Geo-Mar Lett (2005) 25: 98–109
DOI 10.1007/s00367-004-0191-0

ORIGINAL

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Observed storminess patterns and trends in the circum-Arctic coastal regime

Received: 5 December 2003 / Accepted: 29 April 2004 / Published online: 4 June 2005

Abstract Storm event statistics for the open-water season (June–October) were extracted from the terrestrial-based observational record throughout the circumpolar coastal regime over the period 1950–2000. The Barents/Norwegian and Kara regions exhibited an active spring/quiet summer signature typical of the mid-latitudes. The Kara and Laptev Sea regions had a strong June peak possibly associated with early sea ice breakup. The Chukchi sector exhibited large storm power values (defined as speed^2*duration). Storm counts declined from 1950 to 1970, shifted rapidly from 1970 to 1974 to a level of greater mean activity and greater inter-annual variability, and declined after 1988.

Introduction

Coastal regions are particularly sensitive to the impact of high magnitude weather events. These areas receive storm energy in a concentrated form, due to a transfer of momentum from wind to water, which focuses the wind energy into waves, delivering it more effectively into the coastal zone. In addition to waves, surges in water level that can accompany storms are also an important issue because they allow wave action to reach higher coastal elevations and thus into areas that are at other times inaccessible, and they can inundate lower lying areas (e.g. Solomon et al. 1994; Harper et al. 1988). Impacts from storm activity are varied. Storm-induced wave action can have significant geomorphological, infrastructure, and ecological impacts. Surges can have significant ecological impacts in low-lying areas. Reimnitz and Maurer (1979) reported that, for example, as a result of a significant surge caused by a large storm in the fall of 1970, all vegetation in the surge zone (i.e. up to 5,000 m inland) was killed. Surges can potentially affect infrastructure because the strength of positive buoyancy of wooden or hollow objects and structures can introduce a virtually irresistible strain. For example, Hume and Schalk (1967) provide a detailed description of the severe infrastructure damage at Barrow, Alaska, resulting from a storm occurring in October of 1963.

In sedimentological terms the ocean is able to move potentially large quantities of material both to and from the coastal zone, i.e. accretionary and erosional coasts (e.g. Grigoriev et al. 2002; Hume and Schalk 1967), with the net result that a given coastline can undergo significant change on an annual basis. In fact, a number of researchers report that most geomorphological work done to a coast occurs during significant events, i.e. the mean background rate is relatively low (Reimnitz and Maurer 1979). Solomon et al. (1994) report that as much as 3+m of shore retreat was observed in the Tuktoyaktuk region in less than a 3 day period during each of two separate storm events in 1970 and 1985.

In the polar regions, the impact of storms is moderated by the presence of ice and the variety of forms it can take. The presence of sea ice at high concentrations will reduce wind fetch and thus limit the potential impact of a storm. At lower concentrations, sea ice can dampen wave action. However, sea ice can also increase storm impact by the action of ice floes driven ashore. This includes a mechanical erosive capacity on the shoreface as well as their ability to scour the sea floor, which can increase the amount of sediment in suspension, making it available for removal or redistribution (Reimnitz and Maurer 1979). The presence of ground ice, and the

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forms it can assume, must also be considered. A terrestrial ice-rich zone is thermally stressed by relatively warm water or air, which causes melting and an associated loss of structure (Are et al. 2004; Vasiliev et al. 2003). This can increase the amount of material available for removal. Some ice structures by their inherent morphology possess natural failure planes, such that when the ice melts, various types of rapid mass-wasting failures are possible (Vasiliev et al. 2003). For example, the melting of ice-wedges, combined with thermal notching (cliff undercutting by wave action), can result in the failure of large blocks, which can give very high rates of coastal retreat.

Despite the importance of storm activity, researchers in the circum-Arctic margins currently have little information about storm frequencies or potential strengths. The objective of this work is to summarize 50 years of storm data for coastal regions of the circumpolar arctic that border the Arctic Ocean. The interior of the Canadian Arctic Archipelago, most of the Canadian mainland north coast, Hudson's Bay, and Greenland south of 80°N are excluded. The storm data are derived from wind observations gathered at terrestrially based weather stations situated throughout the circum-polar coastal margin (Fig. 1). Summaries focus on storm events, which will be specifically defined below. Climatologies, consisting of aggregate totals and means by region, will be presented along with results from trend analyses. Data over the period 1950–2000 were utilized. The nature of the parameters selected for presentation and the ensuing discussion are directed more towards a geomorphological audience rather than a pure meteorological audience. A brief treatment of possible causes for the observed patterns is presented.

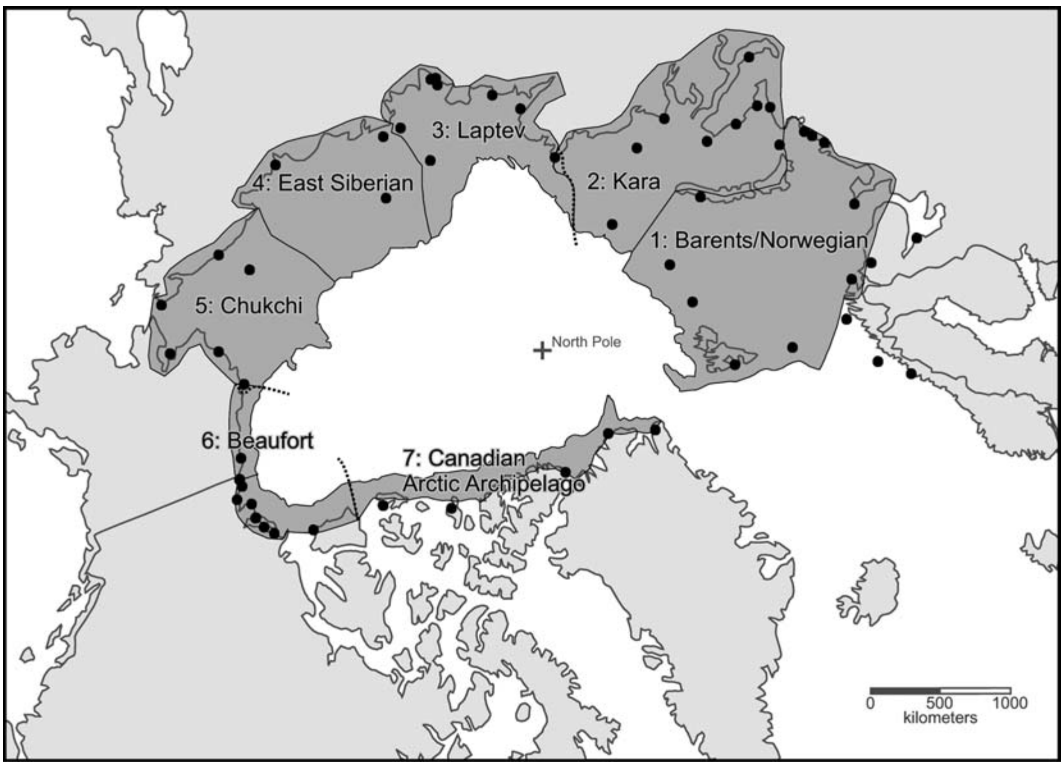
Method

Station selection and data preparation

Initial station selection was conducted to satisfy the requirements of the Arctic Coastal Dynamics (ACD) project (Rachold et al. 2004), which included: proximity to established Arctic Coastal Dynamics monitoring sites, uniform spatial coverage, coastal representation, station record length >20 years with data available within the last two decades, high frequency observational regimen (e.g., hourly or 6-hourly), and meeting World Meteorological Organization standards for station set up. For this work, observational data from 59 stations were retained and processed (Fig. 1).

Data pre-processing was necessary to handle the wide variety of observing regimens noted amongst the stations. Many of the stations gathered observations on an hourly basis, however many stations had 3- or 6-hourly frequencies. Further, many stations possessed not only inconsistent frequency of observation, but inconsistent timing as well. For example, for several years a given station might record observations every 6 h, at 0100,

Fig. 1 The circum-polar region. Sectors identified by the Arctic Coastal Dynamics project are identified as *grey zones*. Minor modifications adopted in this paper are indicated with heavier *dashed lines*. Station locations are indicated by *black dots*. In some cases, two stations are located very close together and appear as *one dot*



0700, 1300, and 1900 UTC, but then switch the timing of observation to 0000, 0600, 1200, and 1800 UTC. Greater precision in storm event characterization can be made using hourly data. For this work, experiments were conducted to establish if there was a difference in resultant storm counts when the frequency of observation differed. Differences were noted (not presented), so it was decided to subsample all data series to six hourly and then run the storm extraction algorithm on the subsampled data sets. In this way, differences between stations would not be an artefact of differences in observation frequency. This will tend to result in underestimation of speed and may eliminate events of short duration. It was felt that this consequence was preferable to either excluding the large number of stations and years that did not possess hourly records, or to try to compare storm statistics derived from differing observing regime frequencies. The possibility of these sorts of biases was indicated in work by Eid and Cardonne (1992).

In the case of differences in timings, all timings were treated as equivalent and standardization to some specific regime, e.g. 0000, 0600, 1200, and 1800, was not carried out. The data pre-processing also ensured data counts were high enough to properly represent time periods selected for analysis, that is, at the month and year level. Stations with insufficient observation counts were dropped because that situation would potentially artificially reduce the number of observable events. Another issue concerned stations that did not operate during the evening hours (common at community airport stations). They could present overall counts sufficient for monthly and annual analysis, but do not properly represent a 6-hourly regimen. Years for which a given station exhibited this pattern were discarded. Thus, to be included in the storm event analysis, a station had to possess in excess of 115 observations for each hour over the June–October period (75%) and had to have representation in each of these months, and yet not possess a ‘‘daytime only’’ observing regime. If these criteria were not met that particular year was discarded. Note that this means a given station can come and go over the life of its operation. For example, a station in operation from 1970–2000 that was missing all July observations in 1982 would be discarded from this study for that year.

Storm identification

The identification of a ‘‘storm’’ is an exercise possessing a certain amount of subjectiveness that further varies depending on the requirement. For example, hydrologists are typically interested in precipitation aspects (e.g. Restrepo-Posada and Eagleson 1982), structural engineers are concerned with gust loading, and emergency response organizations are interested in certain types of storms. In terms of coastal issues, the concern is focussed on storms that possess the right combination of wind speed, duration, and direction such that the wave-generating and/or surge generation potential is maximized. Depending on the specific application a range of threshold speeds, durations, and form of wind profile (e.g. MacClenehan et al. 2001) must be considered. Several projects have focussed on the issue of storm identification from wind records. Perhaps the most relevant in terms of location and objectives was that conducted by Solomon et al. (1994). They established a methodology that required input only from observed surface parameters. A storm event was identified when wind speed exceeded 37 km/h for at least 6 h. Hudak and Young (2002) utilized surface winds for the identification of storms and then classified the storms using upper atmosphere parameters from the NCEP/NCAR reanalysis data set (Kistler et al. 2001). Eid and Cardonne (1992) required a storm database for their extreme wave hindcast study. Their method was more geared to the offshore region and tends to overestimate both speed and duration for the coastal zone (Solomon et al. 1994). MacClenehan et al. (2001) utilized coastal wind speed records to define storm events, also for geomorphological purposes.

For this project the interest was in storms that can produce waves and/or surges that are of sufficient magnitude to impact a coastal region. By ‘‘impact’’ is meant damage to habitats or infrastructure, and potential to perform geomorphological work. Only storms with winds above a certain speed that are maintained for a certain period of time are able to create this sort of impact (e.g. MacClenehan et al. 2001; Solomon et al. 1994). An ‘‘event threshold’’ for wind speed was thus set at 10 m/s. This speed was selected because there is precedence for utilizing it as a storm threshold in general and, in particular, it has also formed a threshold for storms with winds able to generate waves sufficient to cause the impacts described above (e.g. Solomon et al. 1994). MacClenehan et al. (2001) set their speed threshold with reference to one of the more powerful storms to reach the Irish coast, although the selection of a final threshold was also influenced by the need to have a reasonably populated event database. The ‘‘duration threshold’’, that is, the minimum length for a storm event, for the project described here was set to 6 h. This value is based on the duration threshold used by the Beaufort Weather Office to define a storm, although Hudak and Young did not themselves use that duration threshold. Solomon et al. (1994) used a 6-h duration threshold.

Once the storm event criteria are established the next step in the creation of a storm event identification algorithm was to identify what information is required. The following parameters were selected:

- Core mean speed (identified by $\bar{w}_c$): the mean of the speed values in the upper 50th percentile of all the wind speeds retained for a given event
- Core duration (identified by d_c): the duration in hours of the core mean speed winds;

– Core mean direction (identified by $\bar{v}_c$): the mean direction of the core mean speed winds
– Synoptic duration (identified by d_s): the total length of the storm event; and
– Storm start and end times.

The distinction is made between "core" and "synoptic" because for many derived applications, such as coastal geomorphology, only the strongest speeds are of interest. However, from a climatological perspective it is of interest to have an estimate of the total duration of a storm event.

For this project the following, multi-stage algorithm for identifying a storm event was utilized. A running mean approach, such as was used in Hudak and Young (2002) and MacClenahan et al. (2001), was not adopted here due to limitations imposed by the previously mentioned observational frequency, and thus wind speeds were used as they appeared in the record. To begin with, any wind speed exceeding event threshold is tagged. The tagged observations are then assessed for grouping into discrete storm events. In performing this task two morphological features in the presentation of a storm event in a wind speed profile are recognized: "lulls" and "shoulder events" (Fig. 2). A lull is a temporary decrease in wind speed during a synoptically contiguous storm event. In this case, lulls were defined to be the occurrence of a single wind speed observation that dropped below threshold, with tagged observations immediately previous to and following the lull. A shoulder event was defined as a wind speed occurring before the first, or after the last, tagged observation in a contiguous set of tagged observations, that was just a bit below event threshold, i.e., and most likely associated with the synoptic storm event.

To evaluate lulls and shoulder events, a secondary threshold, termed the "continuity threshold", was defined. This value was arbitrarily set at 0.7 x event threshold. If the lull dropped below this value the tagged events on either side were considered to belong to separate storm events. If a shoulder dropped below this value then the event count tagging was stopped for that event. Without use of lulls the algorithm returned too many storm events that were too short in duration. Without use of shoulder events the synoptic duration of storm events was overly shortened.

After the addition of lulls and shoulder events to the storm events the six-hourly wind speed observations were linearly interpolated to a 1-h frequency. This served to refine estimates of duration and mean speed. Counting began when the hourly wind speed estimate rose above the continuity threshold, and similarly ceased when it dropped below.

This resulted in the generation of a storm event database for each station used in the study. This database served as the basis for the analyses described next.

Analyses

The analyses were based on the aggregation of station results into sector boundaries established by the ACD (Rachold et at. 2003) and modified slightly for this project (Fig. 1). The number of observing stations in each sector are presented in Table 1. For all analyses, climatological and trend, the time period used to form an "annual" value is a roughly-specified open water (ice-free) season running from June 1 through October 31, inclusive. It is understood that this definition of an open water season does not precisely match many of the areas under consideration, however in general it serves as an adequate basis from which to undertake the comparisons presented here.

Climatologies

The first set of analyses dealt with the preparation of 50-year climatologies of selected parameters for each sector, by month. The parameters included: mean event count,

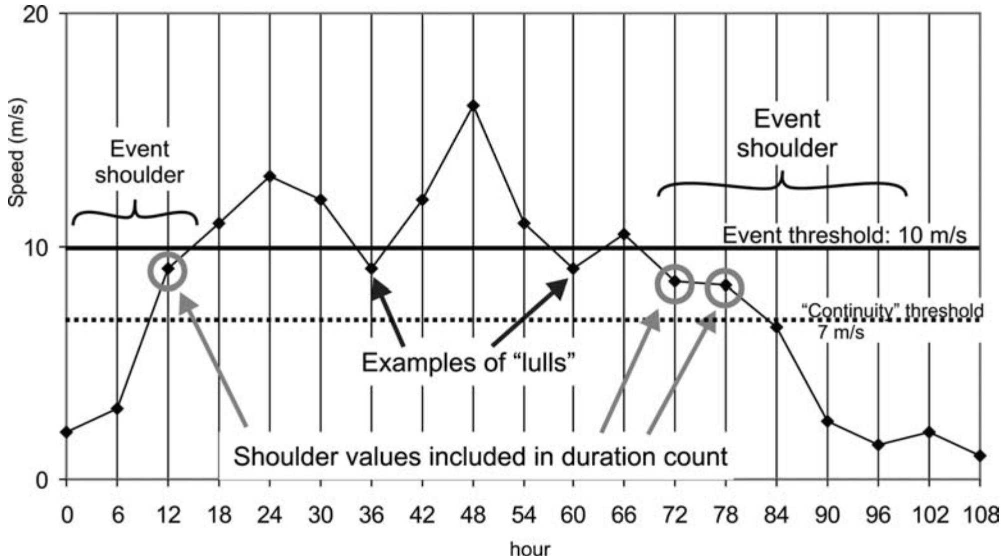


Fig. 2 Schematic representation of storm representation in the wind speed profile with various components indicated

Table 1 Total number of stations used in each ACD defined sector

Sector	Regional name	No. of stations
1	Barents and Norwegian Seas	15
2	Kara Sea	9
3	Laptev Sea	8
4	East Siberian Sea	3
5	Chukchi Sea	6
6	Beaufort (encompasses ACD Beaufort Canada and ACD Beaufort Alaska sectors)	12
7	Canadian Arctic Archipelago	7

mean core wind speed, mean core duration, and mean total power (defined below). The aggregation method varied slightly depending upon the parameter being considered. Determination of a sector mean event count was performed in the following manner. First a mean event count by station s by month m was obtained:

$$\bar{e}(s,m) = \frac{\sum_{1}^{e_{s,m}} 1}{y_s} \tag{1}$$

where $e_{s,m}$ is the total number of events at a station s for month m averaged over the number of years that station is in operation y_s. Note that the month into which an event is classed is determined by its start date. Next the sector mean count E was computed:

$$E(z,m) = \frac{\sum_{1}^{s_z} \bar{e}(s,m)}{s_z} \tag{2}$$

where s_z is the total number of stations in sector z. This two-step approach eliminates potential problems introduced by varying station record lengths.

Mean synoptic and core durations by sector by month were calculated in a manner similar to that used for the frequency count, i.e. a mean duration by station was first determined, then a mean duration by sector was calculated:

$$d_c(s,m) = \frac{\sum_{1}^{s_z} d\left(s,m|w > w^{p^{50}}\right)}{y_s} \tag{3}$$

where $w^{p^{50}}$ represents the wind speed at the 50th percentile, d represents duration and d_c is core duration.

From the parameters retained for each storm event a derived parameter, storm wind "potential power", was calculated. This parameter is designed to provide a rough indication of the total power potentially available from a storm event, and is defined for power P for sector z for year y as:

$$P(z,y) = \frac{\sum_{1}^{s_{z,y}} \sum_{1}^{e_{s,y}} \left(\bar{w}_c^2 d_c\right)}{s_{z,y}} \tag{4}$$

where s_z represents the number of stations s in sector z, and e represents the number of discrete storm events observed for a given station s for a given year y. Note that not all stations had a record that spanned the 50-year period of interest. Thus the number of stations in a sector can change from year to year, which means s_z has to be specified for each year. Calculations for wind power were based on a subset of storm events selected on the basis of mean direction, that is, if the storm mean direction was in a sector that ranged from 270° through north to 90°, termed herein the "north sector", the event was retained. This is a very rough representation of the fact that many of the coastal observing stations are situated on a coastline oriented east-west and are exposed to water in the north and land in the south. Further, use of a "mean" direction to represent a storm obscures the fact that most storm events exhibit a direction shift. This could result in an under representation of power totals. Given the potential uncertainty, it was felt prudent to err on the conservative side, that is, underestimation.

Trends

The second analysis concerns trends in open-water season storm frequency. This was explored using a mean storm count per station, rather than an overall total (e.g. Serreze et al. 1993), because the method used to determine storm occurrences at a given station has no way of linking storms at neighbouring stations together. If the individual station counts were simply totalled, the possibility of counting a particular storm two or three times would be high, given the close proximity of some stations. For this reason, mean counts per station were used.

Results and discussion

This section presents descriptions of the results and includes discussion about the nature of observed patterns, along with possible explanations. Note that the main objective of the paper is to present various aspects of the storm climatology, and that a detailed analysis of physical causal mechanisms is beyond its intended scope. However, while detailed explanations of the observed patterns will not be pursued here, various aspects of the north Russian coast will be identified as possibly relevant to storm activity.

Individual storms identified in this study compared well with those identified in Solomon et al. (1994) for the Tuktoyaktuk DEW line weather station, although events identified in the present study tended to be of longer duration. This discrepancy was caused by the incorporation into the duration count of wind speeds in lulls and shoulder events possessing cutoff values lower than event threshold, which will increase the duration of a storm. These values would not have been counted in Solomon et al. (1994). Other sources of storm counts that may be available for the Russian north coast were not found.

Climatologies

Storm counts

The mean annual counts (Fig. 3) revealed a mid-latitude, northern oceanic influence in zone 1, situated closest to the Atlantic. The low point in July, coupled with the steady rise into the fall, is a typical mid-latitude storm activity cycle brought about by the strong seasonal changes in the north-south energy gradient, from a summer minimum to a winter maximum (this pattern, as exemplified by zone 1 in Fig. 3, will be referred to as the "mid-latitude signature"). The vicinity of zone 1 is also situated northeast of the Icelandic Low, a region of frequent atmospheric low-pressure system activity in the winter, and is also in an area of strengthened east-west flow that directs weather systems into the region (Wallén 1970, pp 26–27). The pattern in zone 2 is similar in form to that in zone 1 but in each month the mean annual number of storms is greater. This pattern is deemed to be a mixing of two signals, one being a vestige of the mid-latitude signature, and the other being the increase in storminess potential due to temperature differences between the land and the sea. A strong thermal gradient superimposed on an existing, non-coincident pressure gradient can initiate storm activity (Henderson-Sellers and Robinson 1986, p 173), and any time open water is present in the arctic such thermal gradients exist, either between land-sea or between sea-ice. Open water also provides energy to maintain storm events that do form. By zone 3 the mid-latitude signature in the storm count pattern is virtually gone, and zone 4 in fact sees more activity in the summer and exhibits a small drop into the fall.

Comparison of zones 2, 3, and 4 for the months of June and July reveals that zones 3 and 4 have higher counts in July than does zone 2, a point that has already been made in terms of Atlantic influence and regional thermal gradients. However zones 2 and 3 both have relatively high counts in June, compared with zone 4. Three possible explanations for this pattern will be briefly outlined. First, the Kara and Laptev Seas are both fed by large rivers, the Ob, Yenisei and Lena. These rivers have strong discharge peaks in June/July; the Yenisei is especially strong in June (Lammers and Shiklomanov 2000). This discharge introduces heat into this region, which could increase storm activity with respect to the East Siberian Sea sector, which does not have rivers of this magnitude emptying into it (for example, the combined discharge of the Indigirka and Kolymya Rivers, which empty into the East Siberian Sea, is approximately one third that of the Lena–Lammers and Shiklomanov 2000). Next, there is a large area of early-season sea-ice disappearance in the area off of the Lena Delta (Arctic Climatology Project 2000). This is a large polynya that often forms in June to the north/northwest of the Lena delta (Bareiss et al. 1999). Polynyas and leads are important sources of energy in

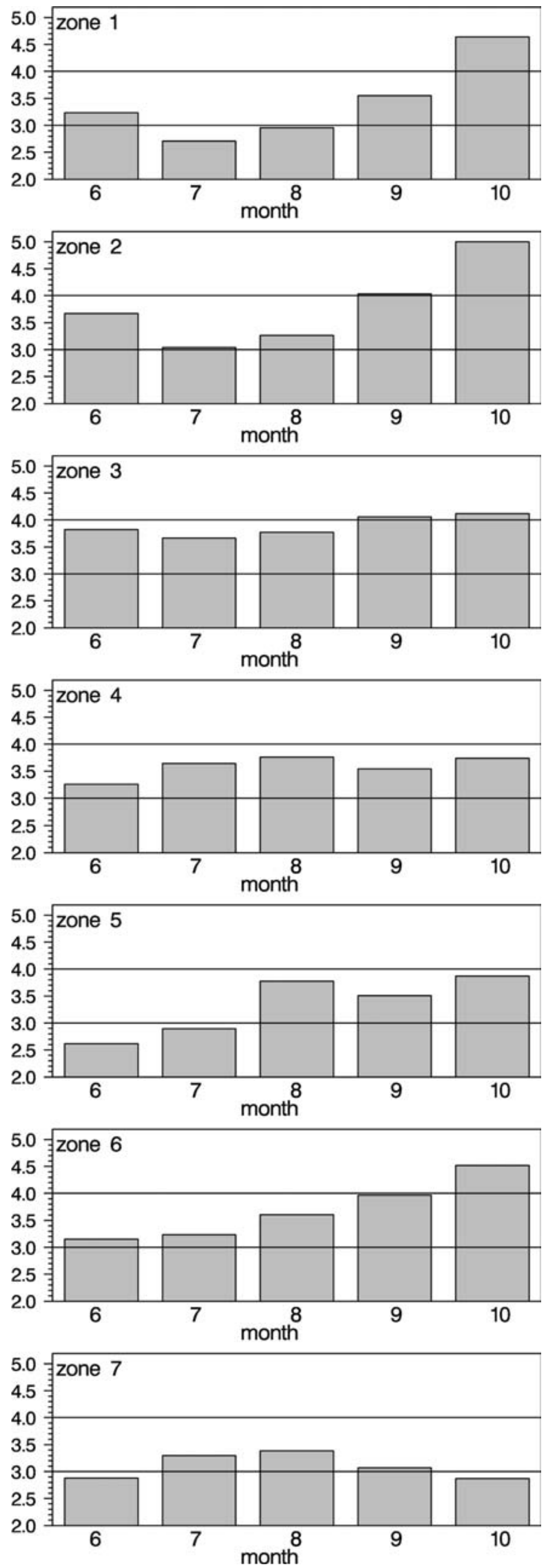


Fig. 3 Mean annual storm event counts by month, by sector

this region; their presence could aid in storm formation and/or strengthening. There is another region of early sea-ice disappearance in the region where the Ob and Yenesei empty in to the Kara Sea as well. The East Siberian Sea does not have zones of early sea ice clearance and in fact has the latest mean melt onset date in the Eurasian sector (Belchansky et al. 2004). Finally, general patterns in circulation can also drive regional variability in storm formation (e.g. Lydolf 1977), and an explanation might be that storms track into one area and not another.

It must also be noted that "climate" modifies the sea ice condition. The implicit assumption so far has been the reverse, that polynyas provide energy to synoptic weather events by releasing heat. While this is true, and while sea ice patterns in general can influence the climate (Walsh 1983), polynyas are often established by persistent prevailing atmospheric flow patterns (Agnew et al. 1997; Bareiss 1999).

In zones 3, 4, and 5 the storm counts reach a high level in August. Even though open-water has not reached its greatest extent by August, the temperature of the land is at its highest level, thus providing the strongest land-sea thermal gradient of the annual cycle. This is able to compensate for a relative lack of open water, resulting in a storm count peak. Counts in September and October remain high in zones 3, 4, and 5 due to the rapidly increasing open water extents, even though the thermal gradient is dropping.

Zone 5 has lower counts in June and July most likely because the storm tracks that develop in the summer channel systems towards zones 2–4 and not 5 (Lydolph 1977).

Zone 6 comes under the influence of systems that can move up from the Pacific Ocean either through the Bering Straight or across Alaska. Increasing open water amounts over the five-month period coincide with a general increase in storm activity.

Zone 7 is located farther north than the previous six zones. It does not have the same open water season, and the northwest edge of the archipelago can have virtually no open water season. Here general storm activity is low compared to other regions. Its peak occurs in July and August as a result of changes in prevailing synoptic pattern; specifically, in the summer, weather from the south can penetrate into this region more readily than at other times of the year.

Storm core speed and maximum speed

Two statistics regarding storm speed were extracted: storm core speed (Fig. 4) and storm maximum speed (Fig. 5). Storm core speed was obtained as described above. Storm maximum speed was obtained by identifying the maximum speed for each storm event and averaging these values over the time period of interest.

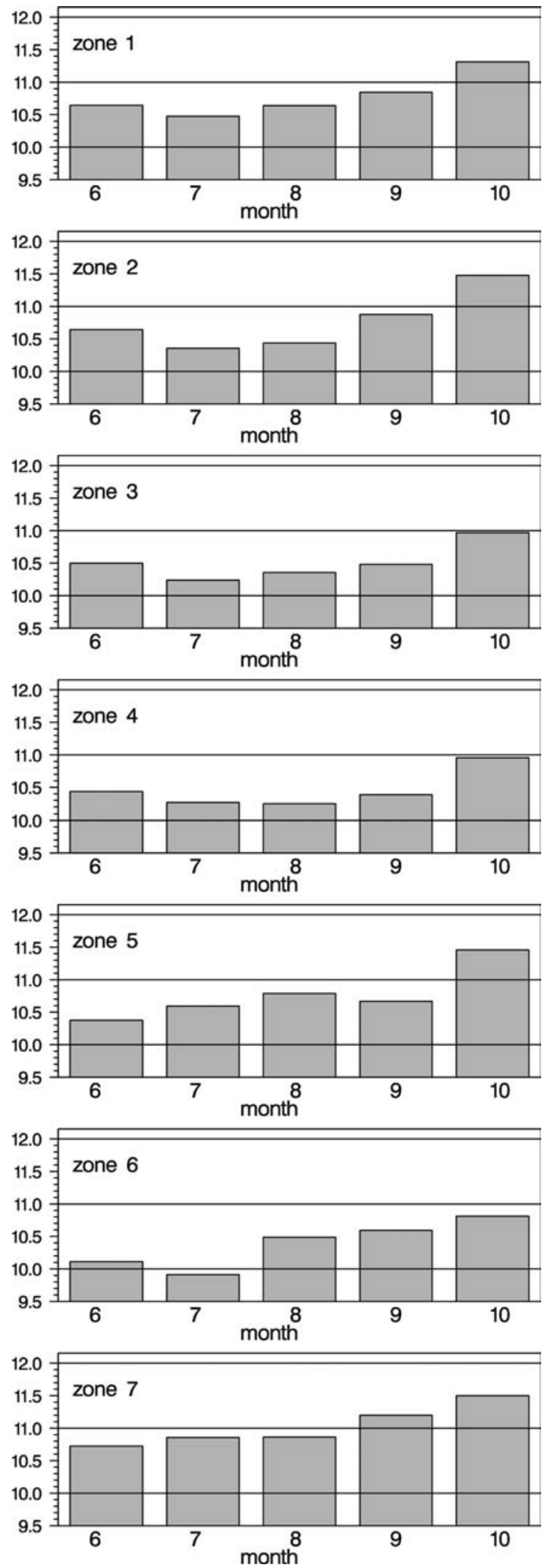


Fig. 4 Mean storm core speed (m/s) by month, by sector

The patterns for each zone were generally similar, indicating that storms with greater core wind speed tended to produce the greatest maximum speed values as well. Zones 1–4 were similar, with summer (July and August) representing a speed low point, June representing a secondary peak, and September stronger leading up to October, which possessed the strongest mean winds in all zones. In Zone 5, the June secondary peak was reduced to a level below July and August. Zone 6 had low speeds in general, especially for June and July. Zone 7 had consistently strong winds.

Storm core durations

Storm core durations (Fig. 6) in zones 1 through 4 exhibit the mid-latitude signature. Storms in zone 2 exhibited the longest durations of any sector for each month. The pattern breaks down in zone 5 because June storm durations are significantly lower relative to the other months. The pattern is apparent again in zone 6, although durations are short compared to other zones. Zone 7 does not have as strong an increase into September and October as other zones, and durations are generally short here as well.

Storm potential power

Storm potential power (Fig. 7) was calculated as described. To obtain storm maximum power (Fig. 8) the storm exhibiting the largest power value was extracted for each station by month and then averaged by zone. A rise in mean power values from a low point in July (zones 1,2,3,5,6) or August (zones 4,7) leading up to October was apparent in all zones, as was a large variability in June. Overall, zones 1,2,3 and 4 exhibited consistently high mean power values, zone 5, a large relative difference between June and October, and zones 6 and 7, consistently lower power values. Many of these patterns were echoed in the maximum power statistics (Fig. 8).

Climatology discussion

Comparison between the mean annual counts (Fig. 3) and the storm wind statistics (Figs. 4, 5) indicated that the strongest winds were not necessarily associated with the stormiest periods or regions. Zones 1 and 2 were most closely coincident, with both exhibiting lowest storm count and speed activity in July and August. Zone 3 represents a transition: here the speed signatures are similar to zones 1 and 2, but the count signature is only marginally similar. At zone 4 the patterns were reversed with an activity peak in July and August (Fig. 3; zone 4), yet the lowest wind speeds in the same period (Figs. 4, 5; zone 4). For zone 5 and 6 some correspondence between

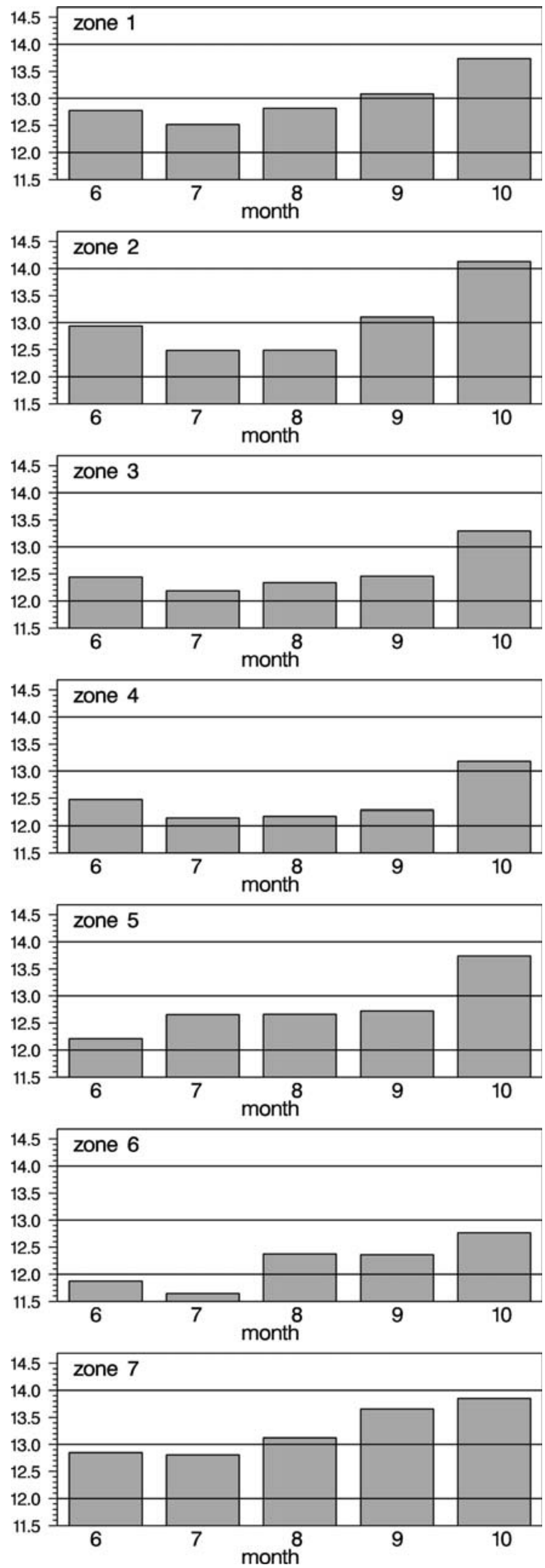


Fig. 5 Mean storm maximum speed (m/s) by month, by sector

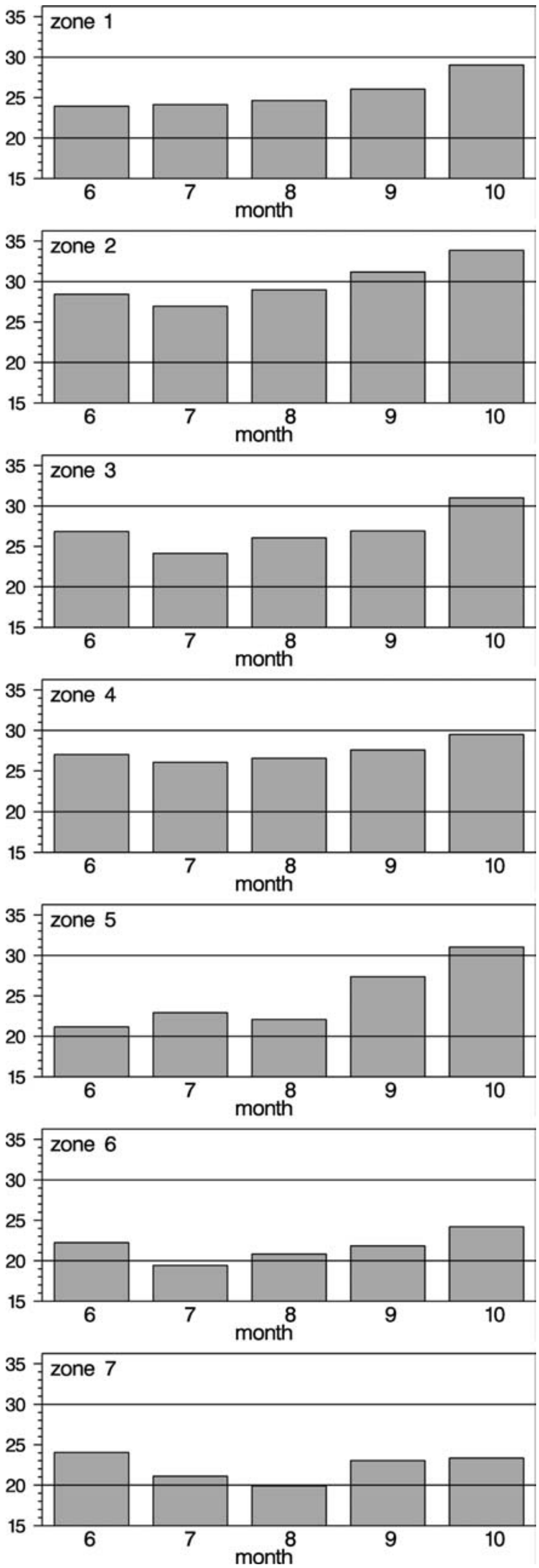


Fig. 6 Mean duration of core winds (hours) by month, by sector

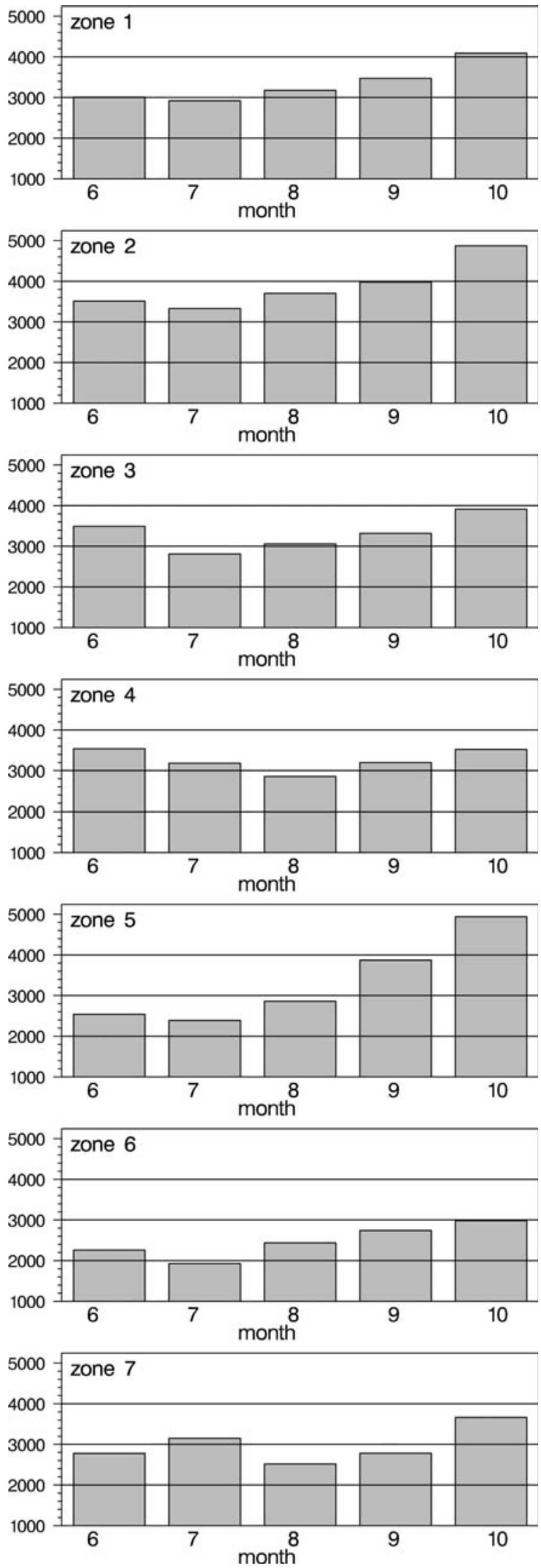


Fig. 7 Mean storm power (speed^2* duration) by month, by sector

counts and speeds was noticeable, especially core mean speed. Zone 7 exhibited the strongest divergence between counts and speeds, with relatively high speeds occurring as counts drop rapidly off in September and October.

Temporal trends

From 1950 to the early 1970s a gradual but persistent decline is noted in the mean count per station (Fig. 9). Over the span of a few years in the early 1970s the decline stops and is replaced by a regime exhibiting increased storminess. From 1973 through 1989 the storminess count remains high and appears to be slightly more variable year to year than the early period. After 1989 the level of activity drops and a period of storminess decline is entered that persists up to 2000. It is of interest to compare the trend results with those found in Serreze et al. (1993). They show a steadily increasing trend in circum-polar storminess counts from 1952–1989. That result is generally similar in overall form to what was obtained here, although it differs on two points. First, the magnitude of increase is not the same here as in Serreze et al. (1993). If a least-squares straight line were fit to the trend curve (Fig. 9) between 1950 and 1989 the rate of increase would be lower than that found in Serreze et al. (1993). Second, the morphological detail of the trend differs considerably between the two. In Serreze et al. (1993) the trend is reasonably steady, whereas here a distinct regime shift is indicated, with the early period trending in the opposite direction from that found in Serreze et al. (1993). Another interesting point is that for the years not covered by Serreze et al. (1993), that is, 1990–2000, the declining trend is opposite to that suggested by an extrapolation of the curves found in Serreze et al. (1993). Several points must be borne in mind when comparing these two studies. First, Serreze et al. (1993) does not provide results for the calendar autumn season, whereas this study includes results from September and October. Second, the storm counts in Serreze et al. (1993) are based on analyses of gridded pressure data over the entire polar basin. Overall, this means the nature of the conclusions extracted from a comparison between Serreze et al. (1993) and the present study should be limited to the very general, and a certain discrepancy is not unexpected.

Another important study of trends that must be discussed in light of these results is that by Savelieva et al. (2000). This study does not deal directly with storms but provides an overview of changes in meteorological and related hydrological parameters over the Siberian region of Asia over the last 50 years. One of the key features identified in Savelieva et al. (2000) is a shift that occurred in the baselines of several parameters, including positions, intensities and extents of major atmospheric circulatory features, air and soil temperatures, and river

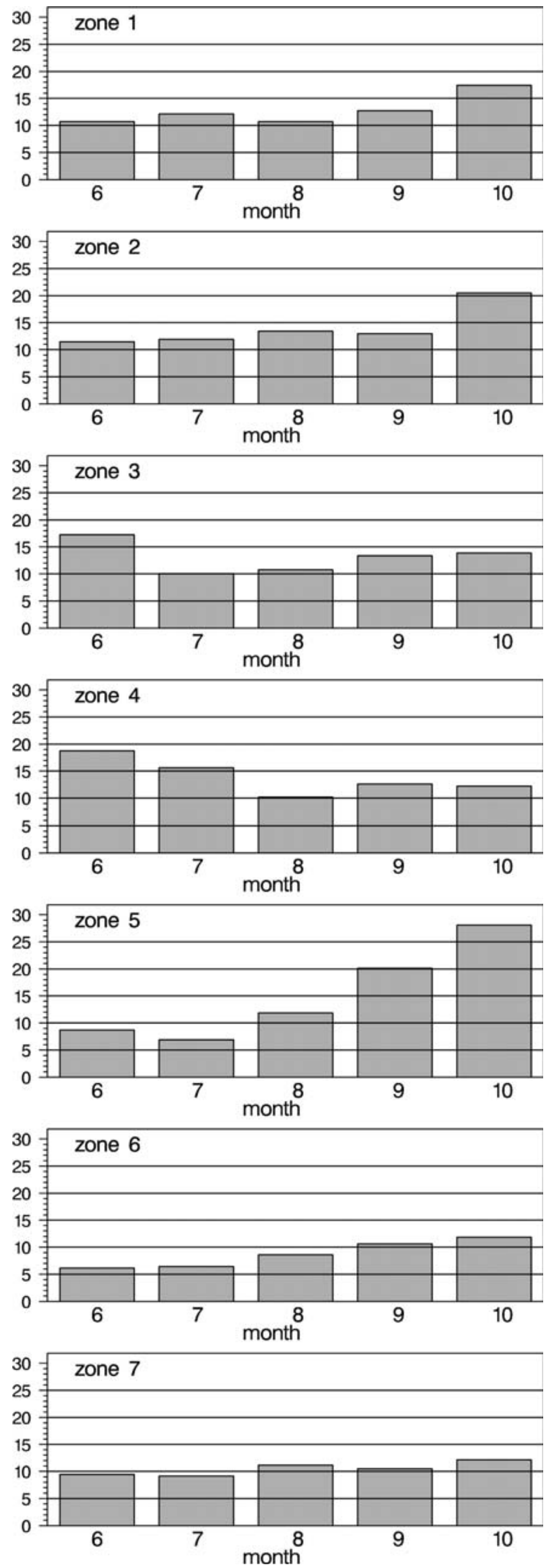


Fig. 8 Storm maximum power (speed^2*duration*1,000) by month, by sector

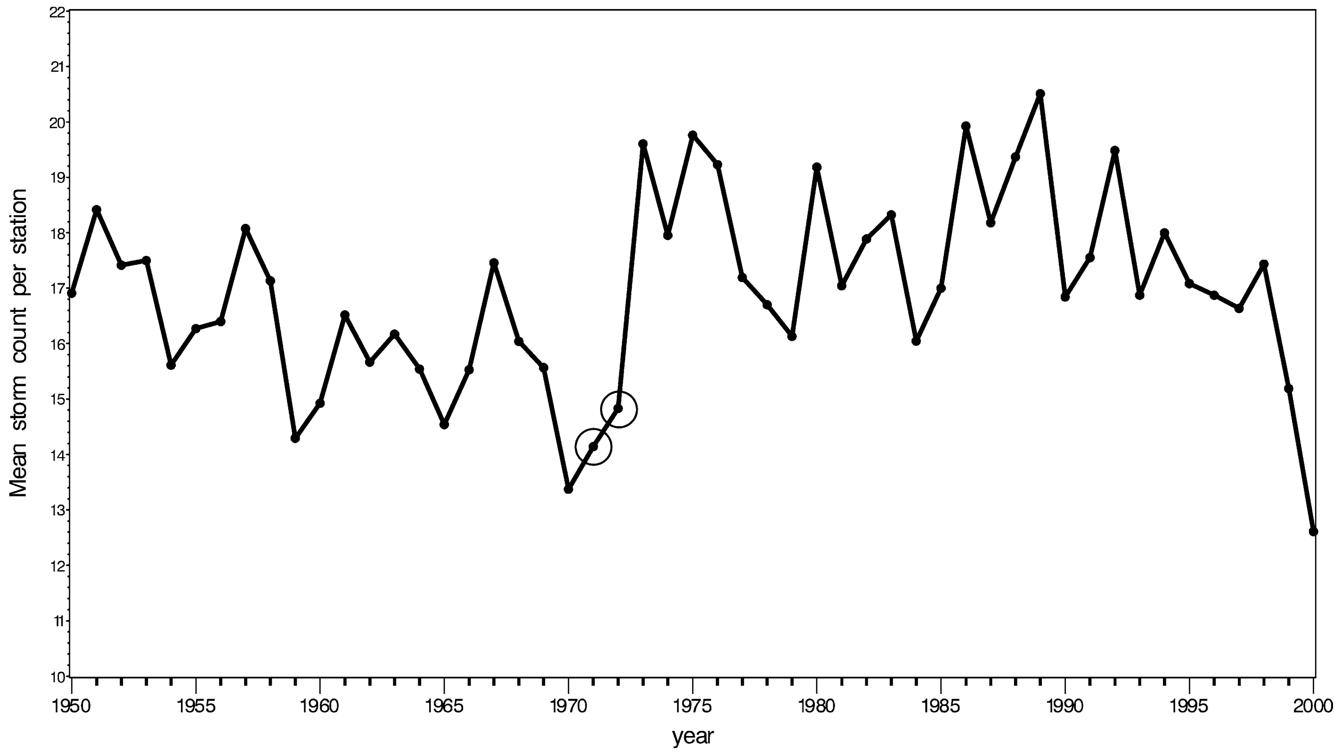


Fig. 9 Mean storm count by station, by year, for all stations. Open water season considered (June–October inclusive). *Circled years* 1971 and 1972 are supported by low station counts and should be treated with caution

discharge. These changes are most conspicuous in winter. However, alterations to the winter cryospheric situation will also influence the subsequent open-water season. The most salient changes they identify are alterations in the structure of major pressure features and associated changes to storm track positions, which "determine the characteristics of the hydrometeorological regime over Amerasian sectors of the Hemisphere" (Saveliava et al. 2000). The time frame of the shifts identified in Saveliava et al. (2000) coincides with the early 1970s shift in storm count trends noted in the present study.

Conclusion

The general climatological patterns of storm frequency, duration, wind speed, and power vary by region over the circum-Arctic domain, and reflect the influence of the Atlantic and Pacific oceans in regions near these oceans, with an increasingly important Arctic coastal signal appearing for regions far from the oceans. Specific observations include:

– The greatest mean and maximum potential power, as defined in this paper, was not in the Atlantic zone but in zone 5, the Chukchi zone, late in the season.
– The Kara Sea zone (2) is a very active region, having numerous storms with long durations.
– A strong storm-count peak that appeared in June in the Kara Sea zone (2) and the Laptev Sea zone (3) was noted to be relatively distinct and possibly linked to the frequent occurrence of early open water off the mouths of the Ob and Yenesei Rivers in the Kara and the Lena River in the Laptev, caused by voluminous June discharges from these rivers and/or polynyas in both of these Seas.

The time series of circum-Arctic mean open-water season station storm counts did not exhibit a steady trend but showed distinct time periods in which different circulation regimes prevailed. The temporal pattern identified here corresponded to trends identified in Savelieva et al. (2000), which suggests that climatic response of the arctic regions to global warming may come not as a general trend in atmospheric parameters, but as shifts among various "preferred states" of circulation patterns that are manifested as relatively rapid jumps in mean activity and variability.

Acknowledgements Thanks to John Walsh and Andrew Cooper as reviewers for useful suggestions to improve the document. This work is supported by funding from the International Arctic Research Center (IARC) in Fairbanks, Alaska, USA, and comes through the Arctic Coastal Dynamics (ACD) Project operated out of the Alfred Wegener Institute for Polar and Marine Research, Potsdam, Germany.

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