Some statistics of freezing precipitation and rime for the territory of the former USSR from ground-based weather observations

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In memory of Professor A.D. Zamorsky

Abstract

This work is a continuation of the previous climatological study of freezing precipitation and rime over the USSR territory (Bezrukova et al., 2000, 2004) aimed at creating an atlas of the frequency of these phenomena. This study gives considerable information about and a statistical analysis of freezing precipitation and rime events observed over the territory of the former USSR during a decade (1981-1990) and over the European territory of the USSR during two decades (1971-1990). This paper intends to draw the attention of the reader to the atlas and statistics by showing some interesting points. The authors used the data provided by the ground-based weather stations involved in the international exchange of meteorological data. The USSR network's Monthly Meteorological Tables comprising selected daily ground-based meteorological observations from more than 220 stations served as a basis for the analysis. All the types of freezing precipitation (FP) events were given as WMO Codes 56, 57, 66, 67, 24 and freezing fog (FF) deposited rime as WMO Codes 48, 49. The entire territory was divided into six major regions: the Arctic, the European part of the USSR, the Trans-Caucasus, Central Asia, Siberia, and the Far East. The frequency and distribution of events by regions versus temperature, atmospheric pressure, clouds base height, and some other meteorological parameters concerned were obtained. Climatic maps of annual mean, monthly mean, and seasonal mean occurrences of FP and FF were constructed for these regions.

The study also analyses the space-time variability of monthly mean ice-coating duration in hours for the 20-year period of 1971-1990 as observed at over 80 stations in the European part of the USSR (ET), and climatic maps of annual mean and monthly mean ice coating duration for the ET are constructed. The correlation between ice coating duration and height has been evaluated.

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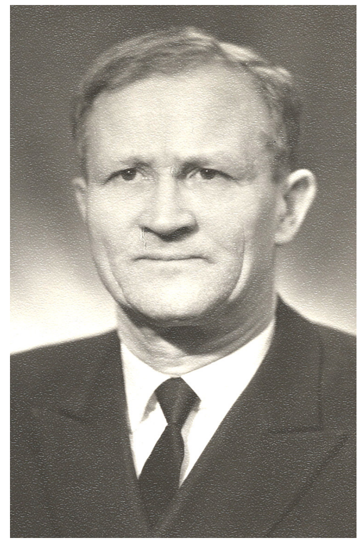
1. Introduction

Ice accretion, i.e. freezing rain, freezing drizzle deposition on objects in the air or on the ground, is one of the most hazardous phenomena for ground-based communication lines and transport, and aviation in particular. Glaze-ice or grained rime may deposit on an airplane body on land thus causing the deterioration of the airplane's aerodynamics, increasing its weight, and leading to its intense icing at take-off when it encounters supercooled clouds. Our knowledge of the spatial distribution of glazed-frost occurrence, based on ground observations, is very important for aircraft servicing at take-off and landing.


Professor A.D. Zamorsky

As a result of recent aircraft accidents or incidents that seem to be associated with flight in freezing rain or freezing drizzle, there is a need to learn more about these conditions on a worldwide basis. The US Federal Aviation Administration, in the research plan developed in 1997, listed thirteen research tasks which it agreed to support, that centered on the need to ensure flight safety in FP. Task 13 of the FAA In-flight Aircraft Icing Plan states that "Records of freezing rain and freezing drizzle from ground-based observations in many countries… are valuable for assessing the threat worldwide and for determining the opportunities for possible flight tests or additional measurements in these conditions." A good climatology for the FP exists for the U.S. and Canada, e.g., Gay and Davis (1993), Strapp et.al (1996), Stewart and Isaac (1999), Cortinas (2000), Changnon and Karl (2003), etc., but not for the other areas of the globe where winter icing conditions occur.

Extensive experimental and theoretical studies in this field were carried out in Russia as early as at the beginning of the 20th century and continued until the late 1980s. The only atlas edited by A.D. Zamorsky[1] and A.V. Rudneva was published 45 years ago (Rudneva, 1961). Unfortunately, practically no publications on FP and rime by Russian and Soviet authors have been translated from Russian and therefore they are not widely known to the scientific community.

The purpose of this work is to help fill in these gaps with recent data on the FP space and time distribution over the former USSR, including its European territory (ET), for the last decades of regular observations when the condition of the observational network was still satisfactory.

[1]A.D. Zamorsky who headed a group of the hydrometeorological network's methodological guidance was the first in Russia to suggest that two types of rime – crystalline and grained - should be distinguished. In 1951, on Zamorsky's initiative, a special "Instruction for hydrometeorological stations and posts on instrumental observations of wire icing" was issued.

2. Background data

2.1. Data sources and data sets

1. For the whole USSR network of over 220 stations involved in the international exchange, the data on the frequency of icing and rime phenomena in International Code numbers (24, 56, 57, 66, 67, 48, 49) and related meteorological parameters such as temperature, wind, pressure, cloud amount, and humidity have been accumulated based on regular daily 4-time observations (03, 09, 15, and 21 MLT) for the period 1981-1990. This data set was used to construct the maps included in the atlas of monthly mean frequency of the FP and FF for the USSR territory and to determine the relationships between these phenomena and meteorological parameters.

2. For the network of over 80 stations on the ET, data on the duration of ice coating on wires and the duration of liquid precipitation at negative air temperatures have been accumulated based on daily continuous visual 8-time observations (00, 03, 06, 09, 12, 15, 18, and 21 MLT) for the period 1971-1990. "Ice coating duration" implies the period, in hours, during which ice remains on a wire. This data set was used to construct mean monthly maps of these parameters for the ET.

2.2. Terminology and interpretation

This section presents definitions for the types of the FP and FF Codes corresponding to the standard WMO categories taken from different sources. In Russian scientific meteorological publications and meteorological dictionaries one can see a double interpretation of this phenomenon: 1) smooth compact deposit of ice, generally transparent, formed by freezing of supercooled drizzle droplets or raindrops on objects with surface temperature below or slightly above 0ºC; and 2) supercooled precipitation drops which form a coating of glaze on the ground and on exposed objects.

In the English-Russian meteorological dictionary by Mamontova L.I and Khromov S.P. (the 1955, 1959, and 1973 editions), commonly used in Russia, the term "*freezing rain*" is rendered as "*glaze, glazed frost"[supercooled rain, freezing on impact with objects]"*.

The problem is that even at an observation stage, there is some difference in interpretation: the same definitions imply different aspects of the same phenomenon. The definitions in Table 1, taken from the WMO Four-Language International Meteorological Vocabulary (1992) and the USSR Instruction for meteorological stations (1985), may serve as an example.

The following discrepancies have been revealed between the definitions from the two sources:

- *Freezing drizzle, freezing rain* (codes 56, 57 and 66, 67 for observation time and code 24 for the last hour prior to an observation time) rendered as “glaze” or “icing”, are therefore

Table 1
The definitions of the types of Weather Codes 56, 57, 66, 67, and 24 used by the authors to designate freezing precipitation and freezing fog phenomena

Weather Code	International Meteorological Vocabulary, Second edition WMO-No182, 1992	Instruction for meteorological stations USSR, Hydrometizdat, 1985
Codes: **56, 57** **66, 67** **24**	F1150 **freezing rain, Freezing drizzle**, (**freezing precipitation)** Precipitation drops freezing on impact to form a coating of clear ice (glaze) on the ground and on exposed objects. G0470 **glaze,** glazed frost A smooth compact deposit of ice, generally transparent, formed by freezing of supercooled drizzle droplets or raindrops on objects the surface temperature of which is below or slightly above °C.	The rendering of this term from Russian could be something like **‘Ice crust’** - an ice layer on objects, formed by freezing supercooled rain, drizzle or fog as well as by raindrops coming in contact with surfaces whose temperature is equal to or lower than 0°C . Generally, glaze covers all parts of surface exposed to precipitation, which freeze to form a compact and sometimes glassy ice crust. A glaze deposit can be several centimeters thick and may cause the breaking of tree branches, wires, poles, etc.
Codes: **48, 49**	R1820 **rime** (FF-deposited rime) Deposit of ice generally formed by freezing of supercooled fog or cloud droplets on objects the surface temperature of which is below or slightly above 0ºC.	The Instruction for meteorological stations is recommending for records two types of rime. **Grained structure rime** formed by freezing supercooled fog droplets. As air temperature goes up and droplets grow to reach the size of drizzle, precipitation density increases resulting in the formation of glaze. As air temperature goes down, the rime density decreases, leading to the formation of **crystalline structure rime** - rime crystals form directly through the sublimation of water vapor resulting from the evaporation of droplets of fog or haze. Under severe frost, crystalline rime may form from water vapor contained in the air in the absence of fog or haze.

erroneously defined in the Instruction for meteorological stations as “an ice layer formed on objects due to freezing supercooled rain, drizzle, or fog…” In accordance with the International Meteorological Vocabulary (1992), *freezing rain, freezing drizzle* imply “precipitation drops freezing on impact to form a coating of clear ice (glaze) on the ground and on exposed objects”.

- *Rime (or freezing fog deposited rime)* (codes 48, 49) corresponds to “frost”, which, in contrast to the Vocabulary, is subdivided in the Russian source into “grained structure rime“ and “crystalline structure rime“ (formed through water vapor sublimation or the evaporation of fog droplets).

Thus the term "freezing rain" is primarily interpreted as "glaze", i.e. ice crust formed by precipitating supercooled rain or drizzle, its second meaning only being "freezing rain" proper.

This shifting of accents has occurred due to the hazards of glaze and grained structure rime and practical importance of weather forecasts for overland and airway transportation as well as for communication lines.

The history of shifting accents in the definitions of glaze phenomena dates back to the 1920-1930s. At that period, large-scale observations of glaze were initiated under the authority of the USSR Ministry of Railway Transportation which controlled a wide network of weather stations and observational posts. The interest in the practical aspect of this weather phenomenon, i.e., ice deposition on wires due to supercooled precipitation, has led to certain small changes in the definition of the term "freezing rain". This tendency can also be seen in meteorology, as concerns observations, and in handling climatological data for monthly bulletins. To avoid ambiguity, we only selected data in the WMO Codes.

All the types of FP and FF events have been subdivided in accordance with the standard weather international categories (WMO Doc. No. 306, Ed. 1988): 24 - freezing drizzle or freezing rain (observed at the station during the preceding hour but not at the time of observation); 48 - fog, depositing rime, sky visible; 49 - fog, depositing rime, sky invisible; 56 - drizzle, freezing, slight; 57 - drizzle, freezing, moderate or heavy (dense); 66 - rain, freezing, slight; 67 - rain, freezing, moderate or heavy.

2.3. Data characteristics

In particular, the following data were presented for each weather station: FP or FF events, location (city) observation date/time, current weather and the weather between observations, temperature, dew point temperature, relative humidity, air pressure, wind speed and direction, visibility, total and low cloud amounts, height of cloud base. Thus the collected ground observations have formed a data bank of 11141 FP and FF events reported across the whole territory for a decade.

We defined “FP event” or “FF event” as one record in 4-time observations. If we have one whole day of FP or FF, the event would correspond to 4 consecutive records. Fig. 1 shows the distribution by months of all the FP and FF events observed.

Apart from the Codes, data (the second data set) on the duration of wire ice coating have been collected for the 20-year period of 1971-1990 from 80 stations on the USSR ET and analyzed. As was noted above data on icing are considered to be of high importance for practical purposes. Therefore, we have analyzed the fields of both the duration of wire icing (caused by FP) and the daily duration of liquid precipitation at negative air temperatures. These durations are calculated based on continuous visual 8-time observations. Weather characteristics associated with FP and FF phenomena are also collected and analyzed for the territory of the former USSR.

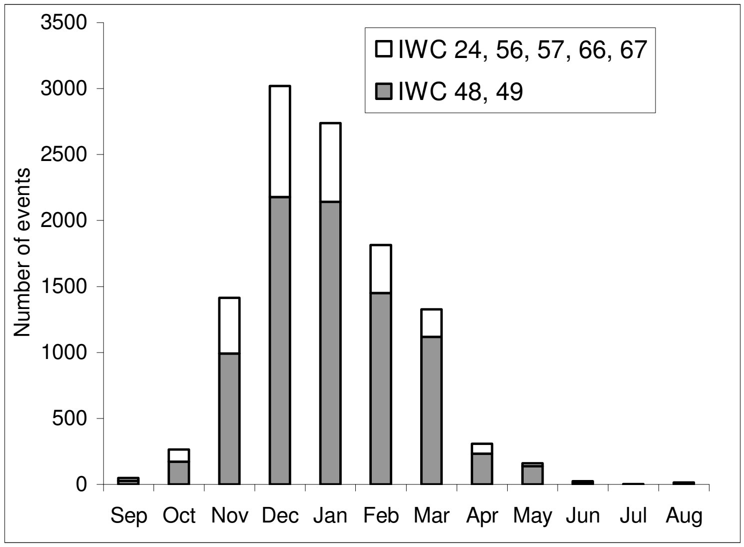


Fig. 1. Distribution by months of the total number of freezing precipitation (IWC 24, 56, 57, 66 and 67) and freezing fog (IWC 48, 49) events over the former USSR territory during a decade (1981-1990).

3. Weather conditions

For many years, some research teams in Russia were involved with studying atmospheric ice, freezing rain and such phenomena as glazed frost or rime, as well as their detrimental effects on aircraft, power lines, transport and communication (Zamorsky, 1955; Mazin, 1957; Buchinsky, 1955; Pchelko, 1963; Rudneva, 1967; Jakovlev, 1971; Abramovich, 1979; Baranov, 1983, Dubrovina, 1982 and others). Based on measurements from a specialized observational network, weather conditions under which ice accretion caused by FP and FF occurs have been summarized.

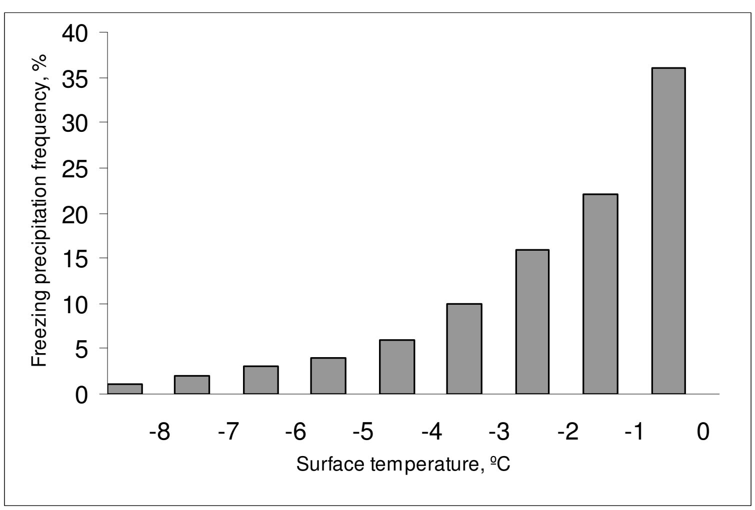


Fig. 2. Freezing precipitation frequency (%) versus surface air temperature (ºC) for the USSR European part (Buchinsky, 1960).

The extreme values of FP temperature range between 0º and –16ºC. Temperatures between 0º and –2ºC accounted for 58% of all FP events (Fig. 2). As temperature goes down, FP frequency decreases abruptly. On the average, glaze sheet density varies between 0.5 and 0.9 g cm^{-3}. According to Buchinsky (1960), Abramovich (1979), and others, the mean monthly air temperature for icing varies as shown in Table 2 for freezing precipitation and, for comparison, grained rime.

Table 2
Mean monthly air temperatures for icing over the USSR ET (Abramovich, 1979).

Precipitation type	X	XI	XII	I	II	III	IV
Freezing Precipitation	–	-1.6	-2.3	-2.9	-2.2	-1.4	–
Grained rime	0.0	-3.3	-5.1	-8.7	-11.8	-3.8	2.3

The FP frequency and its intensity depend on relative humidity. A 91-100% humidity accounts for 90% of all icing events. Observational stations at locations elevated relative to the surrounding terrain generally register 94% of icing occurrences at a 96-100% humidity.

Glazed frost thickness is defined as the thickness of an ice deposit (‘thin’ <5 mm, ‘moderate’ from 5 to 20 mm, ‘thick’ from 20 to 50 mm, and ‘very thick’ >50 mm). The thickness of an ice deposit depends on the duration and intensity of supercooled rain and freezing drizzle precipitation or the passing of advection fog, its liquid water content (in the case of rime). hours. Longer supercooled precipitation duration from 6 to 18 hours or more may results in the formation of severe glazed frost. With higher wind the number of drops falling onto an object per unit time increases, with icing intensity increasing as wind speed reaches 12 m/s (Abramovich, 1964). With wind direction normal to the ground surface, icing becomes more intense, resulting in thicker ice deposit on objects on windward slopes. Ice thickness also increases at wind-blown sites with an elevation over 50 m.

Rime can form in two essentially different ways - through water vapor sublimation and the freezing of supercooled fog drops, resulting in the formation of two types of rime - crystalline (CR) and grained (GR), respectively. The two processes generally occur at temperatures above –30ºC and, as a rule, in conditions of fog. It was only after numerous attempts by Bergeron (1938) that the WMO accepted his definitions of ice deposits in which the two types of rime represent different phenomena.

Grained rime (GR) is formed by the freezing of supercooled fog droplets on objects or on already frozen droplets of supercooled fog. This phenomenon is referred to as “freezing fog” (FF). Grained rime from the FF is a hazard to power lines, communication lines, and railway infrastructure. In the mountains, its deposits may be as thick as 2 m. “On February 24-25, 1939, the thickness of rime deposit formed from fog droplets in conditions of slight frost and wind reached 3-4 cm in Mineralnye Vody (H=302 m), 5-7 cm in Pyatigorsk (H=503 m), 12-20 cm on the slopes of the mountain Mashuk, and 100 cm on the mountain top (H=984 m).

Table 3
The frequency (%) of grained rime intensities at Debaltsevo station (177 events) (Buchinsky,1960).

Temperature range, ºC		Intensity (thickness) of grained rime accretion, mm			Frequency, %
From	to	Thin, 6-10mm	Moderate, 11-25mm	Thick, >26mm	
–1	–2	31	61	8	8
–3	–4	29	60	11	25
–5	–6	13	54	33	22
–7	–8	21	41	38	22
–9	–10	19	53	28	18
–11	–12	11	56	33	5

Rime extensions on the observation tower were as long as 1.5 m, and even the road was covered with rime extensions 10-20 cm long. The rime accretion rate was as high as 2 cm/hr.“ (Zamorsky, 1955)

The basic values of GR temperature range between –2º and –12ºC. Air temperatures between –3º and –8ºC account for 70% of all GR events (Table 3). On the average, GR density varies from 0.1 to 0.4 g cm^{-3}, or maximum 0.6 g cm^{-3} (Buchinsky, 1955).

Crystalline rime (CR) is a slight deposit of ice crystals formed through the sublimation of the air water vapor or that evaporated from fog droplets. The CR density is 0.01-0.05 g cm^{-3}, with a maximum density of 0.23 g cm^{-3}, according to observations on the mountain Yuksor, the Hibiny (Belenky, 1958), and the mean rime formation temperature ranges from –11° to –25°C. Generally, the CR does not make wires much heavier. However, if fog without wind persists for many days, the CR gradually grows, and the thinner the wire (or any other object), the sooner the CR layer grows thick enough to worsen communication via telephone and telegraph (Zamorsky, 1959). Zamorsky’s observations in Sverdlovsk (Ekaterinburg) and Leningrad (St. Petersburg) evidence that at temperatures from –20° to –30°C rime crystals’ growth rate in conditions of fog is 1 mm/hr, while at temperatures between –1 and –8°C it is not more than 0.5 mm/hr, which is in agreement with observations by F. Malmgren (1927).

The temperature range of CR formation is rather wide. The upper limit for the two types of rime is –1.2°C according to B.S. Gaponov (1939) and from –2° to –32°C according to A.D. Zamorsky (1955). The lower limit depends on the possibility of the existence of fog, i.e. liquid water droplets, whose lower temperature limit, according to Zamorsky, must be below –40°C. At some Siberian stations, rime was occasionally observed to form at temperatures below –40°C and even –50°C. Rime is often observed concurrently with fog even under severe frost (below –40°C). For example, rime and fog were observed on 8 January 1939 at Erofey Pavlovich station (Chita Region) at temperatures varying from –38° at night to –43°C before sunrise. Both rime and fog persisted till 11 a.m. (Zamorsky, 1955). Cases when rime and fog develop simultaneously are numerous, although at some stations (e.g. Yakutsk), rime is quite often observed in the absence of fog. As observed by Zamorsky (1955), only one case out of 37 failed to reveal any relation between rime and fog.

Note that the connection between fog and rime at temperatures below –40°C has been studied insufficiently. According to Zamorsky (1955), ”in the range from –2° to –30°C, a clear connection exists between rime and fog, while at very low temperatures (e.g. < –30°C) rime may occur without any visible signs of fog. This has led Zamorsky (1955) to introducing the new term ”Siberian rime”[2] (SR), or “Polar rime”, which is a specific type of rime at temperatures below –40°C without fog (i.e. without any visible signs of fog) under the conditions of the Siberian anticyclone. For crystalline rime to develop, even a very slight fog may be enough, the latter quickly turning to ice [3]. In this case, fog may lack the necessary formal feature – a less than 1-km visibility (without visible fog, rime develops much slower).

These considerations are reflected in the domestic “Forecast Handbook” (USSR, 1954), which states that for Siberian regions it is typical that rime forms at air temperatures less than –25°C without any condensation products observed, the air being close to saturation.

According to our data (see Section 5, Figs. 7b and 10b), 651 (in the Arctic) and 1418 (in Siberia) rime events were recorded, respectively, during the observational period; about 1/3 of these events in the Arctic and nearly 1/2 in Siberia occurring below –32°C. Our analysis builds upon the data obtained by independent observers from remote meteorological stations for decades. All the reports evidence the occurrence of Code 48 and 49 events under severe frost.

Thus, during the decade under consideration, numerous rime events with fog were recorded under severe frost. A question arises whether a water fog, though very slight, can occur at temperatures as low as –50°C or lower, otherwise it should be treated as an ice one. Natural condensation and sublimation processes at such low temperatures have been studies insufficiently. According to laboratory data, the minimum temperature for pure water drops is close to -45°C (Pruppacher and Klett 1989). In discussing the relationship between sublimation and condensation, Zamorsky (1955) wrote that with the lowering of temperature, the relative difference between the pressure of water vapor saturating air over water and that over ice increases. At -15°C, the relative difference between saturated water vapor pressure over water and that over ice amounts to 14%. Below –40°C, the air is considerably supersaturated over ice

[2] Siberian rime – a deposit of small ice crystals that slowly accretes (1 cm per day) on thin objects in very cold and calm weather without fog or haze.

[3] According to the Federal Meteorological Handbook (USA, 1998), sometimes, ice fog may occur simultaneously with fog. Such a condition usually persists for a few hours, while the normal fog changes to ice fog.

and undersaturated over water, and sublimation seems more likely. “However, these physical estimates must be corrected for the real atmosphere where a water drop is a solution of hygroscopic substances,” he said. Danilin A.I. (1936) showed that liquid water fog forms at negative temperatures even if humidity is less than 90%. It is also confirmed by P.I. Zimich (1988) based on observations of fogs at Pevek in the Arctic. The experimental evidence by B.V. Kiriukhin (1945) also shows the closeness of the densities of saturated water vapor over a droplet of water solution and over ice. “This leads one to the conclusion that the frequency of water vapor reaching ice supersaturation, without condensation starting simultaneously, is low,” Zamorsky wrote in 1955. Experiments in Wilson chamber (Tverskoi, 1962; Mason, 1957) showed that below –41°C a fog consisting of ice crystals forms at supersaturation over a flat water surface rather than over ice. Therefore, even at –41°C a liquid phase forms prior to a solid phase, i.e. ice crystals.

The Siberian climate is characterized by frequent haze, fog, and ice fog under surface subsidence inversion in the Siberian anticyclone. Excessive water vapor in this case is formed due to the radiative cooling of air, vapor transport from higher layers of surface inversion and from local anthropogenic sources. Different sources of liquid water evaporation - home ovens, running engines, steam locomotives at railway stations, moisture breathed out by herds of cattle and deer, as well as people[4] - lead to rapid air saturation, producing a great number of microscopic droplets to form fog and ice fog. In the 1950s, new sources such as industrial zones, cellulose plants, thermoelectric power stations, and, especially, gigantic partly non-freezing water reservoirs built in Siberia were added.

4. Synoptic and climatic conditions

The most intense and durable ground icing is observed in zones of supercooled rain falling from As-Ns cloud systems that are at an intensive development stage, have the highest moisture content, and are associated with active fronts. Fig. 3 shows the distribution by months of the frequency (%) of different cloud types (Cu-Cb, Ns (As-Ns) as well as St and supercooled Sc with temperatures below -3ºC throughout the layer) for some cities of the former USSR as obtained from airborne measurements (Dubrovina, 1982).

The maximum frequency of clouds, except Cu-Cb, is observed in winter, between January and March (Fig.3). The maximum frequency of freezing precipitation is also observed in winter, between December and January (Fig.1).

According to Dubrovina, the highest frequency of drizzle in winter over the USSR

[4] The breathing of one man only saturates 40 m^3 of air per minute at a 90% humidity and –40°C.

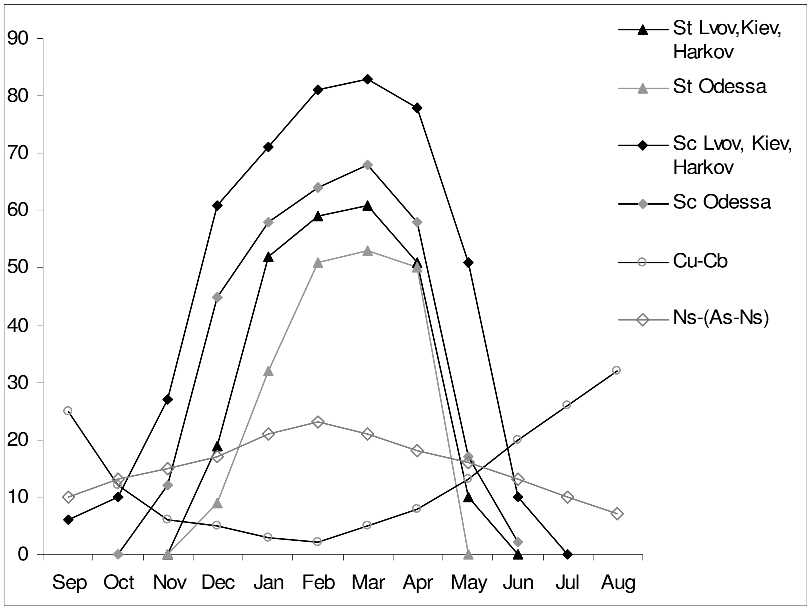


Fig. 3. The distribution by months of the frequency (%) of different cloud types (Cu-Cb, Ns-(As-Ns) as well as St and Sc with temperatures less than -3°C throughout the layer for the southwestern part of the USSR including the Ukraine (Dubrovina, 1982).

territory is due to St clouds (Table 4) accounting for almost 2% of the total winter precipitation amount (based on airplane sounding data). In winter and particularly in autumn, drizzle occurs most closely to the ground in the central and southern parts of the ET (below 0.4 km).

Many authors such as Noth (1930), Pchelko (1963), Alexandrova (1957), and Baranov (1983) believe that 3/4 of all cases of ground icing are related to fronts, while only 1/4 are accounted for by uniform air masses. The mean intensity of ice accretion for the FP connected with atmospheric fronts is 10 g/hr, with a maximum intensity of 40 g/hr per meter length of a wire. The mean intensity of ice accretion for the FP associated with uniform air masses is 5 g/hr, with a maximum of 22 g/hr per meter length of a wire (Buchinsky, 1960).

Table 4
The frequency (% of precipitation amount) of drizzle for different cloud types in winter (December - February) over the USSR (Dubrovina, 1982).

Precipitation type	Sc	St	Ns-(As-Ns)	Ac	As	Cs	Unknown cloud type	Total
Drizzle	0.1	1.7	0.1					1.9
Rain	0.9	0.5	1.6				< 0.1%	3.1
Snow	16.4	2.6	16.4	16.4	15.8	28.4	2.1	90.1
Mixed	0.6	0.2	2.8	0.3	0.9		0.1	4.9
Overall precipitation	18.0	5.0	20.9	16.1	29.3	8.4	2.3	100
The number of aircraft ascents	1934	533	2241	1729	3141	901	233	10712

Ground icing depends on the type of cyclone trajectory, the type of the front and its intensity. In winter, the cyclones over the ET travel along the following trajectories (Krizhanovskaya, 1977; Bezrukova, 1994): northern or northwestern (N-NW), western (W), southern or southwestern (S-SW). The most severe icing events are associated with warm fronts (S-SW) between the masses of maritime tropical air (0ºC to + 5ºC) and the air of middle latitudes (–5º to –10ºC). The mechanism of freezing rain formation due to the melting of hydrometeors in a warm layer between 500 and 1500 m and in the lower air layer with negative temperatures was discussed as early as at the beginning of the last century. This mechanism, as well as some other ones, was considered by different authors, Zamorsky (1955) and Knight (1979) among them.

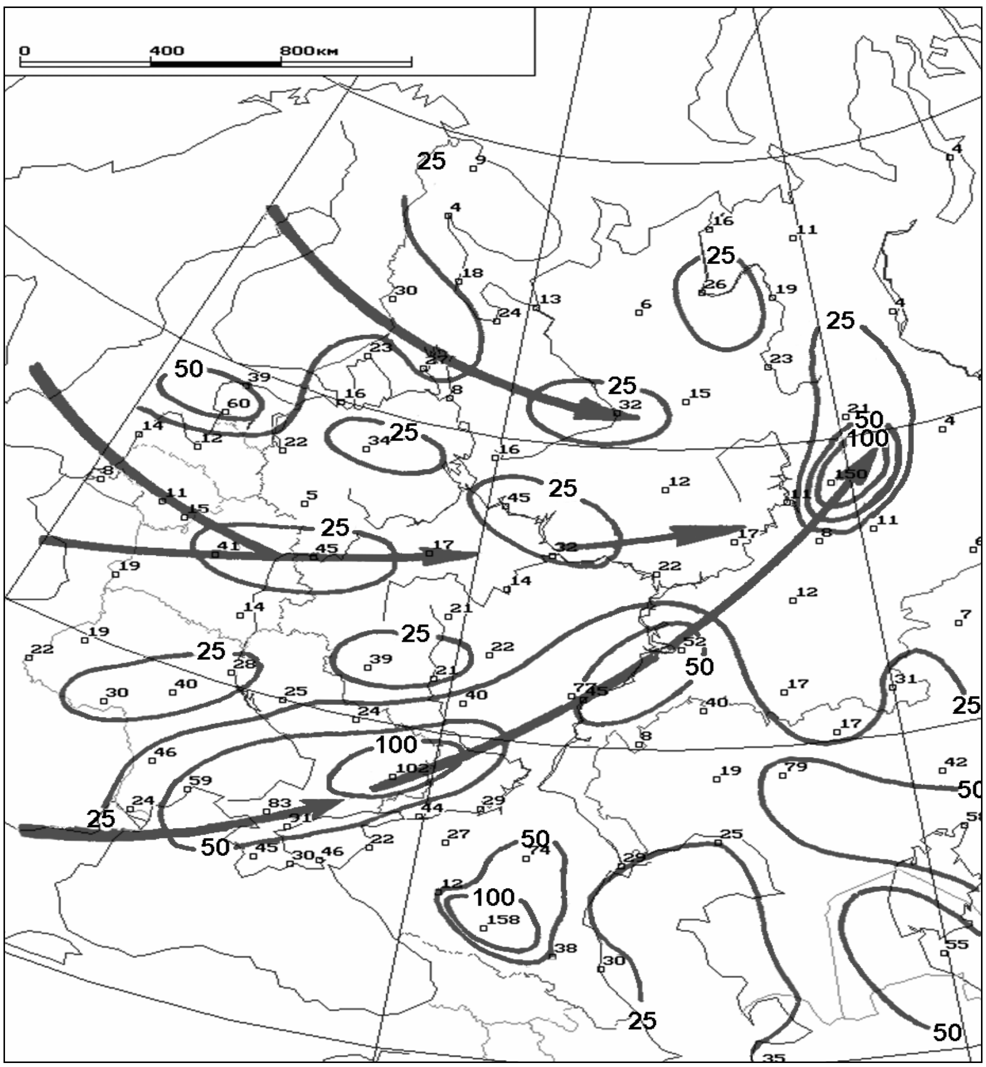


Fig. 4. Mean monthly duration (in hours) of ice coating on a wire caused by freezing rain on the ET in February and typical cyclone trajectories (Krizhanovskaya, 1977). The maps of Atlas analyzed manually and constructed by Prof. L S. Minina on the basis of the second data set (see Section 2.1). The station locations with mean monthly 'ice coating duration' (the period, in hours, during which ice remains on a wire) are indicated.

Our study analyses the spatial distribution of icing duration (in hours) and the basic cyclone paths in cold seasons for the ET taken from Krizhanovskaya's atlas (1977). Figure 4 exemplifies such a map of icing durations (in hours) in February. The frequency distribution of icing events over the ET is far from uniform. However, despite this non-uniformity, the general features of icing duration correspond to the climatic and synoptic conditions of the area concerned. In general, the southern part of the ET, where the Mediterranean cyclones carrying warm and moist air are most frequent, is exposed to icing most of all. In the south, icing is known to damage communication and power transmission lines quite often and at times even to break electric cable poles. Ice deposit weight may exceed that of the wire; the wires may twist, and thus wire dancing begins in the wind.

In the northern part of the ET, icing is far less frequent than frost or rime. As shown in Fig.4, in the central part of the ET, mainly on a high ground, there are zones of ice coating duration maximums associated with the passage of westerly cyclone fronts.

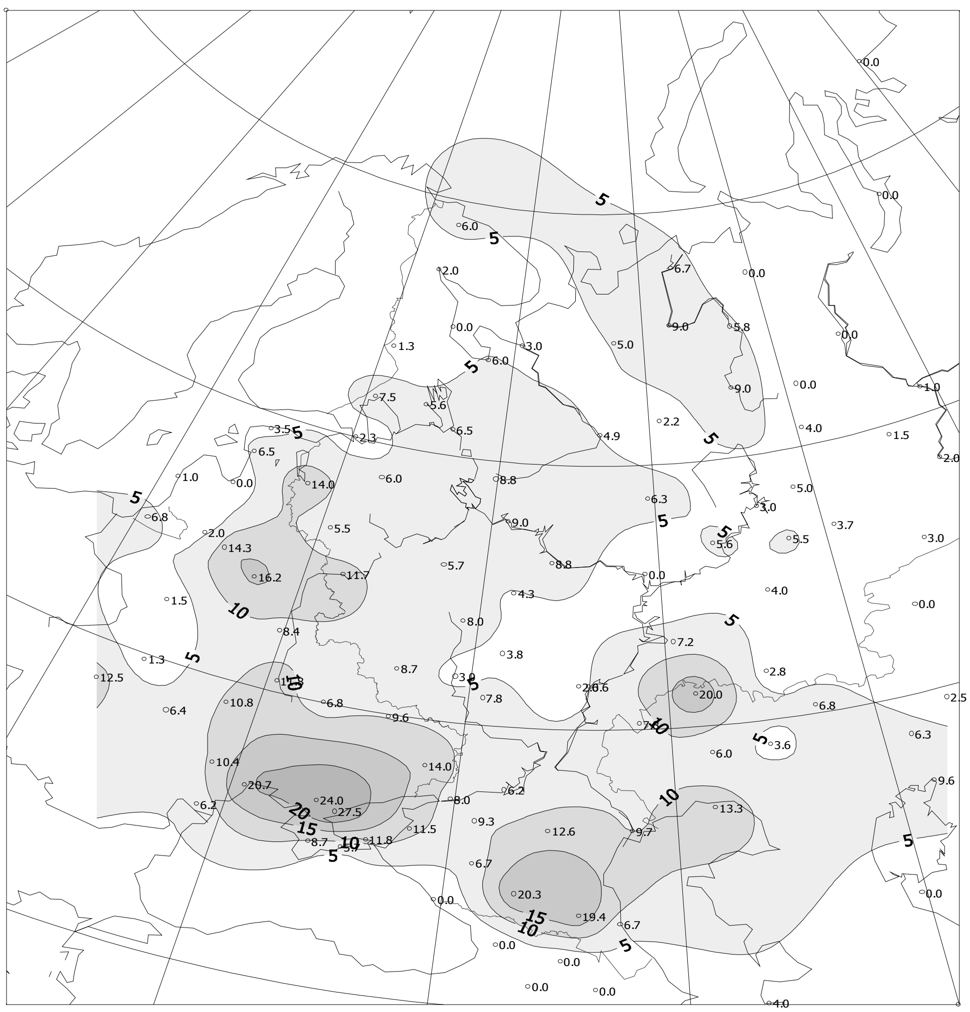


Fig. 5. Mean monthly duration of liquid precipitation at negative temperatures on the ET in February (an electronic version of the map). The station locations with mean monthly duration of liquid precipitation (in hours) are indicated.

In the eastern part of the ET, essentially no freezing precipitation is caused by the Siberian anticyclone which creates a steady background of negative temperatures.

Figure 5 shows a map of the distribution of liquid precipitation at negative temperatures on the ET in February. It can be seen that this pattern is in a fairly good agreement with the previous map that shows the field of ice coating duration due to freezing precipitation for the same period (except Ivdel station, 60°N, which is located as low as 101 m a.s.l. behind the Urals, where at mean liquid precipitation duration in February up to 4 hr. an ice deposit remains on a wire for about 100 hr.) The longest liquid precipitation duration is also recorded in the southern part of the ET most often influenced by the Mediterranean cyclones; at the fronts of these cyclones, the moist air carried by them actively interacts with the ET cold air.

5. Freezing precipitation and freezing fog statistics

5.1 The distribution of FP and FF events by the WMO Weather Codes

The distribution of the overall number of FP and FF events by the Weather Codes is as follows. The overwhelming majority of the events observed, 1998 and 6470 ones (Table 5), respectively, are accounted for by Codes 48 and 49. In 1751 and 533 cases, Code 56 and 66 events, respectively, were observed, while the least number (50) of events are those designated by Code 67.

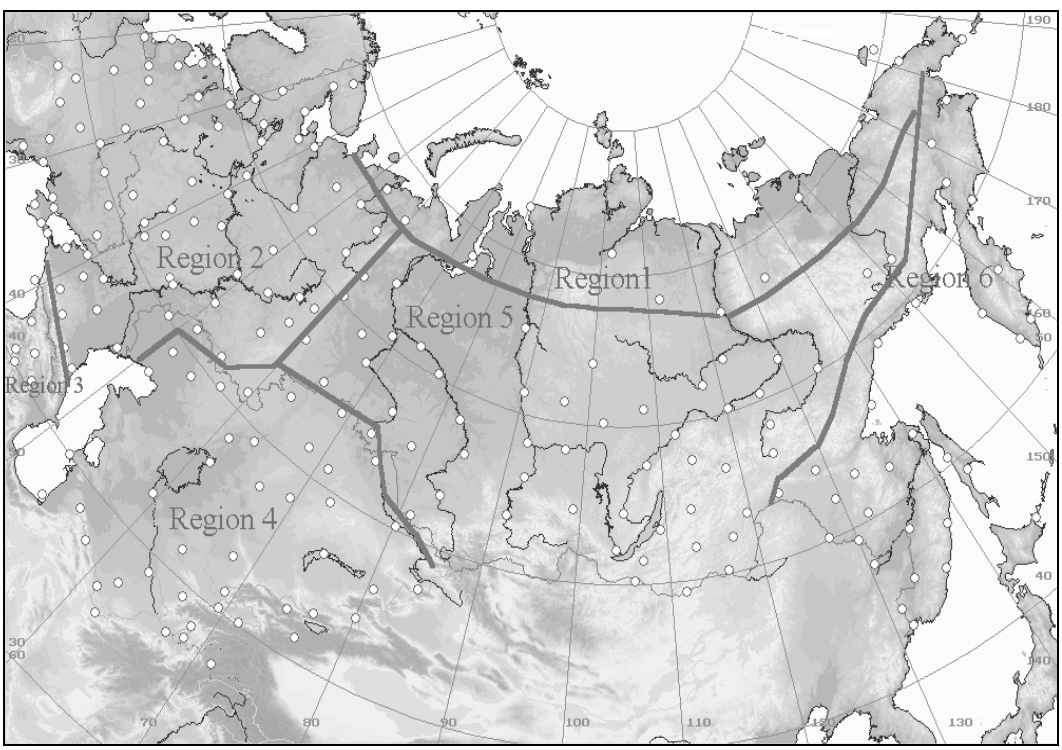


Fig. 6. The station locations (circles) for six USSR regions.

5.2 The distribution of FP and FF events by regions

The raw data on the FP come from 223 stations of the former USSR. These stations are located in various climatic zones, from the Arctic tundra to subtropical deserts. The northernmost station is located at 73°30' N (Dickson Island) and the southernmost (Kushka) at 35°17' N. The western- and easternmost stations are at 20°37' E (Kaliningrad) and 173°16' W (Providenia Bay), respectively. The entire territory was divided into six principal regions in accordance with their physiographical and climatological features (Fig. 6.). Each of the 223 stations corresponds to one of the six regions:

1. THE ARCTIC (11 stations). This region included all the stations located on the Arctic coast and in the northern part of Siberia inside the Polar Circle, with the exclusion of Murmansk and Kandalaksha stations located on the Kola Peninsula.

2. THE EUROPEAN PART OF THE FORMER USSR (80 stations). This region included all the European stations, except the stations located inside the Polar Circle: Hoseda-Hard and Narian-Mar.

3. THE TRANS-CAUCASUS (6 stations). This region included all the stations located south of the Great Caucasus Range.

4. CENTRAL ASIA (42 stations). This region included all the stations located in Kazakhstan, Turkmenistan, Uzbekistan, Kirgizia, and Tajikistan.

Table 5
Distribution of events with freezing precipitation by Weather Codes in different regions of the USSR

Codes		24	48	49	56	57	66	67	Total
Region 1 Arctic	No	12	327	324	94	5	9	–	771
	%	2	42	42	12	<1	1	–	100
Region 2 European part	No	127	541	3529	1410	122	423	32	6184
	%	2	9	57	22	2	7	<1	100
Region 3 Trans – Caucasus	No	–	6	67	–	–	–	–	73
	%	–	8	92	–	–	–	–	100
Region 4 Central Asia	No	23	351	1514	181	34	72	16	2191
	%	1	16	69	8	2	3	<1	100
Region 5 Siberia	No	6	635	783	35	4	28	2	1493
	%	<1	42	52	2	<1	2	<1	100
Region 6 Far East	No	2	138	253	31	4	1	–	429
	%	<1	32	59	7	<1	<1	–	100
Total	No	170	1998	6470	1751	169	533	50	11141
	%	1.5	18	58	16	1.5	5	0.5	100

5. SIBERIA (53 stations). This region included all the stations of Western Siberia and Eastern Siberia, except the stations located on the Pacific coast and the Far East territory.

6. THE FAR EAST (31 stations). This region included all the stations located in Habarovsk Region, Primorsk Region, Kamchatka, Sakhalin, and the coast of the Sea of Okhotsk.

The frequency of the FP and FF in the six regions is given in Table 5. On the whole, the recorded number of the events decreases from north to south and from west to east.

5.3 Statistical characteristics of FP and FF events as related to temperature

The Arctic region experienced 771 events. As for the other regions, weather types coded 48 and 49 (fog-deposited rime) prevail here, accounting for 84% of events. Freezing rain and drizzle are rather seldom - 16% (Fig. 7a). In this region, numerous events with Codes 48, 49 (Fig. 7b) were observed at very low temperatures and higher pressure (>1015hPa). Below –30ºC, 234 events with Code 48 (fog, depositing rime, sky visible) and only 4 with Code 49 (fog, depositing rime, sky invisible) were recorded, i.e. at such temperatures, in the Arctic region, rime formation is mainly associated with 'fog, sky invisible'.

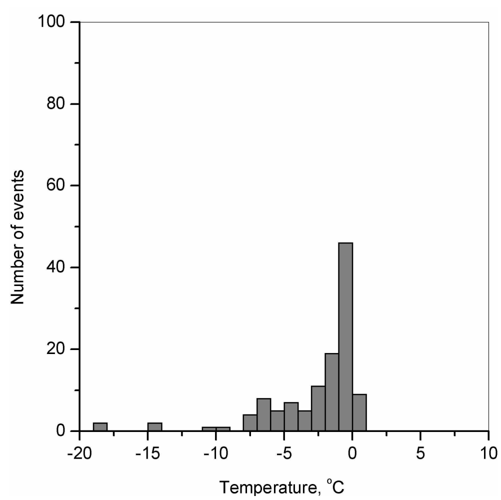


Fig. 7a. The distribution of Codes 24, 56, 57, 66 and 67 versus temperature (the Arctic).

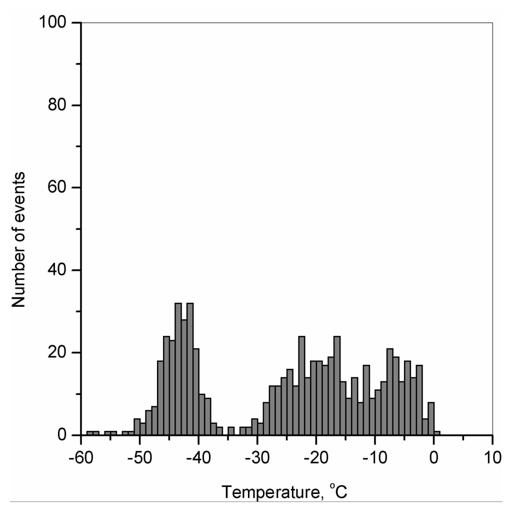


Fig. 7b. The distribution of Codes 48 and 49 versus temperature (the Arctic).

More than half of all the events (6184) occurred on the *European territory of the USSR* (Fig. 8a, 8b). On the average, this region saw 77 events per station during a decade, two thirds of the events being rime (Codes 48, 49). However, as compared to the Arctic region, freezing rain and drizzle are more frequent (33%). This is, naturally, because cyclones from the Atlantic and the Mediterranean play an important role in the FP formation in this region. Most events occurred at temperatures above –10ºC and low pressure (995-1010 hPa), with the number of events increasing as temperature rose to 0ºC. About 40% of the events were observed at a cloud base height less than 100 m.

In the *Trans-Caucasus region*, the relations between the parameters concerned, in terms of statistics, are the least representative as being hard to compare. Only 73 events (with Codes 48 and 49) occurred there, with 5 out of the 6 stations located in mountain valleys at different heights. On the average, this region saw 12 rime events per station, which is much less than in the other regions. No freezing rain or drizzle was observed there.

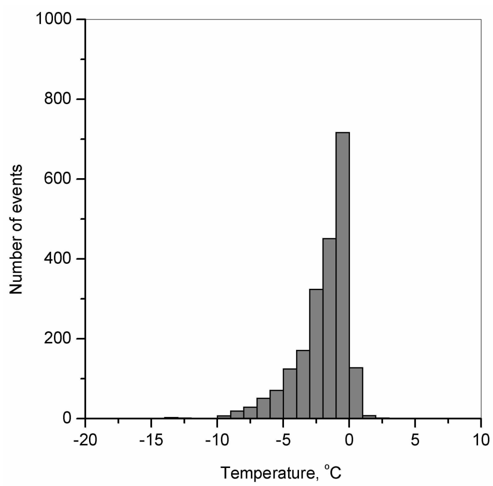


Fig. 8a. The distribution of Codes 24, 56, 57, 66 and 67 versus temperature (USSR ET).

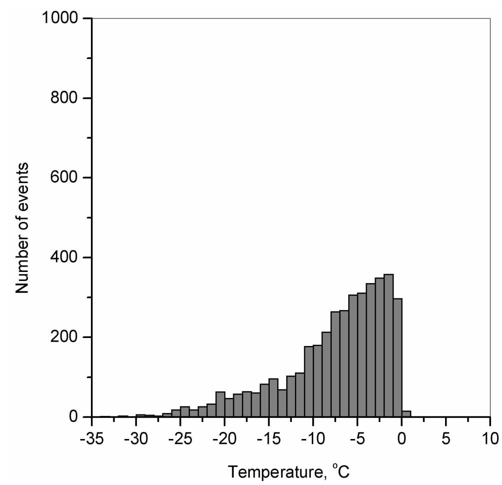


Fig. 8b. The distribution of Codes 48 and 49 versus temperature (USSR ET).

In *Central Asia*, the occurrence of FP events versus temperature was the same as on the ET (Fig. 9a). By the number of events - 52 per station - this region holds the third place, with 69% being freezing rain and freezing drizzle, and 31% being fog-deposited rime. Most events occur at temperatures 0–10ºC. However, the rate at which the number of FP events decreases as the temperature goes down is lower.

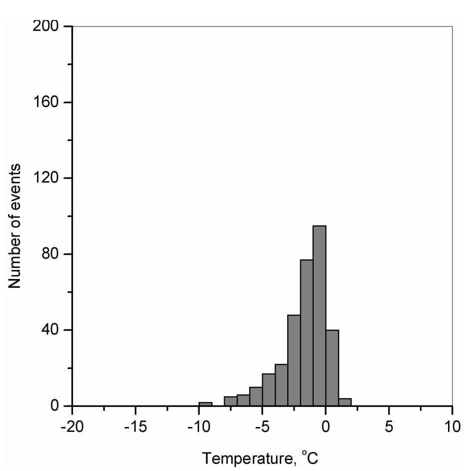


Fig. 9a. The distribution of Codes 24, 56, 57, 66 and 67 versus temperature (Central Asia).

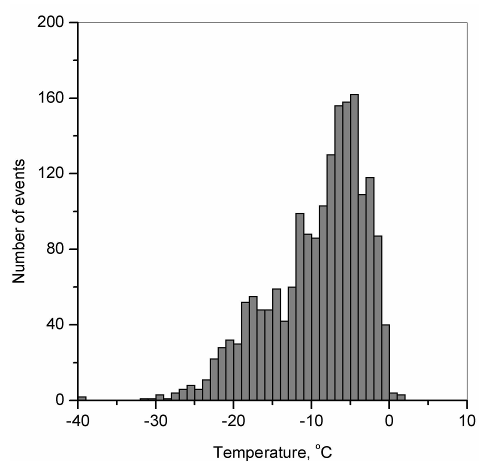


Fig. 9b. The distribution of Codes 48 and 49 versus temperature (Central Asia).

This can be attributed to a more pronounced continental climate and the fact that many stations are located in the central and northern Kazakhstan with the meteorological conditions similar to those in Western Siberia. When analyzing the dependence of the frequency of the events on pressure, one should bear in mind that some stations are located high above the sea level (e.g., Naryn at 2049 m a.s.l. and Khorog at 2080 m a.s.l.).

The total number of events at 53 *Siberian stations* was 1493, or 28 events per station. Freezing rain and drizzle occurred in less than 6% of events. Fog-deposited rime (Codes 48 and 49) contributed 94% of the total number, with half of them occurring below –32ºC. Below –30ºC where, according to Zamorsky, the Siberian rime is not directly associated with fog, 71% of events with Code 48 and 45% with Code 49 were recorded.

In Siberia (Fig. 10b), similar to the Arctic (see Fig. 7b), the distribution of Codes 48 and 49 versus temperature was typically bimodal, with the highest frequency recorded at temperatures from –40 to –50ºC, which is characteristic of the Siberian winter under anticyclone conditions. These estimates are also supported by the distribution of the number of events versus pressure. The largest number of events was observed at 1010-1015 hPa. Most stations in the region are situated several hundred meters a.s.l.[5]

It is noteworthy that in the variation of the dependence of Codes 48 and 49 occurrence on temperature, two maximums in the Arctic (Fig. 7b) and two ones in Siberia (Fig. 10b) can be seen. The first maximum in each case is in the range from –10 to –20°C, the second maximum in both regions is between –40° и –50°C. Between these maximums, one can see a clear minimum of the occurrence of such events, which is the same for the two regions in a temperature range from –32° to –35°C, i.e. practically no rime forms here. It is quite clear that the two sets of maximums are due to different microphysical rime-formation conditions.

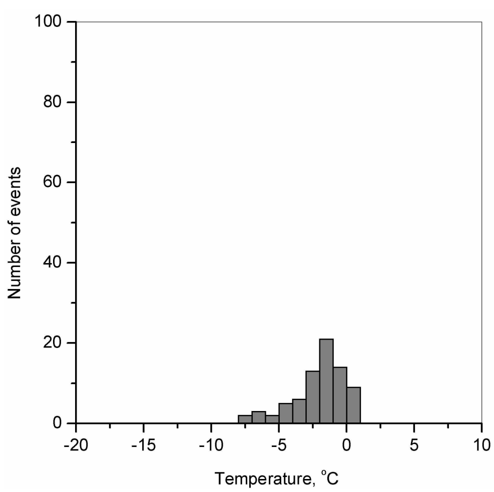


Fig. 10a. The distribution of Codes 24, 56, 57, 66 and 67 versus temperature (Siberia).

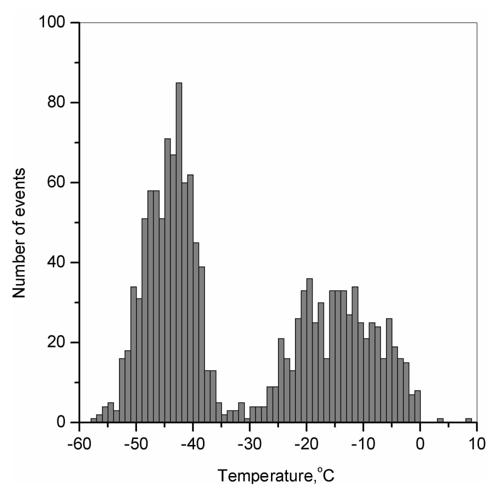


Fig. 10b. The distribution of Codes 48 and 49 versus temperature (Siberia).

[5] A higher station level is associated with a higher fog occurrence due to forced updrafts as well as to the decrease of the level of clouds that cover the highland and may be taken by the observer for a fog

The Far East region includes 31 stations, half of which are located directly on the Pacific coast of Russia. This region is characterized by a small number of FP events. On the average, 13.8 events per station were observed there (429 events all in all). The Codes 48, 49 (fog-deposited rime) contributed 91% of events. Their maximum occurrence was observed between 0 and –10ºC (Fig. 11a) with the cloud base height within 0-100 m.

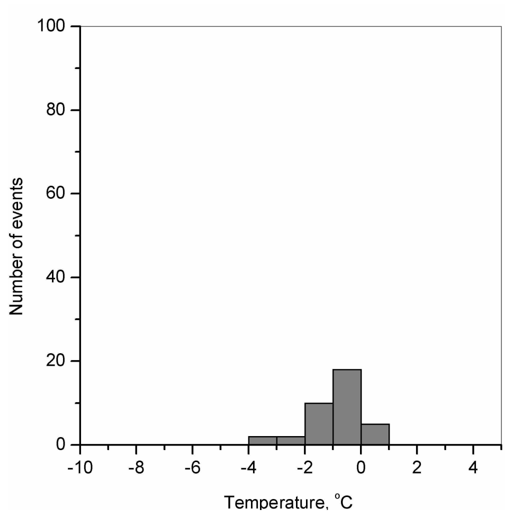


Fig. 11a. The distribution of Codes 24, 56, 57, 66 and 67 versus temperature (Far East).

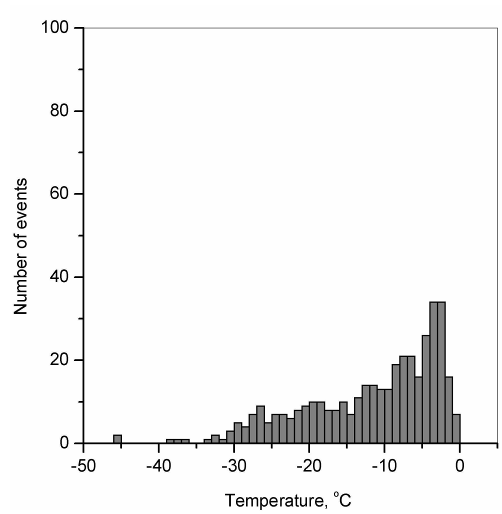


Fig. 11b. The distribution of Codes 48 and 49 versus temperature (Far East).

6. Ice coating duration depending on altitude

Apart from the conditions discussed above, the spatial distribution of both ice coating occurrence and duration depends on the altitude and relief of the site. Most exposed to icing are areas located at higher levels and on upwind slopes. We ventured to estimate the relation between the altitude and ice coating duration for various ET areas. This relation has proved to be quite pronounced for the central part of the ET within the region 45–60ºN; 30–60ºE.

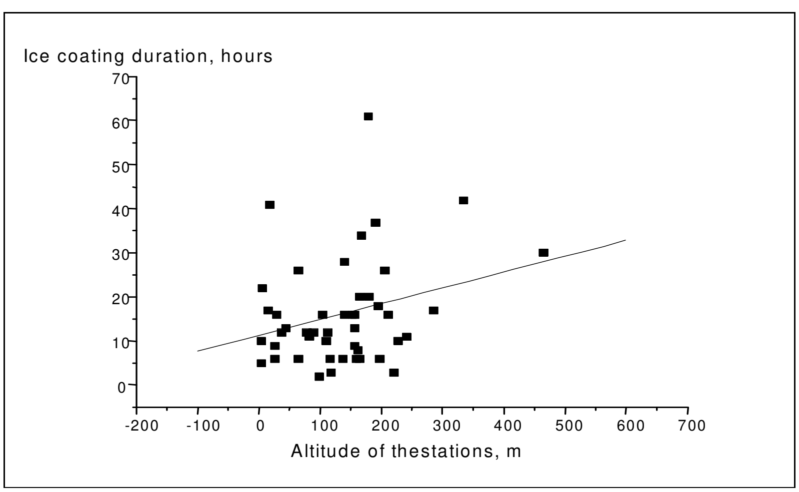


Fig. 12. The dependence of ice coating duration on altitude in the central part of the ET, November, $P < 0.01$ (P is a significance level).

The correlation coefficient has been found to be 0.2-0.3 in October, 0.6-0.7 in November and December (Figs. 12 and 13), and 0.5-0.6 in January.

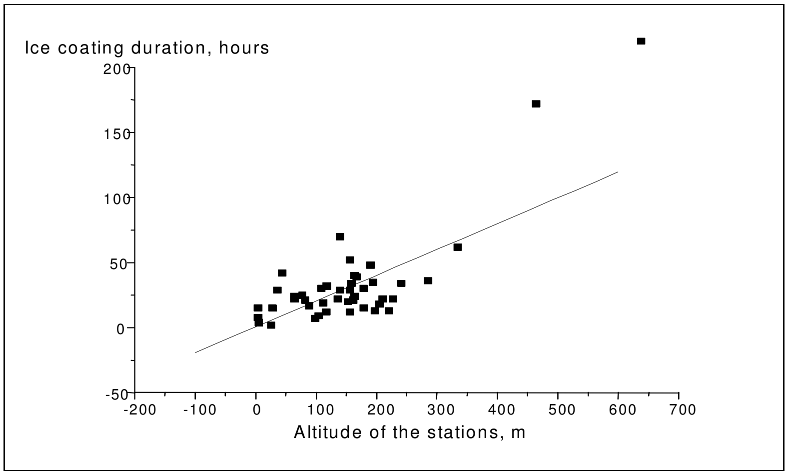


Fig. 13. The dependence of ice coating duration on altitude in the central part of the ET, December, $P < 0.01$ (P is a significance level).

The closer relation between the duration of ice coating and altitude in November – January is due to the climatic factors: a steady winter circulation with low ground air temperatures settles, i.e. the likeliness of significant contrasts and deep inversions is preserved at the fronts with relatively warm air advection.

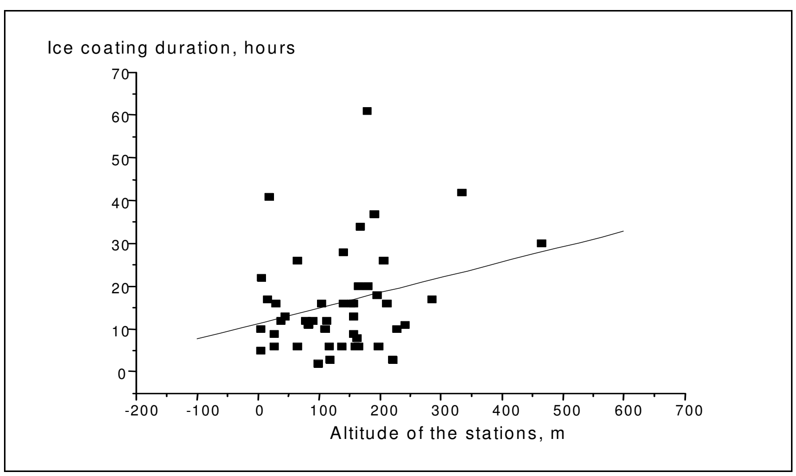


Fig. 14. The dependence of ice coating duration on altitude in the central part of the ET, March, $P=0.06$ (P is a significance level).

The correlation coefficient has been found to be 0.2 -0.3 in February and March (Fig. 14). The loosening of this relation in February and March is due to the circulation change, the warming, and the lower probability of considerable temperature contrasts at the fronts, i.e. of the fronts' activity and deep inversions.

7. Maps of freezing precipitation and rime distribution

The construction of climatic maps presents certain difficulties. Particularly, this refers to observational data on glaze and rime as the investigation of the regularities of such phenomena is complicated by the complexity of their spatial distribution, the methodological imperfection of their measurements, and confusion in their definitions. In order to avoid this ambiguity, the authors used a decade-long database on freezing precipitation and rime (1981-1990) recorded in the WMO Codes. The maps constructed present the occurrences of the respective codes. Also constructed are maps of the mean monthly duration (in hours) of both icing on wires and liquid precipitation at negative temperatures on the USSR ET for two decades (1971-1990).

The only atlas of glaze and rime occurrence for the USSR territory was compiled 45 years ago by A.D. Zamorsky and A.V. Rudneva and has to be updated based on current observations. The basic features of the spatial distribution of the freezing precipitation and rime occurrences mapped in the atlas being constructed by the authors of this paper are in agreement with the old one. Below we present the maps of the distribution of mean monthly FP (Codes 24, 56, 57, 66, and 67) and FF (Codes 48 and 49) occurrences over the USSR territory for some cold months.

Conclusion

The output of this work is a set of maps of freezing precipitation and rime for the territory of the former USSR, which is to be included in the new atlas, with part of the maps presented in this paper. A 10-year statistics was used by the authors to construct the maps of the annual mean and monthly mean occurrences of these phenomena for the whole USSR. The entire territory was divided into six major regions: the Arctic, the European part of the USSR, the Trans-Caucasus, Central Asia, Siberia, and the Far East. For the USSR ET, maps of the duration (in hours) of icing on wires and liquid precipitation duration at negative temperatures were constructed based on a 20-year statistics. A good agreement is observed between icing duration maximums and the main cyclone paths.

The relations between the distribution of the number of events, air temperature and elevation of the stations have been obtained for all the six USSR regions considered. This work has been fulfilled at the Central Aerological Observatory jointly with several co-authors from other research institutes. The atlas of maps discussed is available at CAO's Web site http://www.cao-rhms.ru.

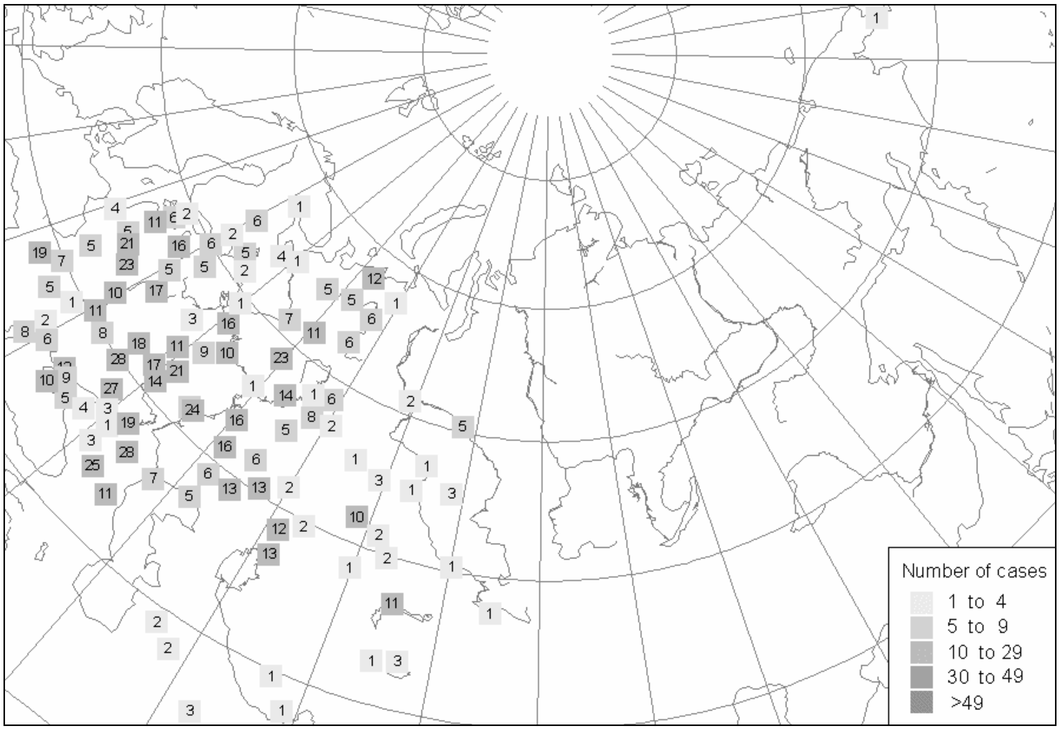


Fig. 15. The number of events (cases) with freezing precipitation (Codes 24, 56, 57, 66, and 67) over the USSR territory in December.

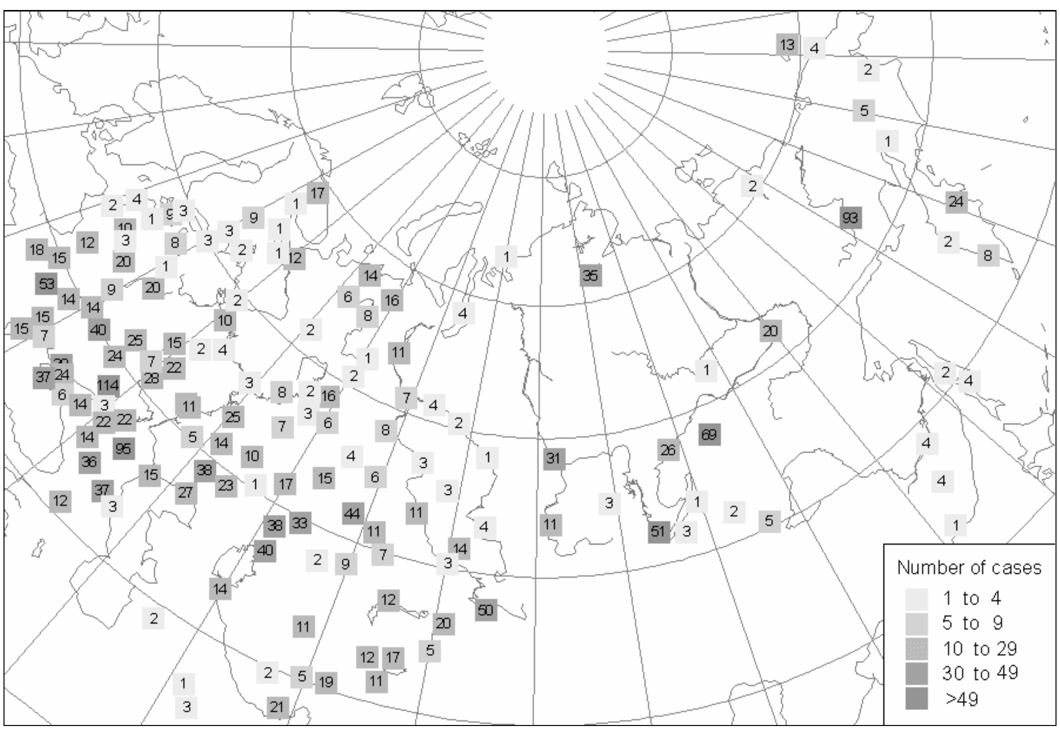


Fig. 16. The number of events (cases) with freezing fog-deposited rime (Codes 48 and 49) over the USSR territory in December.

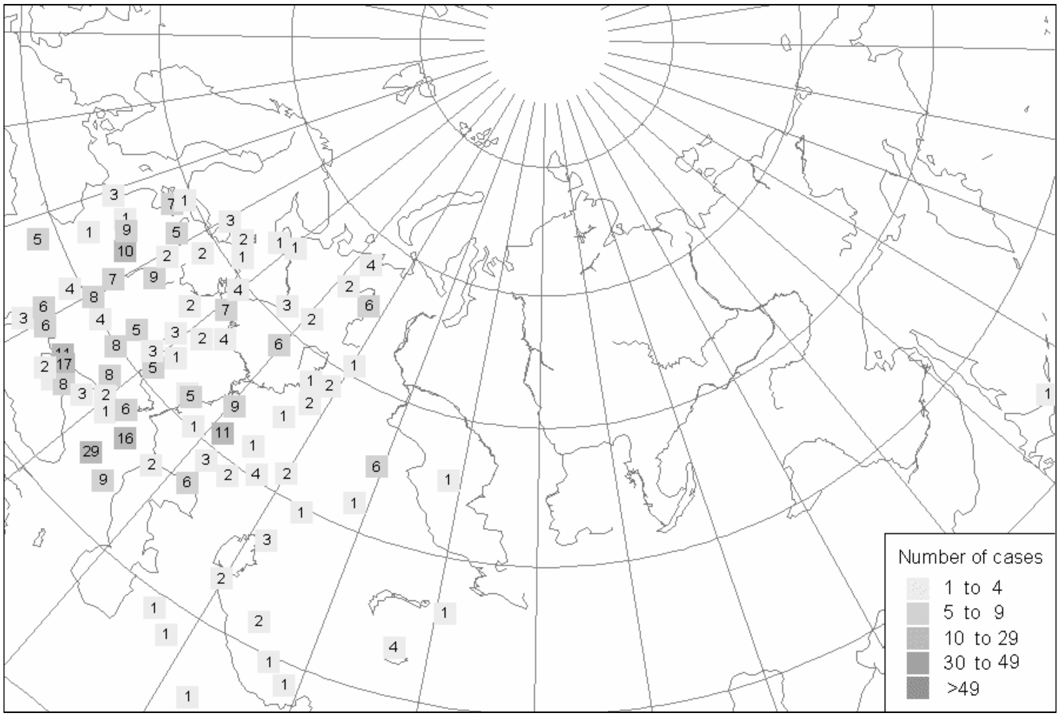


Fig. 17. The number of events (cases) with freezing precipitation (Codes 24, 56, 57, 66, and 67) over the USSR territory in February.

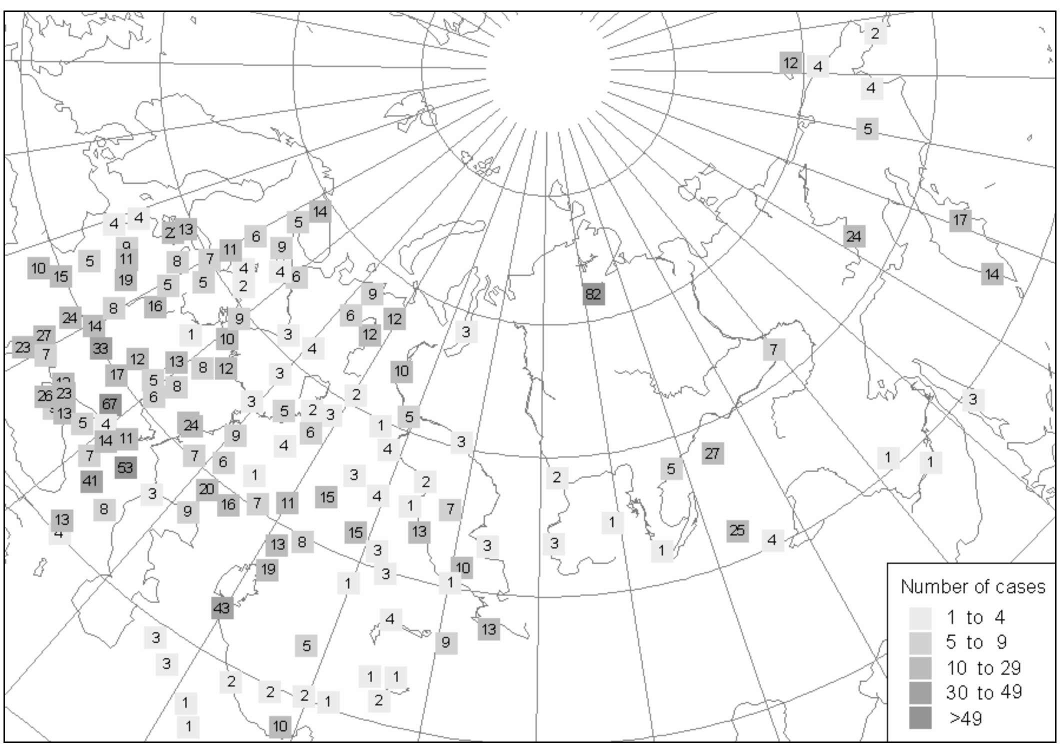


Fig. 18. The number of events (cases) with freezing fog-deposited rime (Codes 48 and 49) over the USSR territory in February.

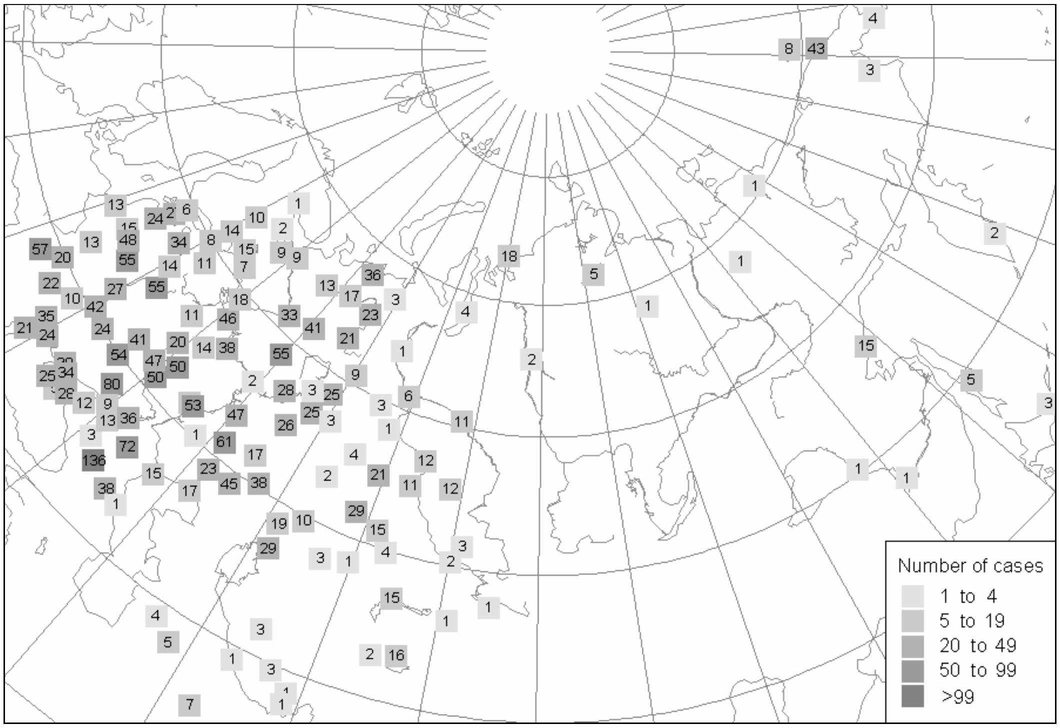


Fig. 19. The total number of events (cases) with freezing precipitation (Codes 24, 56, 57, 66, and 67) over the USSR territory during 10 years.

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The maps were first manually constructed in isohyets and analyzed by Prof. Ludmila S. Minina and then transformed to an electronic version by Galina A. Kalugina who greatly contributed to making the maps more complete.

Sincere thanks are also extended to the specialists from different institutes and archives who assisted a lot in the collecting of data.

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Figure captions

Photo: *Professor A.D. Zamorsky*

Fig. 1. Distribution by months of the total number of freezing precipitation (IWC 24, 56, 57, 66 and 67) and freezing fog (IWC 48, 49) events over the former USSR territory during a decade (1981-1990).

Fig. 2. Freezing precipitation frequency (%) versus surface air temperature (ºC) for the USSR European part (Buchinsky, 1960).

Fig. 3. The distribution by months of the frequency (%) of different cloud types (Cu-Cb, Ns-(As-Ns) as well as St and Sc with temperatures less than -3ºC throughout the layer for the southwestern part of the USSR including the Ukraine (Dubrovina, 1982).

Fig. 4. Mean monthly duration (in hours) of ice coating on a wire caused by freezing rain on the ET in February and typical cyclone trajectories (Krizhanovskaya, 1977). The maps of Atlas analyzed manually and constructed by Prof. L S. Minina on the basis of the second data set (see Section 2.1). The station locations with mean monthly 'ice coating duration' (the period, in hours, during which ice remains on a wire) are indicated.

Fig. 5. Mean monthly duration of liquid precipitation at negative temperatures on the ET in February (an electronic version of the map). The station locations with mean monthly duration of liquid precipitation (in hours) are indicated.

Fig. 6. The station locations (circles) for six USSR regions.

Fig. 7a. The distribution of Codes 24, 56, 57, 66 and 67 versus temperature (the Arctic).

Fig. 7b. The distribution of Codes 48 and 49 versus temperature (the Arctic).

Fig. 8a. The distribution of Codes 24, 56, 57, 66 and 67 versus temperature (USSR ET).

Fig. 8b. The distribution of Codes 48 and 49 versus temperature (USSR ET).

Fig. 9a. The distribution of Codes 24, 56, 57, 66 and 67 versus temperature (Central Asia).

Fig. 9b. The distribution of Codes 48 and 49 versus temperature (Central Asia).

Fig. 10a. The distribution of Codes 24, 56, 57, 66 and 67 versus temperature (Siberia).

Fig. 10b. The distribution of Codes 48 and 49 versus temperature (Siberia).

Fig. 11a. The distribution of Codes 24, 56, 57, 66 and 67 versus temperature (Far East).

Fig. 11b. The distribution of Codes 48 and 49 versus temperature (Far East).

Fig. 12. The dependence of ice coating duration on altitude in the central part of the ET, November, $P < 0.01$ (P is a significance level).

Fig. 13. The dependence of ice coating duration on altitude in the central part of the ET, December, $P < 0.01$ (P is a significance level).

Fig. 14. The dependence of ice coating duration on altitude in the central part of the ET, March, $P=0.06$ (P is a significance level).

Fig. 15. The number of events (cases) with freezing precipitation (Codes 24, 56, 57, 66, and 67) over the USSR territory in December.

Fig. 16. The number of events (cases) with freezing fog-deposited rime (Codes 48 and 49) over the USSR territory in December.

Fig. 17. The number of events (cases) with freezing precipitation (Codes 24, 56, 57, 66, and 67) over the USSR territory in February.

Fig. 18. The number of events (cases) with freezing fog-deposited rime (Codes 48 and 49) over the USSR territory in February.

Fig. 19. The total number of events (cases) with freezing precipitation (Codes 24, 56, 57, 66, and 67) over the USSR territory during 10 years.