for the Pyramiden (SKO) inland stations. All correlations are significant at the $p < 10^{-4}$ level. We used SVE30 data to test the hypothesis that long-term data should have even better correlation values. The result was positive as SVE30 had a correlation of .96. Their $r^2$ values imply that over 80% of inter-monthly variability in the land–sea breeze circulation event frequency can be explained by the difference in temperatures between inland Spitsbergen and the adjacent ocean. Of significance is that for SKO, the only available station close to the centre of the island (as well as for the 30-year data series of Sveagruva, the station in southcentral Spitsbergen), and therefore the best proxies for inland Spitsbergen temperatures, the $r^2$ value implies that over 90% of the inter-monthly variability of Spitsbergen’s mesoscale land–sea breeze circulation frequency is controlled by the land–ocean temperature difference. The statistically significant high correlations also mean a rejection of the alternative hypothesis of channelling effect, which would not be dependent on the thermal forcing of the ocean–land temperature difference.

5 | CONCLUSIONS

We studied the wind circulations of two fjords in the west coast of Spitsbergen Island, separated meridionally by a latitude of two degrees (approximately 200 km). We show that the local winds are largely independent of large-scale circulation direction, with most winds blowing along the main axes of the fjords and the easterly direction preferred for most directions of the large-scale wind field (with the exception of large-scale winds blowing from the opposite direction along the fjord’s main axis). We explain it as breeze-type circulation between the ice-free sea areas of the warm Spitsbergen Current in the west and much colder glaciers in the east. The force inducing air movement due to the temperature difference between the east and west of the studied area occurs all year round because it is mainly caused by the fact that the waters of the West Spitsbergen Current do not freeze and the glaciers are brighter all year.
round (a large albedo) which together with the much larger heat capacity of the ocean creates a constant difference of temperature. Radiation fluxes, both shortwave and longwave, are generally the dominant vertical energy fluxes in the Arctic atmosphere (Porter et al., 2010). In addition to this, the heat is horizontally transferred by the West Spitsbergen Current (Walczowski and Piechura, 2011). Of course, in many situations the wind caused by this difference can be unrecorded, because the large-scale pressure structure and the pressure gradients occurring in it can mask this mesoscale effect. Furthermore, especially in summer, there may be induced smaller-scale movements related to the terrain and orography, such as, for example, katabatic wind from single glaciers or winds caused by the temperature difference between a part of land and sea. In Spitsbergen, the surface on the land is heated by its exposure (slope) to the sun. Many parts of land can heat up in a completely different cycle than the daily cycle of temperate latitudes. The lowest probability of land–sea breeze circulation events during summer, when this difference in temperature is smallest, supports this interpretation which is largest in winter when an opposite situation is the case. A Monte Carlo analysis of land–sea breeze circulation probabilities rejects the null hypothesis of independent land–sea breeze circulation events in both fjords. The correlation coefficient between the simultaneous land–sea breeze circulation event frequency and sea–land temperature difference explains over 80% of the frequency variability on monthly timescales (over 90% for land temperatures near the centre of the island). Therefore, we posit that land–sea breeze circulation occurrence is largely controlled by the synoptic situation. This large-scale phenomena mean they may have an impact on air–sea fluxes off the Spitsbergen coast in the region of the West Spitsbergen Current. This will be the subject of a future study.

However, we do not claim that there are no other factors of smaller than mesoscale range influencing circulation in the studied area. Based on the analysis of atmospheric kinetic energy spectra (Nastrom and Gage, 1985; Skamarock, 2004), it is known that there is the large-scale $k^{-5/3}$ dependence found in the mesoscale (tens of kilometres length) and smaller scales. So between mesoscale processes and turbulence there is a lot of circulation on different scales. The present work is not dedicated to the analysis of air movement on a whole scale, but to one phenomenon that is characteristic for the entire island and that is the temperature difference.

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CONFLICT OF INTEREST
The authors declare no potential conflict of interest.

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