Wind Field Climatology, Changes, and Extremes in the Chukchi–Beaufort Seas and Alaska North Slope during 1979–2009

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ABSTRACT

Wind field climatology, changes, and extremes at ~32-km resolution were analyzed for the Chukchi–Beaufort Seas and Alaska North Slope region using 3-hourly North American Regional Reanalysis (NARR) from 1979 to 2009. The monthly average wind speeds show a clear seasonal cycle with a minimum of 2–4 m s\(^{-1}\) in May and a maximum up to 9 m s\(^{-1}\) in October. The 95th percentile winds show a similar seasonality with a maximum up to 15 m s\(^{-1}\) in October. The 31-yr domain averaged 3-hourly wind speeds display a clear diurnal cycle over land and sea ice areas during the warm seasons. Weaker radiation during winter and larger heat capacity over open water reduce the diurnal signal in the wind field diurnal variations. There were increasing trends of areal averaged monthly mean and 95th percentile wind speeds for July through November. The strongest increase in the areal averaged 95th percentile wind speeds occurred in October from 7 m s\(^{-1}\) in 1979 to 10.5 m s\(^{-1}\) in 2009. The frequency of extreme wind events (speed above the 95th percentile winds) shows an increasing trend in all months, with the greatest increase occurring in October, showing 8% more extreme wind events in 2009 comparing to 1979. The prevailing wind direction was northeast with a frequency of 40%–60% for most of the year. The frequency for southwest and northwest winds was small (<20%) except for two anomalous areas along the Brooks Range in Alaska and the Chukotka Mountains in easternmost Russia where the frequency has increased to 35%–50% during the cold season months.

1. Introduction

The Chukchi–Beaufort Seas and the adjacent continental region (Fig. 1) is a prominent geographical feature, which is largely covered by sea ice on a seasonal basis over the ocean and bounded by the Brooks Range in the south on land. The complex orographic dynamics and seasonally changed surface conditions significantly complicate the mesoscale weather systems and the associated surface winds (Kozo 1979, 1980; Lynch et al. 2003, 2004). In addition, substantial environmental changes have occurred in the Arctic over the past several decades, including an increased storm invasion (e.g., Zhang et al. 2004), a large fluctuation in the surface pressure pattern (e.g., Thompson and Wallace 1998; Overland et al. 2008; Zhang et al. 2008), a conspicuous warming of surface air and ocean water temperatures (e.g., Comiso 2006; Shimada et al. 2006), and a drastic retreat of sea ice (e.g., Comiso et al. 2008; Polyakov et al. 2012). These great changes and variability in the Arctic sea ice, atmosphere, and ocean will definitely further complicate the atmospheric circulation and associated wind field in the Chukchi–Beaufort Seas region. Significant modeling and data analysis efforts have been inspired to better represent, understand, and predict these changes (e.g., Bromwich et al. 2009, 2010; Zhang and Zhang 2010; Cassano et al. 2011).

Meanwhile ongoing oil development in the Chukchi–Beaufort Seas is always potentially accompanied by the threat of oil spills. As the recent event in the Gulf of Mexico has unfortunately demonstrated, such spills can
have an extraordinary impact on the sensitive ecosystems in surrounding regions. In the event of such a spill, timing is of the essence in direct mitigation, cleanup, and recovery efforts, and thus improving the prediction of oil spill transport is of great importance to all concerned. As the surface wind field is the primary factor in driving upper ocean currents, and thus the dispersal of oil spills, understanding and accurately modeling the region’s surface winds is essential in assessing and enhancing the prediction of oil spill transport.

High wind events at Barrow along the northern coast of Alaska have been extensively studied by Lynch et al. (2003, 2004) and it is reported that the strong sustained winds of 25 m s\(^{-1}\) occurred at Barrow, Alaska, on 3–5 October 1963 and 10–11 August 2000. How often did the extreme wind events like this occur in the Chukchi–Beaufort Seas and the Alaska North Slope? What are the climatological features of the surface wind field in this area? All of these have not been well documented, and are essential information for accurate oil spill transport assessment and modeling. This study will describe the wind field climatology and analyze wind extremes for the Chukchi–Beaufort Seas and the Alaska North Slope region with a long-term reanalysis data. The data we used for this study and the analysis methodology are described in section 2. Section 3 compares the reanalysis winds with the in situ measurements for the study area. Then the wind speed and direction climatology are analyzed in sections 4 and 5. Finally a summary of this study is given in section 6.

2. Data and methodology

The data we used for this study are the 3-hourly, 10-m surface winds and sea level pressure from North American Regional Reanalysis (NARR; Mesinger et al. 2006) at ~32-km resolution for the 31-yr period of 1979–2009. First the monthly average, maximum, and 95th percentile wind speeds were calculated at each NARR grid point for the study area covering the Chukchi–Beaufort Seas, the Alaska North Slope, and the adjacent Brooks Range, as well as northwestern Yukon and easternmost Russia. The monthly average wind speeds were calculated by averaging all the 3-hourly NARR surface winds for each month for the 31-yr period. The monthly maximum wind speeds were determined by selecting the maximum wind speed from the 3-hourly NARR winds for each month over the 31-yr period. The monthly 95th percentile winds were determined by sorting the 3-h NARR winds over the 31-yr period from the lowest to highest for each month and then locating the 95th percentile values.

The trends of monthly average and 95th percentile wind speeds for the entire 31-yr period were also analyzed with linear regression coefficients, in which a positive value indicates an increase in wind speed and a negative value represents a decrease over the 31-yr period. To investigate the variations of extreme wind events we define the extreme wind event as a wind speed greater than the monthly 95th percentile wind speed over the entire 31-yr period. Then the occurrence frequency of the extreme wind events expressed as a percentage is calculated over a time period. The 31-yr domain averaged 3-hourly winds were calculated to represent the diurnal variation of wind speeds on each day of the month. The calculations were broken into land-only and ocean-only areas so that the diurnal cycles between the land and ocean winds can be compared.

For the wind direction climatology, we first divided all the directions into quadrants between 0° and 90° representing the winds from the north-northeast (NNE), northeast (NE), and east-northeast (ENE); 90°–180° from the east-southeast (ESE), southeast (SE), and south-southeast (SSE); 180°–270° from the south-southwest (SSW), southwest (SW), and west-southwest (WSW); and 270°–360° from the west-northwest (WNW), northwest (NW), and north-northwest (NNW). Then the monthly frequency of wind directions in each quadrant was calculated for each month for the 31-yr period.
3. Comparison of NARR surface winds with observations

A comparison of the NARR reanalysis surface winds with the in situ measurements was conducted. A total of 194 surface stations data were collected from different data networks including the National Climatic Data Center (NCDC; 103 stations), Remote Automated Weather Stations (RAWS; 32 stations), Water Environmental Research Center (WERC) at the University of Alaska Fairbanks (UAF; 28 stations), Bureau of Ocean Energy Management, Regulation, and Enforcement (BOEMRE; previously Minerals Management Service; 5 stations), the Atmospheric Radiation Measurement (ARM) network (2 stations), the National Data Buoy Center Coastal-Marine Automated Network (C-MAN) program (2 stations), the industry well sites and coastal measurements, and some short-term offshore measurements by UAF and Shell company (22 stations). All of these collected data have been quality controlled with three quality control (QC) procedures (Shulski and You 2011). These procedures check for instances of an observation falling outside of the normal range, consecutive values that have too large of a difference, and instances of too high or too low variability in the observations. Criteria for the quality control were defined based on a stations' climatology.

The NARR reanalysis winds were interpolated to the locations of these stations for a direct comparison with the observational data. The Taylor diagram (Taylor 2001) was first used for this evaluation analysis (Fig. 2). Standard deviation of the reanalysis wind direction was calculated based on wind persistence following Farrugia and Micallef (2006) and then normalized by the observed value. The correlation of wind direction was calculated following the method introduced by Crosby et al. (1993) in which the wind vector correlation was calculated with a formula in terms of the orthogonal components of two vectors. The data were grouped into inland and coastal stations (Fig. 2a) and four seasons (March–May for spring, June–August for summer, September–November for autumn, and December–February for winter) (Fig. 2b). The coastal stations are those where measurements were taken offshore or onshore but within a distance of 30 km from shoreline. The inland stations include those where measurements were taken onshore 30 km away from shoreline. In total there are 59 coastal stations and 81 inland stations available in this comparison analysis when the data requirement is applied that the number of valid hourly measurements within each month be larger than 360 for the 30-yr study period.

The NARR reanalysis winds show a better correlation with the coastal observations. The averaged correlation coefficients are 0.71 for direction and 0.66 for wind speed along the coast, and 0.57 for direction and 0.58 for wind speed inland (Fig. 2a). The normalized standard deviations of the NARR wind direction are as high as 0.97 along the coast and 0.98 inland (Fig. 2a), suggesting that the variance pattern of NARR wind direction is very close to the observed one. The variance of NARR wind speed is slightly off from the observed pattern. The normalized standard deviations of the NARR wind speed are 0.88 inland and 0.85 along the coast.

In terms of the performance of NARR winds in each season, it is shown that the variance patterns of summer and autumn winds are closer to the observations than the winter and spring winds, especially for wind speed (Fig. 2b). The correlation between the reanalysis and the observed winds does not vary very much across each season, although a better correlation occurs in autumn with a correlation coefficients of 0.73 for wind speed and 0.63 for wind direction. Overall the NARR winds have a reasonable agreement with the in situ observations for the study area, especially over the coastal region, which can be further shown from the geographical distribution of wind vector correlation between the NARR reanalysis and the observation (Fig. 2c). To have an estimate of the reanalysis error for the offshore area, all the collected offshore observations regardless of the length of the measurement period, at a total of 22 stations, were also included in this analysis as shown by the cross in Fig. 2c. The correlations are generally better alongshore and offshore than inland. It is also noticeable that the NARR winds have a relatively poor correlation with the observations at some stations. The correlations for a total of 13 stations are smaller than 0.5; among them are 9 stations from the WERC network. When applying the QC procedures to all the collected observations, it has been found that the flagged number of questionable data is the highest in the WERC data (Shulski and You 2011). More strict QC procedures can be applied to the observational data, but this can significantly limit the quantity of valid data (Shulski and You 2011). The wind speed bias analysis (Fig. 2d) shows that the NARR reanalysis tends to have negative biases alongshore and offshore and positive biases inland. The positive bias inland can be attributed to the coarse resolution in NARR.

4. Wind speed climatology, changes, and extremes

a. Seasonal and diurnal variations

Monthly average wind speeds in the study area demonstrate a clear seasonal cycle (Fig. 3). The minimum wind speeds occur in May and June at \( \sim 2.5-4 \text{ m s}^{-1} \). Then the wind speeds in the Chukchi Sea begin to increase steadily and reach 5–6 m s\(^{-1}\) in July; however,
FIG. 2. Taylor diagram of wind speed (cross) and direction (dots) variances and correlations between (a) NARR reanalysis winds and station measurements for land (blue) and coast stations and (b) four seasons of spring (green), summer (red), autumn (orange), and winter (blue). Wind vector correlation between (c) NARR reanalysis and station observations and (d) NARR wind speed biases (m s\(^{-1}\)). Dots represent onshore stations and crosscrosses offshore station.
the winds in the Beaufort Sea do not change very much
from May to July. In August the maximum speeds in
the Chukchi Sea basically keep the same as in July but
the 5–6 m s\(^{-1}\) isotachs cover a much larger area. On
the other hand, the winds in the Beaufort Sea begin to in-
crease by about 1 m s\(^{-1}\) in August. The wind speeds
reach a maximum of \(\sim9\) m s\(^{-1}\) in the Chukchi Sea in
October and \(\sim6\) m s\(^{-1}\) in the Beaufort Sea in September.
The isotachs in the Chukchi Sea have a maximum at the
center of the Chukchi Sea. Starting in November, the
winds begin to decrease, becoming less than 4 m s\(^{-1}\) in
the Beaufort Sea and around 5 m s\(^{-1}\) in the Chukchi Sea
in December. Overall the seasonal variation of wind
speed in the Chukchi Sea is much stronger than in the
Beaufort Sea. The wind speed annual ranges are about
6 m s\(^{-1}\) in the Chukchi Sea and 3 m s\(^{-1}\) in the Beaufort
Sea. The wind speed in the North Slope has relatively
small seasonal variation except that a greater wind of
\(\sim6\) m s\(^{-1}\) occurs over the Brooks Range during the
winter months. When the monthly mean contours of 50%
sea ice concentration (purple curves in Fig. 3) are overlaid
on the monthly wind speeds, they show a clear synchro-
nized behavior between the poleward retreat of sea ice
extent and poleward shift of the maximum winds.

The maximum and 95th percentile wind speeds over
the 31-yr period were also analyzed for each month to
investigate the seasonal extreme wind field features in
the study area. A similar seasonality as seen in the
monthly average wind was found, with strong winds in
fall and calm winds in spring (not shown). The monthly
maximum wind speeds over the 31-yr period for the entire study area are 8–11 m s\(^{-1}\) in May and 18–28 m s\(^{-1}\)
in October. The 95th percentile wind speeds are around
5–7 m s\(^{-1}\) in May and then increase to 9–11 m s\(^{-1}\) in
July in the Chukchi Sea and show little change in the
Beaufort Sea. In September and October, the 95th
percentile winds reach maximum values of 10–15 m s\(^{-1}\)
over the study area.

To illustrate the systematic distribution of the entire
domain winds, we also conducted a seasonal probability
analysis for the 31-yr period (Fig. 4). The monthly
probability density function (PDF) (Fig. 4a) and cu-
mulative distribution function (CDF) (Fig. 4b) of the
entire domain winds show that the chance of wind
speeds between 2 and 5 m s\(^{-1}\) dominates the study area
by about 60% (CDF 80% around 5 m s\(^{-1}\) minus CDF
20% around 2 m s\(^{-1}\)). These 2–5 m s\(^{-1}\) wind speeds do
occur the most for every month, but the probability
during the early summer months (May and June) is
greater than during the autumn months (September and
October) by about 20% (CDF 90% in June minus CDF
70% in September around 5 m s\(^{-1}\)). The monthly

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**FIG. 3.** Monthly mean wind speed (color; m s\(^{-1}\)) and 50% sea ice concentration (purple curves) during 1979–2009.
The probability of relatively strong winds (>5 m s\(^{-1}\)) demonstrates a completely opposite distribution where the greater winds occur more frequently in autumn than the early summer. For instance, winds greater than 5 m s\(^{-1}\) occur in September and October with a frequency of 30% (CDF 100% around 12 m s\(^{-1}\) minus CDF 70% around 5 m s\(^{-1}\)), but only about 10% (CDF 100% around 12 m s\(^{-1}\) minus CDF 90% around 5 m s\(^{-1}\)) in May and June. The seasonal variability of domain winds' PDF and CDF is consistent with the seasonal wind speed climatology in the study area.

The 31-yr domain averaged 3-hourly winds on each day of the month show a clear diurnal cycle over land during the warm seasons (April–September) and over ocean during spring (mid-March–May) (Fig. 5). The diurnal cycle of the land winds, with the strongest variations in June and July, is obviously attributable to the strong diurnal solar radiation forcing and small land heat capacity, which gives rise to more stable conditions and low wind speeds around midnight and more unstable conditions and higher wind speeds around noon. In winter the weak radiation forcing and the associated cold surface condition tend to create a very stable boundary layer; thus, the changes in surface wind speeds should be largely influenced by the weather system. Note that the ocean in the study area is covered by sea ice seasonally. The sea ice–covered Chukchi–Beaufort Seas have more continentality and thus a lower heat capacity compared to the open water. As a result, the diurnal cycle of sea ice surface thermal properties are closer to that of the land rather than the ocean; the sea ice surface winds show a diurnal variation during mid-March to May when the solar radiation forcing is getting greater day by day. The diurnal signal is negligible in the open ocean surface winds due to a large water heat capacity.

b. Long-term trend

Domain-averaged monthly mean and 95th percentile wind speeds were calculated for each month in each year. A pronounced increasing trend exists from July through November during the entire 31-yr period although the upward trend occurred throughout the year at a significance level of 95% through an \(F\) test (Fig. 6a). The largest increase for the monthly average and 95th percentile winds all occurs in October, in which the average winds increase from \(\sim 4.0\) m s\(^{-1}\) in 1979 to \(\sim 5.5\) m s\(^{-1}\) in 2009 and the 95th percentile winds from \(\sim 7\) m s\(^{-1}\) in 1979 to \(\sim 10.5\) m s\(^{-1}\) in 2009.

It has been well understood that the sea ice extent over the Chukchi–Beaufort Seas demonstrates a drastic decreasing trend and a large variance of variability (e.g., Comiso et al. 2008). Changes in sea ice and its associated upper ocean thermal and kinematic conditions (e.g., air temperature gradient and surface roughness) may alter the overlying atmospheric circulation and weather to impact winds. This encourages us to investigate how sea ice and surface wind are related. The correlation coefficients between the monthly mean sea ice extents and monthly mean wind speeds over the study area show a strong negative correlation during the months of July–December with a 95% confidence level as summarized in Table 1. The correlation between sea ice extent and wind speed during January–June is much weaker and not significant.

Monthly linear trend distributions were analyzed with the linear regression coefficients of monthly wind speeds at each grid point of the study area (Fig. 6b) and it is shown that the wind speeds in the Chukchi–Beaufort Seas generally have an increase trend from July through November over the entire 31-yr period. The strongest increase, which is as high as 0.7 m s\(^{-1}\) decade\(^{-1}\), occurs in the northern Chukchi Sea and eastern Beaufort Sea. However, a relatively strong decreasing trend also exists around the southern Chukchi Sea region in September.
and along the Beaufort Coast in November. That increasing trend in the northern Chukchi Sea concurs with decreasing trend in the southern Chukchi Sea seems to correspond with the poleward shift of northern Pacific storm track (Zhang et al. 2004), which deserves further investigation. A comparison of decadal probability density function of the entire domain winds further provides an insight into how the wind spectra change during three decades of 1980–89, 1990–99, and 2000–09. An obvious shift of wind speed PDF pattern occurs in the most recent decade especially during the autumn months: reduced density in calm winds (around 3 m s$^{-1}$) and enhanced density in strong winds (>6 m s$^{-1}$). The PDF patterns between the first two decades of 1980–89 and 1990–99 are very close (Fig. 6c).

We defined the frequency of extreme wind events as the occurrence of wind speeds greater than the 95th percentile winds for the study period. In detail, the frequency is calculated as a percentage of the counting number of wind speeds greater than the 95th percentile winds divided by the total number of available data for a given period. Once this is calculated at each grid point of the study domain, the domain averaged frequency of extreme wind events is taken for each month in each year. The increasing trend in the frequency of extreme wind events occurs almost every month (black lines in Fig. 7a), unlike the increasing trend in wind speeds, which mainly occurs from July through November (Fig. 6a). A relatively large frequency increase (>5%) occurs in fall [September–November (SON)], when the sea ice extent in the study area reaches a minimum and also shows the strongest decreasing trend during the 31-yr study period (not shown). Possibly the widely opened water provides energy to force more frequent extreme wind events. With more open water there would be more sensible and latent heat fluxes release into the atmosphere from ocean, which can further destabilize the atmosphere and enhance low-level baroclinicity (Businger and Baik 1991). Synoptic weather systems and the associated surface winds can be further strengthened because of increased baroclinic instability in atmosphere. Again we see the greatest frequency increase in October, when we have 8% more extreme wind events in 2009 comparing to 1979.

The strongest frequency increase of extreme wind events in October concurs with the strongest increase of
wind speeds (both monthly mean and 95th percentile winds) in October (Fig. 6a). It is noticeable that the frequency of extreme wind events is relatively high during most months of 2006 and 2007. Thus a question arises naturally: How much of the increasing trend is due primarily to the high values in 2006 and 2007? We conducted two more trend analyses, one (red line of Fig. 7a) excluding 2007 and the other (blue line of Fig. 7a) excluding both 2006 and 2007; that is, the frequency values for the excluded years were set to missing values and the trend was recalculated. The increasing trend still exists during most months although the rate of increasing trends decreases. The strongest increase still happens in October with more than 4% more extreme wind events in 2009 comparing to 1979 when both 2006 and 2007 were excluded.

We further investigated the frequency distributions of extreme wind events that occurred in the autumn months of September to November for three decades of 1980–89, 1990–99, and 2000–09.

**TABLE 1.** Correlation coefficients between monthly mean sea ice extents and monthly mean surface winds during July–December with 95% significant level.

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<td>-0.76</td>
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<td>-0.85</td>
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**FIG. 6.** (a) Domain averaged monthly (July–November) mean (blue) and 95th percentile (red) wind speeds from 1979 to 2009. (b) The monthly (July–November) linear trend distributions during 1979–2009. (c) PDF of October winds during three decades of 1980–89, 1990–99, and 2000–09.
1980–89, 1990–99, and 2000–09, which gives us some insight into how the frequency of the extreme wind events varies by decade and where the extreme wind events are increasing or decreasing (Fig. 7b). Over most study areas, the frequency of extreme wind events increases with time. The frequency was less than 2% over the northern Chukchi Sea and western Beaufort Sea during the first decade (1980–89), then increased to 4%–7% during the second decade (1990–99) and reached 10% and higher in the third decade (2000–09). On the other hand, the frequency of extreme wind events over the southern Chukchi Sea, northern Bering Strait, and the North Slope does not change much from the first decade to the third decade. Obviously the distribution of frequency increase (Fig. 7b) is basically consistent with that of the long-term trend (Fig. 6b), suggesting that the increase of wind speed is accompanied by more frequent extreme wind events.

5. Wind direction climatology and mesoscale structures

a. Seasonal variation

The monthly frequency of wind directions in four quadrants of northeast (0°–90°), southeast (90°–180°), southwest (180°–270°), and northwest (270°–360°) during the entire 31-yr period depicts a seasonal variation. The northeast quadrant (NEQ) represents winds approximately from the NNE, NE, and ENE; the southeast quadrant (SEQ) from the ESE, SE, and SSE; the southwest quadrant (SWQ) from the SSW, SW, and WSW; and the northwest quadrant (NWQ) from the WNW, NW, and NNW. The prevailing wind direction in the Chukchi–Beaufort Seas and the North Slope is from NEQ with a frequency around 40%–60% during most of the year (Fig. 8), although the area under the NEQ winds is much greater during the cold season months (October–May). The frequency of 60% or higher of the NEQ winds is along the Arctic coast. This persistent NEQ winds are mainly controlled by the Beaufort high located in the area almost year round, although with the greatest strength in March and least in August (Fig. 9).

Starting in June, the areal extent of NEQ winds quickly shrinks to the coast region and the frequency begins to decrease in July and reaches minima in August. From October, the areal extent of NEQ winds begins to expand again. The seasonality in the frequency and areal extent of NEQ winds are consistent with the temporal evolution of the Beaufort high as described by Overland (2009). The 30-yr monthly mean sea level
pressure with the NARR reanalysis over the study area (Fig. 9) demonstrates that the Beaufort high reaches its peak strength in spring with a center located over the northern Chukchi Sea. Then the Beaufort high weakens through the summer months and moves eastward to the eastern Beaufort Sea. During the winter months, the Beaufort high begins to intensify and moves westward. On the other hand, it should be also noticed that the low system Aleutian low over the southern study area also displays a clear seasonal variability, peak in fall and flat in spring.

The frequency of wind directions from the other three quadrants (SEQ, SWQ, and NWQ) in the Chukchi–Beaufort Seas and North Slope is relatively low except for some areas characterized by mesoscale features, which will be discussed in section 5b. For the whole year the frequency of SEQ winds is around 10%–20% with little seasonal variation (not shown). The NWQ winds mainly occur over the northeast corner of study domain (the Canadian Arctic Archipelago area) during the cold season months (November–March) with a frequency around 30%–50%, due to the presence of the Beaufort high to the west of the Canadian Arctic Archipelago. The frequency of SWQ winds is less than 20% during most of the year except June through September, when an area with enhanced frequency (30%–40%) occurs to the north of the Chukchi–Beaufort Seas. The weakening of the Beaufort high during these months results in less NEQ winds, and then more SWQ winds occur due to the low system from south (Fig. 9). Similarly, the frequency of wind direction for the extreme winds (wind speeds at or above the 95th percentile wind speed) in each quadrant was also calculated (not shown). The persistence of the NEQ winds is also seen in the extreme wind events. Overall more than 60% of the frequency of extreme winds is from NEQ direction for most of the study domain except for the eastern domain, where the highest frequency (>40%) of extreme winds is from the NWQ direction.

Similarly to the wind speed trend analysis, the frequency of wind directions from each quadrant (NEQ, SEQ, SWQ, and NWQ) was calculated and averaged for the entire study domain in each year and the linear trend was analyzed (Fig. 10). A noticeable decreasing trend is seen in the NEQ winds and increasing trend in the SEQ winds. The trends in the NWQ and SWQ winds are flat. The strongest decreasing trend in the NEQ winds (~10% less in 2009 compared to 1979) occurs in January and November. A relatively strong increasing trend in the SEQ winds occurs in spring and fall. In particular, there are ~5% more SEQ winds in 2009 compared to 1979 during April and ~8% more during
September. The frequency change of wind directions is probably the result of synoptic weather system changes, including strength and location movement, which is worth further investigation.

b. Mesoscale features

The study area features the Brooks Range in Alaska and the Chukotka Mountains in easternmost Russia. The mountain dynamic modification of airflow could leave significant mesoscale fingerprints in the mountainous wind field. The Froude number is a dimensionless number defined to describe the flow pattern over an obstacle (such as a mountain barrier) and calculated as the ratio of kinetic energy (proportional to squared wind speed) to potential energy (proportional to stability times mountain height). Thus, a Froude number smaller than the unit implies that the airflow is blocked from flowing over a mountain range because of either too high mountain elevation or too stable air. The Arctic airflow in our study domain is usually very stable, especially during the cold season months. When the stably stratified airflow approaches toward a mountain barrier, the Froude number of the airflow is relatively small, which suggests that the flow cannot go over the mountain and will be blocked. Then the airflow on the windward slope will slow down, and the original balance between synoptic pressure gradient force (PGF) and the decreased Coriolis force (due to decreased wind flow) will be upset. As a result a mountain barrier flow is generated to the low pressure of the synoptic system due to relatively large synoptic PGF. The flow is parallel to the longitudinal axis of mountain and the Coriolis force then acts on it to generate a component directed toward the mountain. However, the flow cannot easily surmount

Fig. 10. Monthly frequency of wind directions in each quadrant of NEQ, SEQ, SWQ, and NWQ and the linear trend during 1979 to 2009.
the mountain and eventually a region of mesoscale ridging against the mountain slope becomes established, and then the tendency for the Coriolis force to turn the flow toward the mountains will be balanced by the localized mesoscale pressure gradient force (Bell and Bosart 1988; O’Connor et al. 1994; Harden et al. 2011). Thus as Bell and Bosart (1988) discussed, mountain barrier flow is a topographically induced, mesoscale form of geostrophic balance, but not in geostrophic balance with the synoptic-scale pressure gradient field.

As discussed in section 5a, the dominant winds in the study area are from NEQ, especially during the cold season months. When the stably stratified NEQ winds, particularly the NNE winds, approach the Brooks Range, the wind component perpendicular to the east-northeast- to west-oriented mountain range is deflected and an SWQ mountain barrier wind will be set up. A similarly mountain barrier effect occurs along the Chukotka Mountains: when the stable NEQ winds approach the northwest- to southeast-oriented Chukotka Mountains, a NWQ mountain barrier wind is formed. This cyclonic deflection of wind direction along the other mountain ranges has also been extensively investigated (e.g., Parish 1983; O’Connor et al. 1994). The mountain barriers winds are well depicted in the occurrence frequency of the SWQ and NWQ winds during the entire cold season months (October–May) (Fig. 11). Over the whole study area, the frequency of SWQ and NWQ winds is relatively small (<20%) except for two anomalous areas along the Brooks Range and Chukotka Mountains, where the occurrence frequency around 35%-50% occurs for the SWQ and NWQ winds, respectively. It is also obvious that the frequency and area of SWQ winds along the Brooks Range are much smaller than for the NWQ winds along the Chukotka Mountains, which is due to the orientation of these two mountain systems and the prevailing wind directions. Because of the orientation of the mountain systems, only the NNE winds can be potentially deflected by the Brooks Range, and the NNE, NE, and ENE winds can all be potentially deflected by the Chukotka Mountains.

Not only do the wind speeds have a diurnal cycle as shown in Fig. 5, the wind directions also demonstrate a diurnal variation due to the mesoscale sea breeze and mountain valley breeze effects during the warm seasons whenever the land surface is snow free. Figure 12 depicts these mesoscale breezes with the differences of long-term averaged wind fields between the warmer hours [0900, 1500, and 2100 local time (LT)] and the early morning hour of 0300 LT for July. Mountain valley breeze along the Brooks Range starts as early as 0900 LT because of the polar day phenomena (24 h of daylight) in the study area (Fig. 12a). As the land surface and mountain slope continue to warm because of stronger solar radiation, the valley breezes are further enhanced and a well-developed sea breeze is also present along the coast at 1500 LT (Fig. 12b). It should be emphasized that whenever a cross-shore wind begins to blow from north due to the land–sea (ice) thermal contrast, the relatively large Coriolis effect at high latitudes will generate an east wind component. The stronger the cross-shore wind, the greater the east wind component. As a result, northeast sea breezes are present along the coast. Because of the polar day phenomena, the sea breeze can continue to the late evening at 2100 LT (Fig. 12c).

6. Summary

The wind field climatology for the Chukchi–Beaufort Seas and Alaska North Slope region was analyzed with
the 3-hourly North American Regional Reanalysis (NARR) for the period of 1979–2009. The result indicates that the wind speeds in the study area have a clear seasonal variability. The relatively calm seasons are in spring and early summer. Wind speeds over the Chukchi–Beaufort Seas gradually increase while the sea ice retreats back to the Arctic from summer to autumn. The strength of winds over the Chukchi–Beaufort Seas reaches to the maxima of 6–9 m s\(^{-1}\) for monthly average winds and 10–15 m s\(^{-1}\) for monthly 95th percentile winds in autumn (September–October). Wind speeds over land show a much weaker seasonality. The seasonal amplitude of wind speed over the Chukchi Sea wind is around 6 m s\(^{-1}\), which is a double of the amplitude (3 m s\(^{-1}\)) over the Beaufort Sea. The analysis of monthly probability density function (PDF) of the entire domain winds shows a consistent seasonality of more calm winds in spring and greater frequency of strong winds in autumn.

A diurnal variability of wind speed exists over land and sea ice-covered areas during the warm seasons. The warm season’s strong diurnal solar radiation forcing plus relatively small heat capacity over land and sea ice contribute to the diurnal variations. Once the sea ice retreats significantly, the large water heat capacity dampens the diurnal fluctuation of winds over the open water. The diurnal cycle over the land area lasts for six months from April to September with the maximum cycle amplitude in June and July. The diurnal cycle over sea ice lasts only 2.5 months from mid-March to May.

The 31-yr surface wind speed displays an increasing trend for both monthly mean and 95th percentile wind speeds from July through November. The strongest increase of monthly extreme winds (i.e., the 95th percentile wind speeds) occurs in October from 7 m s\(^{-1}\) in 1979 to 10.5 m s\(^{-1}\) in 2009. The frequency of extreme wind events (i.e., occurrence of wind speeds above the 95th percentile winds) also shows an increasing trend and the greatest frequency increase occurs in October again, 8% more extreme wind events in 2009 comparing to 1979. Apparently the study area has a phenomenon of the “October Gale,” with the greatest wind, the highest frequency of strong wind occurrence, and the strongest increasing trend all occurring in October. The northern study area is controlled by the Beaufort high during most of the year and the strength of the Beaufort high varies with season (Fig. 9). On the other hand, the southern part of the study area is under the influence of the Aleutian low, which also displays a seasonal variability (Fig. 9). In October, the Beaufort high begins to strengthen as well as the Aleutian low (Fig. 9). These pressure patterns set up a strong pressure gradient over the study area and as a result the October Gale occurs. The significant retreat of sea ice in the study area during the most recent decade (e.g., Comiso et al. 2008; Polyakov et al. 2012) most likely contributes to the strong increasing trend in both wind speeds and frequency of extreme wind events. The wind direction climatology shows that the prevailing wind in the study area is from northeast with a frequency 40%–60% for most months, which is attributed to the dominant Beaufort high. Because of seasonal variations in the position and strength of the Beaufort high, the areal
extent of the NE wind changes. The frequency of southwest and northwest winds is low (<20%) except for two anomalous areas along the Brooks Range in Alaska and the Chukotka Mountains in easternmost Russia where the frequency increases to 35%–50% during the cold season months. The extremely stable airflow plus the mountain barrier effect causes these mesoscale features in the wind direction climatology. During the warm seasons whenever the land surface is snow free, the mesoscale sea/valley breezes develop along the coast and mountain range, impacting the area’s wind field feature on a diurnal basis. The frequency analysis of wind directions from each quadrant (NEQ, SEQ, SWQ, and NWQ) shows a decreasing trend in the NEQ winds and an increasing trend in the SEQ winds, indicating that the synoptic weather systems in the study area are changing, including the strength and location movements.

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