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Article

Overview of strong winds on the coasts of the Russian Arctic seas

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Abstract
Joint analysis of ground-based standard observations, spaceborne Synthetic Aperture Radar observations and the Arctic System Reanalysis (ASR) v.2 allow us to identify areas with storm and hurricane wind in the Russian Arctic in detail. We analyzed statistics and genesis of strong winds in each region, with the special emphasis on orographic winds. For those regions where wind amplification occurs due to downslope windstorms (Novaya Zemlya, Svalbard, Tiksi, Pevek, Wrangel Island), a statistical analysis of the intensity and frequency of windstorms was carried out according to observations. Reanalysis ASR v.2 demonstrates significantly better strong wind climatology in comparison with another high-resolution Climate Forecast System Reanalysis. ASR v.2 still underestimates speed of strong winds, however it reproduces rather well most of mesoscale local winds, including Novaya Zemlya bora, Spitsbergen foehn, bora on Wrangel Island and some other.

Key words: downslope windstorms, tip jets, ASR, orographic winds.

Introduction

According to criteria for hazard weather of Federal Service for Hydrometeorology and Environmental Monitoring (Roshydromet) (Federal ... 2009), a very strong (dangerous) wind on the coasts of the seas is a wind with 10-min averaged speed exceeding 30 m/s. In addition, the Beaufort scale is often used to determine criteria for dangerous winds: severe and hurricane storm is identified when wind speed > 25 m/s (e.g. Radinovic and Curic 2013). However, a weaker wind can also be accompanied by dangerous weather phenomena, such as ship icing (Samuelsen and Graversen 2019), fast sea ice drift (Buzin and Glazovskiy 2005, Bychkova and Platonova 2014) or high turbulence and difficult aircraft landing and take-off due to a large vertical wind shear (Korablev 2018). Such winds are primarily of orographic nature (downslope windstorms, tip jets and gap flows). For instance, bora on Novaya Zemlya leads to a rapid drift of ice from the coast, to a reduced visibility due to severe blizzards in the wintertime and spray in the summer (Pastusiak 2016). Orographic winds in the area of Cape Zhelaniya lead to severe swell, which makes navigation difficult (Pastusiak 2016). The study of dangerous coastal winds is especially important in terms of the growing interest in the Northern Sea Route.

At present, the climatology of the mean wind in the Arctic is well studied, owing not only to long enough series of surface observations, but also to satellite observations and reanalyses (e.g. Wan et al. 2010, Kostianoy et al. 2014, Hughes and Cassano 2015, Liu et al. 2016). However, most reanalyses have rather rough resolution, therefore, various orographic effects are not taken into account, and even large-scale wind amplification does not reach the observed value (e.g. Dery and Yau 1999, Hughes and Cassano 2015). Satellite wind data also has significant limitations associated with the presence of sea ice, insufficient spatial resolution (especially for microwave radiometers) and a relatively short period of observations. Satellite climatology of mean and extreme winds is usually calculated for individual summer months (Liu et al. 2016).

Spaceborne Synthetic Aperture Radar (SAR) data with a typical resolution of about ten meters are most suitable for studying strong local winds (Gavrikov and Ivanov, 2015, Ivanov, 2016). However, due to the small period of observations, we can only study the phenomenon on the example of individual cases, analyzing its spatial structure. At nowadays, a full-fledged statistical analysis of strong winds is possible only according to station observations, and high-resolution reanalysis data in those areas where data are not available. Therefore, in this study, we decided to use a joint analysis of ground-based observations, SAR data, and a rather new Arctic System Reanalysis (ASR) version 2 with the best resolution in the Arctic region to obtain a more complete view on extreme winds in the coastal regions of the Russian Arctic.

Data and methods

The climatology of extreme winds and their genesis are considered on the basis of station observation data from Roshydromet network (standard 3-hour observations), as well as ASR v.2 reanalysis (https://doi.org/10.5065/D6X9291B) with spatial resolution 15 km, time span 2000-2016 and a time resolution of 3 hours. Calculation of the climatic characteristics of the wind according to station data was carried out for the period 1979-2017, when the largest number of observations is available. For downslope windstorms, a threshold of 8 m/s (which approximately corresponds to gusts of up to 15 m/s) for wind speed and the corresponding wind direction were used as a formal criterion for identifying episodes. For a qualitative analysis of the spatial distribution of orographic winds, Level 2 wind speed from Synthetic Aperture Radar (SAR) from Radarsat-2 and Sentinel-1 were used from free-access archives of U.S. National Ice Center (https://www.natice.noaa.gov/products/kml_radarsat_wind.html), NOAA National Centers for Environmental Information (https://www.nodc.noaa.gov/sog/sar_wind/) and Sentinels Scientific Data Hub (https://scihub.copernicus.eu/) for the period 2014-2018.

Extreme winds climatology

General features of wind speed climatology in the Arctic (high wind speed in the Atlantic sector of the Arctic and the Chukchi Sea, mainly far from the coasts, and relatively low wind speed in the inland areas of the Arctic Ocean and the East Siberian and Laptev Sea) may be disturbed by local effects (for example, orographic). It can be seen from the map of average daily maximums of wind speed according to ASR v.2 (Fig. 1), that strong winds rather frequently are observed at the northern coast of the Kola Peninsula, to the north and south of Svalbard, as well as in the central mountain ranges of the archipelago, at the coast of Novaya Zemlya, on Cape Zhelaniya, inside the Kara Gate Strait and Ugorskyi Shar Strait, in the north-west of Severnaya Zemlya, at the coast of Bering and partially Chukchi seas.

Analysis of observational data at weather stations in the Russian Arctic showed that high wind speeds are quite often (the 99th percentile of wind speeds exceeds 17 m/s, a threshold for adverse weather phenomenon (Radinovic, and Curic 2013)) observed at stations in the north of the Kola Peninsula, Kanin Nos Peninsula, Novaya Zemlya, Vaigach Island, Franz-Josef Land, in the north-west of Taimyr (Dikson, Cape Sterlegova), in the bays of Tiksi and Ambarchik, in Pevek, on Wrangel Island, in the Bering Strait (Uelen station), on the coast of the Bering Sea (from Anadyr to Gavriila Bay) (Fig.2). At the same time, at some stations, strong wind blows not only often, but its speed exceeds 30 m/s - these are Malye Karmakuly, Tiksi, Pevek, Uelen, stations of the northern coast of the Kola Peninsula and the White Sea, stations in the Anadyr Bay (Anadyr, Beringovsky, Gavriila Bay) (Table 1). At Egvekinot station on the coast of the Bering Sea, very strong winds often arise, on average every 2.5 years, although in 99% of cases the wind speed is less than 17 m/s (Fig.2).

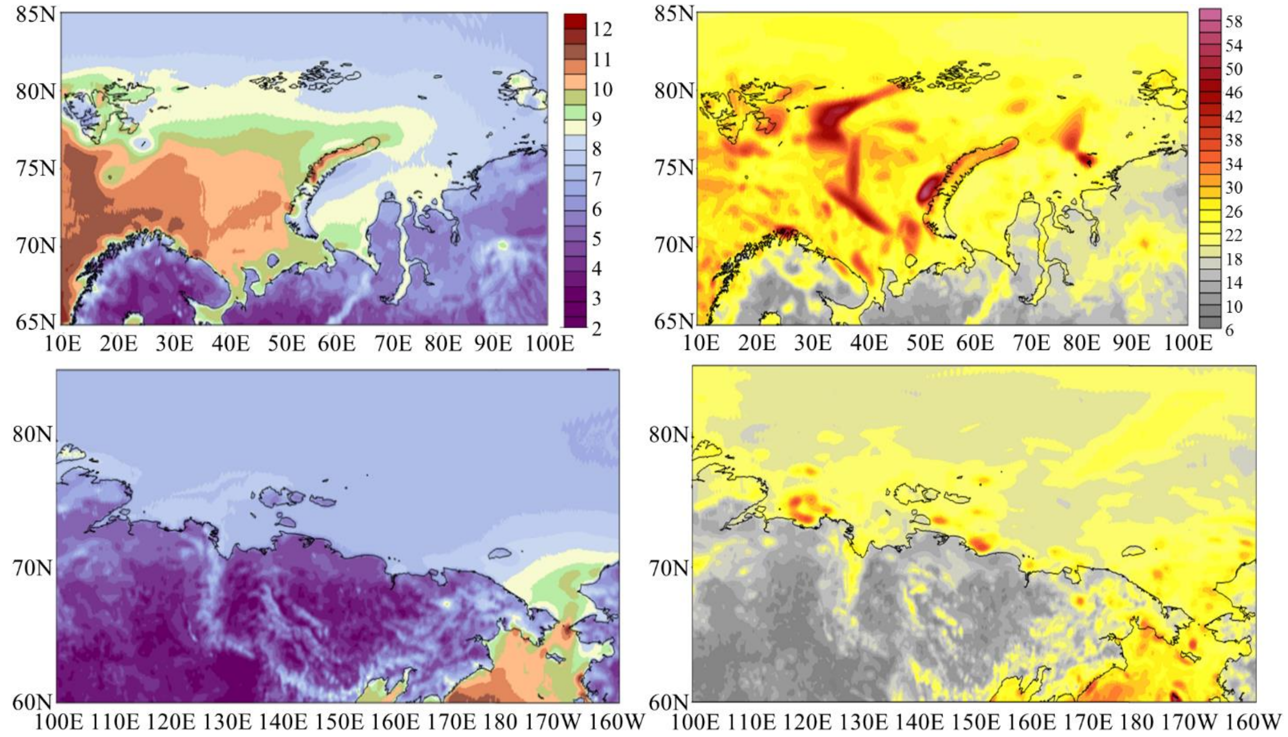

Figure 1. Mean daily maximum (left) and absolute maximum (right) of wind speed (m/s) according to ASR v.2 during 2000-2016

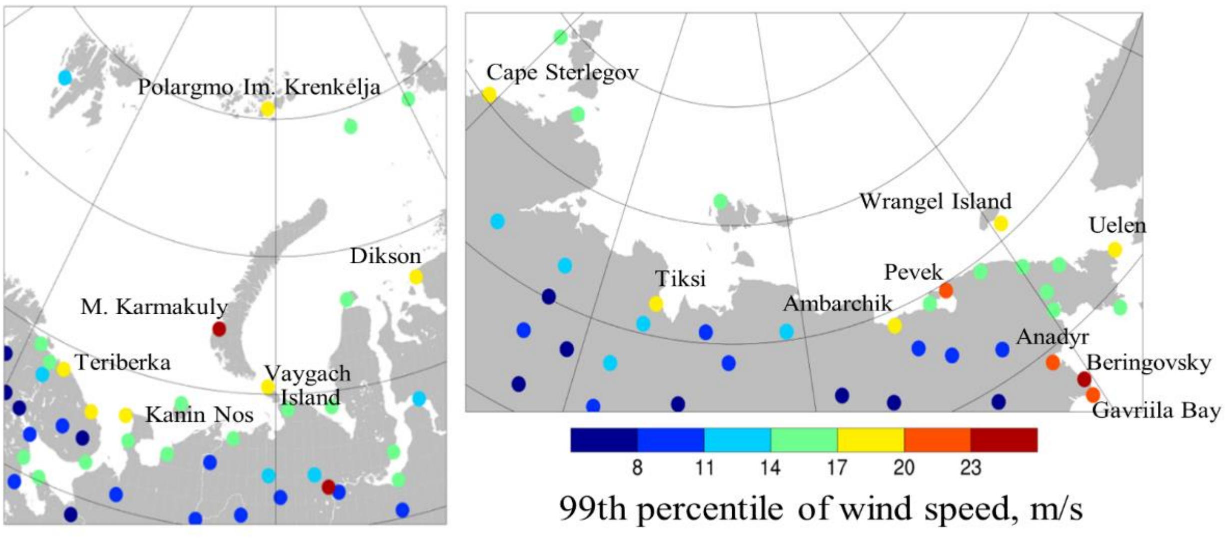

Figure 2. 99th percentile of wind speed (m/s) according to ground-based observations

Comparison with the observational data showed that ASR v.2 significantly underestimates the magnitude (Fig. 3) and frequency (Fig.4) of strong winds. For example, frequency of very strong winds (>30 m/s) in Teriberka, Egvekinot and Malye Karmakuly is underestimated by 2.5, 4 and 14 times, respectively. However, the localization of strong winds on Novaya Zemlya, associated with bora and other orographic flows, on Svalbard, on the northern coast of the Kola Peninsula and many other regions is generally reproduced correctly (Fig.4). Some areas with strong winds are not reproduced in reanalysis (for example, in Pevek, in the southern part of Anadyr Bay coast, in Egvekinot), but new coastal areas with high wind appear in reanalysis - for example, near Kolguyev Island (0.3 times per year), in Olenyoksky Bay, to the east from Big Lyakhovsky Island (Novosibirsk Islands) and near the mouth of the Indigirka River, a part of the coast of the Bering Sea in the north-east of the Anadyr Bay (between Kresta Bay and Providence Bay). The resolution of reanalysis is sufficient to reproduce large mesoscale effects (e.g., Novaya Zemlya bora), but insufficient for micro-scale and meso-gamma effects (Orlanski 1975). Nevertheless, ASR v.2 is much better at reproducing extreme wind speeds than the Climate Forecast System Reanalysis (CFSR) with a resolution of 0.3°. Among all areas with extreme winds in the Russian Arctic identified by ASR (Fig. 4), CFSR reproduces a very strong wind only in the north of Novaya Zemlya, while underestimating its frequency by more than 2 times.

Table 1. Return period of wind speed > 30 m/s at coastal stations in the Russian Arctic

Station	Return period (years)	Station	Return period (years)	Station	Return period (years)
Malye Karmakuly	0.08	Tiksi	3	Cape Sterlegov	34
Beringovsky	0.1	Uelen	4	Vajda-Guba	34
Pevek	0.3	Buhta Gavriila	6	Polargmo Im. Krenkelja	34
Anadyr	0.3	Gridino	7	Ambarchik Bay	34
Egvekinot	3	Sosnovec	9	Svyatoj Nos	34
Teriberka	3	Polyarnoe	11		

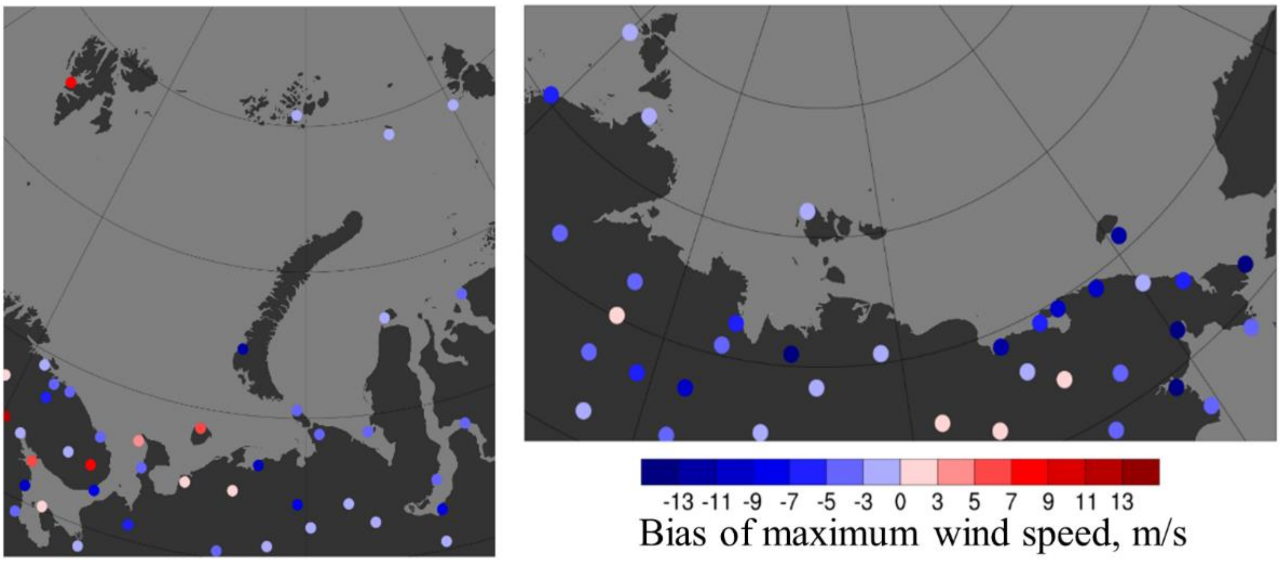

Figure 3. Bias of maximum wind speed (reanalysis “minus” observations) during 2000-2016

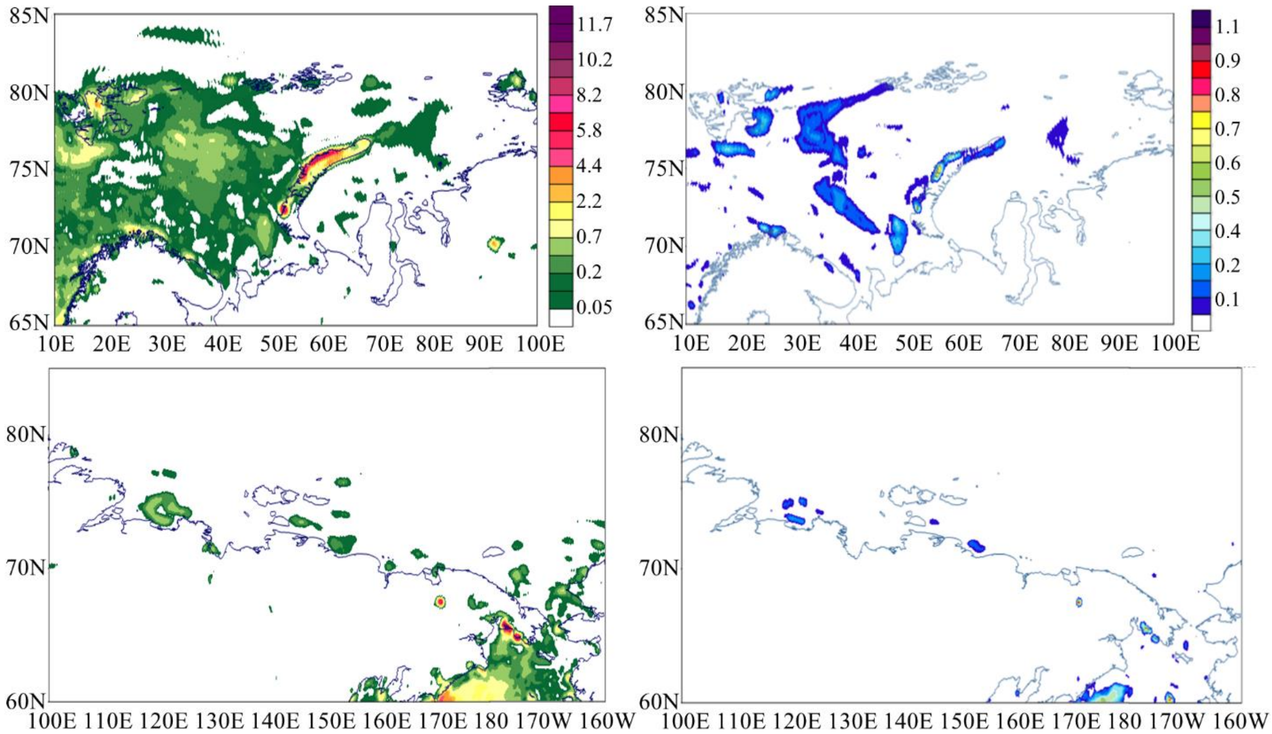

Figure 4. Frequency (number of times per year) of wind speed > 25 m/s (left) and >30 m/s (right) according to ASR v.2 during 2000-2016

Genesis of extreme winds

a) Synoptically-forced winds

In the area of Teriberka and at other stations on the northern coast of the Kola Peninsula, a very strong north-west wind is confirmed by both observational and reanalysis data. According to the Sailing Directions of the Barents Sea (GUNiO 2006), in winter a strong northwest wind in this area can blow continuously for a long time. An analysis of the large-scale situation (according to ASR) for all cases of extreme wind in Teriberka showed that wind amplification is most often associated with a large pressure gradient in the southern or rear parts of cyclones moving over the Barents Sea from the north-west to south-east. Moreover, in all cases, cyclones formed in the Greenland Sea and quickly deepened over the Barents Sea. Storm wind (≥ 20 m / s) of the north-west direction in most cases was associated with large-scale wind amplification in cyclones or with cold-air outbreaks from the north and northeast and only several times was recorded during the passage of polar lows.

According to reanalysis, a very strong wind in the region of Oleneksky Bay and the mouth of the Indigirka River (Fig. 4) was noted only a few times, and all these times were related to the same case. The cause of the wind intensification was two deep cyclones, moving one after another across the Laptev Sea and the East Siberian Sea. However, in general, the Laptev Sea and the East Siberian Sea are characterized by a calm wind climate.

Synoptically-forced wind amplification in the north-west of Taimyr, observed at stations Cape Sterlegov and Dikson, is mentioned in (Pastusiak 2016). Most of the storm wind episodes are observed during the southerly, south-westerly wind when deep cyclones pass through the Kara Sea. Some additional increase in wind in Dikson can also occur due to the tip jet effect, however, reanalysis data indicate a small difference between the background wind and Dikson local wind.

Frantz-Josef Land is known as a windy place, where storm winds occur 5-7 days per month due to the passage of deep cyclones and can attain 44 m/s (Dementiev, Bryazgin 1996). These storm winds must be strongly modulated by the complex topography of the archipelago, but the orography representation in ASR is insufficient to study these possible effects, and the use of satellite data is limited to the almost permanent sea ice in this region.

b) Tip jets and strait winds

Tip jets (Proch 1983) occurs due to streamlines convergence during flow around obstacles. Strong winds in narrow straits and gap winds have the same nature. In the Arctic, the most famous and strong tip jets are southern tip jet in Greenland (e.g. Moore et al. 2003), Svalbard tip jets (Reeve and Kolstad 2011, Sandvik and Furevik 2002), tip jet at Cape Zhelaniya (Novaya Zemlya) (Pastusiak 2016). Tip jets are rarely very strong (and therefore cannot formally be classified as hazardous weather phenomenon), but are observed quite often, so they can be classified rather as adverse weather phenomena (Federal ... 2009).

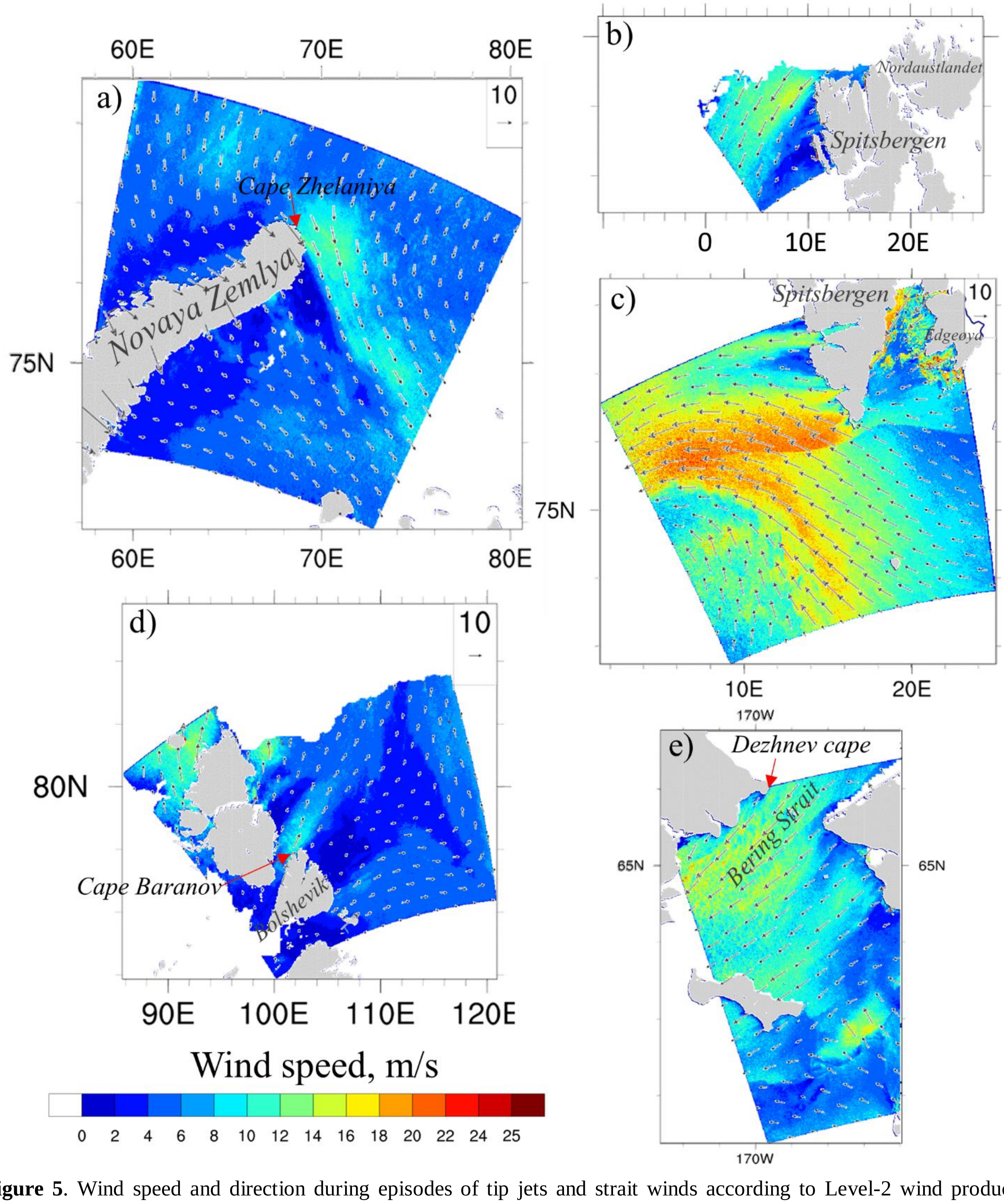

Figure 5. Wind speed and direction during episodes of tip jets and strait winds according to Level-2 wind product obtained from SAR data on Radarsat-2 satellite (regions with sea ice are filtered) in the regions of Cape Zhelaniya (10.08.2014 at 02:29 UTC) (a), northern (b) and southern (c) tips of Spitsbergen (08.05.2015 at 15:44 UTC and 04.12.2014 at 16:04 UTC, respectively), Shokalsky Strait (09.09.2014 at 09:30 UTC) (d) and Bering Strait (18.11.2015 at 04:36 UTC) (e)

Due to the complex orography and configuration of the coastline, Svalbard is the cause of numerous local winds. Analysis of SAR data and ASR v.2 showed, that tip jets are often observed at the northern tip of Spitsbergen (Fig.5b) both in the east and west direction of background flow. Due to the proximity of the sea ice edge north of Svalbard, this jet can be enhanced by baroclinicity (thermal wind). At the north exit from the Hinlopen Strait between Spitsbergen and Nordaustlandet wind amplification (up to 30 m/s according to ASR) is very often observed during a southeast and south flow. There, flow convergence in the strait overlap with the tip jet effect, which was demonstrated in (Sandvik and Furevik 2002). The wind also intensifies in the strait between Spitsbergen and Barents and Edgeøya Islands. Analysis of satellite data and reanalysis in the region of southern cape of Spitsbergen (Fig.5c) has shown, that it is rather difficult to separate the tip jet effect from the synoptic wind amplification (the latter is characteristic of the entire Atlantic sector of the Arctic). For example, the maximum wind speed near the southern tip of Svalbard according to ASR reached 38 m/s, but the wind direction was north, north-west (and not west or east, which could be expected with a tip jet), and wind amplified due to the passage of a very deep cyclone.

According to observations at the weather station Cape Zhelaniya (data for some years (2005, 2010-2014, 2018-2019) are available on the website www.rp5.ru), storm winds are observed during the north-west, west (most often) or east, south-east flow direction. Several times, the wind speed at the station reached 30 m/s (in the reanalysis, the maximum wind speed is underestimated), and storm winds are observed quite often, on average 23 times per year, during all seasons except August-October. Most episodes of wind amplification are associated precisely with the tip jet (for example, as in Fig.5a), although during westerly flow, the tip jet effect is often accompanied by bora. According to reanalysis, it is bora on the northeastern slope of the ridge that leads to the maximum observed wind velocities at Cape Zhelaniya.

In Anadyr, the prevailing direction of strong wind is east, which is associated with the convergence of flows in the mouth of the Anadyr River, stretched from west to east. Additional convergence of flows may occur due to the flow around the Golden Range, located northeast of the city. The reanalysis as a whole reproduces the storm and hurricane wind in the Anadyr Bay and its small (compared with the background wind) additional amplification in Anadyr itself, however, the magnitude of wind is significantly underestimated (on average by 2-3 m/s).

In Egvekinot, located in a narrow bay, stretched from north to south and bounded by steep ridges from west and east, the observed hurricanes are a manifestation of canyon (gap) winds that reach such a force during high-velocity northern background flow. Due to insufficient resolution, orography around Egvekinot doesn't reproduced properly in ASR v.2 and consequently canyon wind does not occur in the reanalysis.

In the area of Cape Dezhnev, wind amplification is associated both with the tip jet effect and with the flow convergence in the Bering Strait (Fig.5e). At the same time, at the Uelen station, additional wind amplification can be associated with downslope windstorm during southeastern and southern flow (the maximum wind speed reaches 35 m/s); much less often storm and hurricane winds were noted with a northwest and northeast direction. The frequency of storm and hurricane winds is about 12 synoptic terms per year. According to SAR data and ASR v.2, tip jet effect is even more pronounceable on the opposite side of the Bering Strait, on the Cape Prince of Wales.

Analyzing observations on Severnaya Zemlya Archipelago, on weather station of the ice base "Cape Baranov" (north of the Shokalsky Strait) during 2013-2018 (http://www.aari.ru/main.php?lg=0&id=405), one can note that all cases of storm wind (up to 31 m/s) were observed mainly in winter and during south-western wind direction, coinciding with the axis of Shokalsky Strait. Frequency of such winds is on average 29 times per year. SAR data shows that additional amplification of the wind also occurs due to tip jet effect of Cape Baranov (Fig.5d). During north-eastern flow, the maximum wind speed is observed in the south-western part of the strait and reaches (according to few satellite data) 22-24 m/s.

c) Downslope windstorms

Downslope windstorms are observed in various regions of the Russian Arctic, some of them are well known, but other winds are little described in the literature. Unfortunately, the use of satellite data for the study of downslope windstorms is practically useless due to the fact that the areas of strong wind are tied to the lee mountain slopes and almost do not propagate far downstream to the open sea. This is true for all downslope windstorms discussed in this Section, as shown by satellite data analysis. SAR images can only help to determine the potential presence of windstorms by the presence of gap flows downstream from the passes and fjords, which usually accompany bora-type winds and are perfectly visible from space (Gavrikov and Ivanov 2015; Ivanov 2016), at least on Novaya Zemlya (Fig.6b), Svalbard, in the north of Anadyr Bay, where these jets are the most obvious.

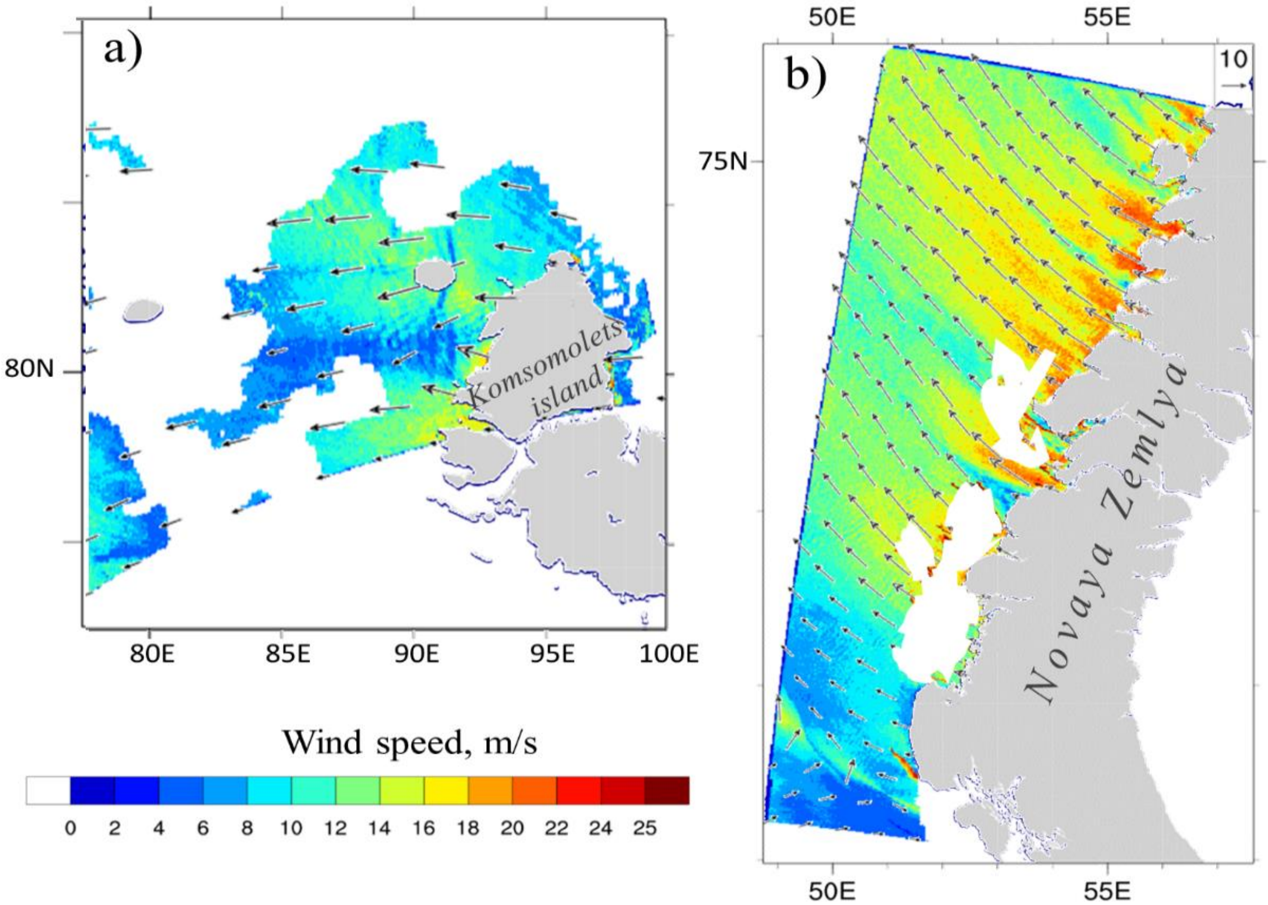

Figure 6 As in Fig. 5, but for downslope windstorms in the regions of Severnaya Zemlya (22.08.2015 at 10:50 UTC) (a) and Novaya Zemlya (07.12.2014 at 02:59 UTC) (b)

Svalbard is one of the areas with well-known downslope windstorms, usually called foehns (e.g. Skeie and Gronas, 2000, Migała et al. 2008). However, weather stations (including Barentsburg) are located in such a way that the amplification of the wind during windstorms is not represented adequately (as they are in the wake of the mountains most of the time). High-resolution simulation results using the mesoscale atmospheric model WRF-ARW (not shown) and also ASR (Fig. 1,4) show that high-velocity regions are localized directly on the lee slopes. In Ny-Alesund, the most representative (due to its proximity to the leeward slope) station among others, downslope windstorm never exceeds 25 m/s, a wind speed of 20-25 m/s is observed in 1.2% of cases, and in more than half of cases it does not reach 12 m/s. On average, there are 40 episodes of downslope windstorm per year. Relatively strong windstorms (wind speed > 20 m/s) are observed only in the cold season, with a peak in February-March.

Novaya Zemlya bora is also a well-known downslope windstorm (Moore, 2013, Ivanov, 2016, Efimov and Komarovskaya, 2018, Shestakova and Moiseenko, 2018). Weather station Malye Karmakuly is situated on the western coast of the South Island, where ridge height is about 500 m. On average, 60 episodes of eastern bora per year are observed at the station. The percentage of terms with bora from the total number of synoptic terms is on average 23%, and in January it reaches 40%. The maximum 10-min wind speed observed during bora is 48 m/s. Strong bora is most often observed in the cold season (with a peak in January), although weak and moderate bora is observed quite often even in summer.

Foehn winds in the Tiksi region is mentioned in the Laptev Sea Sailing Directions (GUNiO 2009), but there are no other references to this wind in the literature. The direction of a very strong wind in Tiksi is strictly southwest, that is, the strengthening of the wind should be connected with the flow over the Verkhoyansk ridge with the height up to 500 m in the Tiksi region. On average, there are 36 episodes of downslope windstorm in Tiksi. A strong windstorm (> 30 m/s) occurs every 5 years (only in the cold season). However, most of the strong episodes were observed during the period 1966-1982, and in subsequent period the frequency of storm and hurricane winds decreased (from 12% to 5%). The greatest frequency of windstorms is observed in December-January.

Extreme winds in Pevek are associated with the so-called “Yuzhak”, a southeast windstorm on the northern slope of a small ridge (Shapaev 1951, Zimich 1991). For the period 1985-2018 the maximum recorded speed of “Yuzhak” is 38 m/s. In approximately 20% of cases, the wind speed exceeds 20 m/s, and the proportion of hurricane velocities is 1-2%. According to the climate study of Yuzhak in (Zimich 1991), this phenomenon is observed 62 days a year, with more often windstorms occur in the warm season, but hurricane speeds are most often observed in the cold period (November-December). November is characterized by the maximum number of episodes of strong windstorm.

On Wrangel Island, very strong wind (more than 30 m/s) is practically not observed, but there is a high frequency of northern storm wind (with a maximum speed of 25-30 m/s) – bora wind, which is mentioned in (Pastusiak 2016). Weather station is located on the southern coast of Wrangel Island, at the foot of the ridge with heights 300-1000 m. On average, there are 44 episodes of bora per year observed at the weather station. As for Tiksi, stormy winds were more often observed in 1966-1982 and became less common in subsequent years. In June-July, the number of synoptic terms with bora is about 4%, most frequent bora is in October-November period (20-25% of terms). The strongest bora is observed in November-March.

Satellite SAR data can also detect downslope windstorms in areas where there are no in-situ observations. In subarctic regions, an analysis of satellite data showed the presence of downslope windstorm in the north of the Anadyr Bay, which is confirmed by reanalysis data (Fig.7 shows wind amplification according to ASR v.2 and SAR image, but for different dates, because time span of these two data sources overlap little). Between Kresta Bay (where Egvekinot station is situated) and Providence Bay, ASR v.2 demonstrates the high frequency of very strong northerly winds (Fig.4). Judging by the type of orography and the structures in the satellite images, gap flows are combined there with downslope windstorm. However, due to poor orography in ASR v.2, multiple jets observed in nature (Fig.7a) are represented by only one jet (Fig.7b). In addition, downslope windstorms were discovered on the islands of Severnaya Zemlya (Fig.6a shows an example of windstorm in the north of Komsomolets Island during southerly flow). However, statistics of windstorms in the Anadyr Bay and Severnaya Zemlya is unknown.

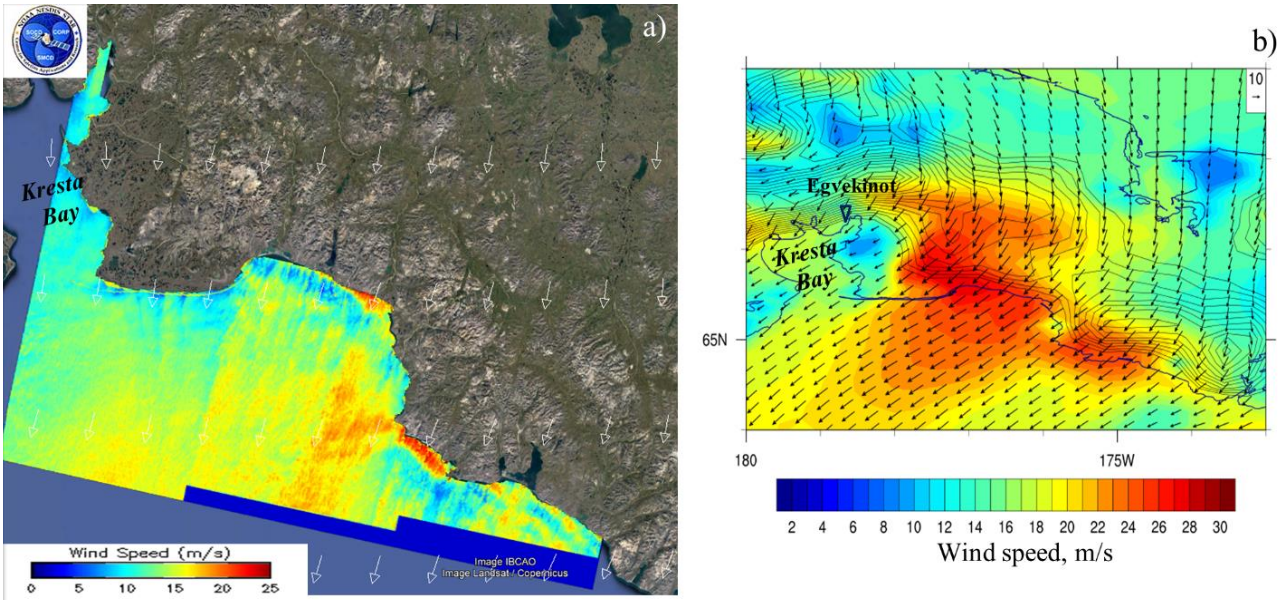

Figure 7. Wind speed and direction in the northern part of Anadyr Bay according to SAR data from Sentinel satellite (image of earth surface is from Landsat satellite) at 18:14 UTC October 16, 2018 (a) and ASR v.2 at 03 UTC January 24, 2000) (b)

Table 2. Statistical characteristics of the reproduction of downslope windstorms in ASR during 2000-2016: N - number of terms with windstorms, reproduced by reanalysis (in % of total number of terms with windstorms), bias V — mean bias of wind speed (m/s) (reanalysis «minus» observation), bias D — mean bias of wind direction (°), R — correlation coefficient of wind speed, V – mean observed wind speed (m/s)

	N	bias V	bias D	R	V
Malye Karmakuly	75%	-2.2	1	0.9	15.9
Ny-Alesund	74%	0.2	2	0.8	11.3
Tiksi	71%	-1.2	6	0.8	12.7
Pevek	49%	-5.3	7	0.3	16.9
Wrangel Island	70%	-1.5	2	0.9	13

Reproducibility of downslope windstorms in reanalysis is determined primarily by the orography scales. On Svalbard, Novaya Zemlya, in Tiksi and on Wrangel Island mountain ranges have a large scale, therefore the lowering of the air along the lee slopes associated with windstorms is reproduced with good accuracy: the percentage of terms with windstorms reproduced by reanalysis is 70-80%, the average wind speed bias is 1-2 m/s, the correlation coefficient is 0.8-0.9 (Table 2). In Pevek, the ridge has the smallest scale — about 6 km wide and 12 km long — and is subgrid in ASR v.2 and especially in other reanalysis. Windstorms in Pevek is reproduced only in 50% of cases, and these 50% of cases are the coincidence of windstorm and the large-scale wind amplification in reanalysis. Thus, the average wind speed bias in Pevek is 5 m/s, and the correlation coefficient is only 0.3 (Table 2).

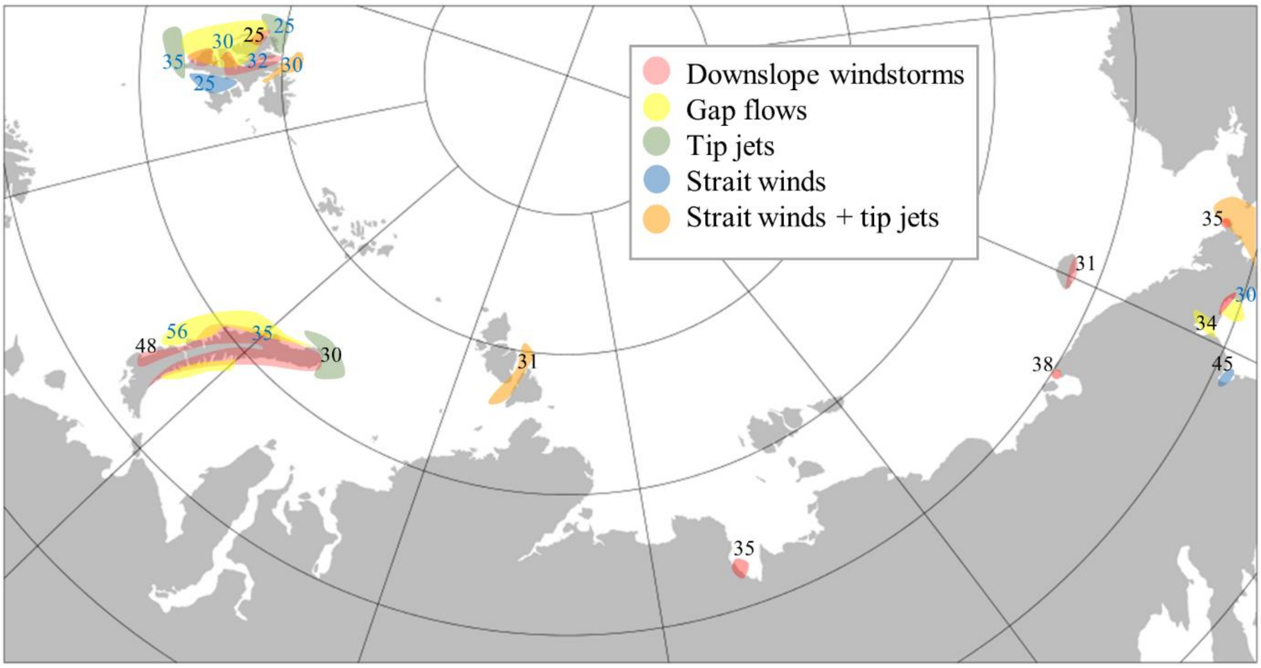

Figure 8. Scheme of local winds (tip jets, gap winds, strait winds and downslope windstorms) in the Russian Arctic, considered in the current paper. Numbers show maximum wind speed (m/s) according to ground-based observations (black) or ASR v.2 and SAR data (blue)

Conclusion

Combining various sources of wind data (satellite data, ground-based observations, high-resolution reanalysis), we were able to draw a more detailed picture of extreme wind in the Russian Arctic. Extremely strong winds on the coasts of the Russian Arctic can have a synoptic nature (including the coast of the Kola Peninsula), or occur due to orographic effects (Fig.8 shows only those, where the amount of data is sufficient to study the wind statistics): tip-jet effects, flow convergence in straits and mountain passes (for example, on Spitsbergen, Novaya Zemlya, Severnaya Zemlya, in Anadyr Bay).

But undoubtedly the most dangerous winds are downslope windstorms, especially in the area of Novaya Zemlya, Tiksi and Pevek, where they often reach hurricane force. The ASR v.2 reanalysis underestimates the maximum wind speeds at all coastal stations, but reproduces most of downslope windstorms and other orographic winds in general.

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