Ice rains in the Middle Urals

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Abstract. This article is devoted to ice rains in the Urals. The occurrence of events in the cold period of 2019–2020 is considered. The diurnal course of an event is revealed, and the frequency of the accompanying ice is established. The physical and synoptic conditions of ice rain are studied. A comparison of the state of the atmosphere during a period of ice rain, freezing precipitation and in the absence of phenomena is carried out. Radar data of ice rain events which cause heavy ice and significant material damage are presented. It has been found that the ice rains in the Middle Urals are formed under the influence of a warm front and in the warm sector of a cyclone. This event is mainly recorded during the daytime. The duration of the event is 31 minutes on average. The prevailing air temperature near the earth's surface is –2.3°C on average.

1. Introduction

Ice rain is a rare meteorological phenomenon: in recent years, in Russia in the transitional periods of the year and in winter, thaws are noted quite often. In some cases, this phenomenon is accompanied by the formation of ice and a complex deposit. Ice rain is small clear ice balls, 1–3 mm in diameter. It is formed when rain drops freeze, when the latter fall through the lower layer of air with a negative temperature [1]. In literature, the term "freezing rain" is given: it is rain that falls liquid, but on the surface of the Earth and on unprotected objects it freezes, forming a layer of ice. In the latter case, precipitation should fall on a surface with a negative temperature in a supercooled form [2]. These phenomena are similar in the physical formation conditions: in the lower troposphere and on the surface of the earth a temperature of 0°C and below should be noted, and a warm layer of air with a temperature of 0°C and above should be located above them. This temperature distribution is characteristic of the removal of a moist warm air mass associated with the passage of a warm front when a cold anticyclone is present in its path of movement.

2. Data and methods

This paper considers the cold season 2019–2020. It is characterized by an increased background temperature and precipitation in various forms. The average monthly air temperature in October was 2–4°C higher than the climatic norm. Positive air temperature anomalies were noted in all three decades. The most significant anomaly was observed in the first decade and amounted to 7°C. The average monthly temperature in November corresponded to the average long-term values. The temperature background in December again increased (4–6°C above the norm) with frequent thaws. In January – February, the average monthly temperature anomalies reached 7–10 °C. March was still warmer than usual, but only by 4–7°C. 44 cases of ice rain were recorded in the conditions of an increased temperature background of the cold period in the Middle Urals. 36 cases were recorded on the territory of Perm region, which corresponds to the windward slope of the Ural Mountains (Figure 1). The considered natural phenomenon clearly dominates in the Cis-Urals. Here the frequency of cases increases sharply by November – December and sharply decreases by January – February. In the Trans-Urals, there is no such jump in the frequency of ice rain. This phenomenon is observed with a
frequency of 2–3 cases per month at the beginning of the winter period, and is almost completely absent in the second half of winter. A concomitant phenomenon, such as ice, was noted in 24 cases (55%), while the diameter of ice deposits on the ice rig is from 0 to 6 mm.

The data on ice rain were selected from the electronic magazine WAREP, which in an online mode generates information about adverse and dangerous phenomena in Russia from the entire ground network of meteorological stations. Information about ice rain includes the place (the meteorological station name), the time of the beginning and end of the phenomenon, and air temperature.

3. Results and Discussion

The ice rain event is local. An exception is the event on December 24, 2019, when ice rain was observed at 8 meteorological stations located both in the Cis-Urals and in the Trans-Urals. The average duration of the event is 31 minutes. The maximum duration of the event – 170 min – was recorded at the Artemovskiy weather station in Sverdlovsk region. 20% of the events occurred in less than 10 minutes, and 16% of the events lasted more than 1 hour. It is interesting to note the presence of a diurnal course of these events. Due to the fact that a certain set of knowledge and skills of an observer at a weather station is required to determine the presence of an ice shell on raindrops, this is probably why this event is recorded less often at night than in the morning and evening (14 and 20%, respectively). In the daytime, 45% of cases are noted, and in the middle of the day (from 11:00 to 15:00 local time) 34% of cases occur.

The air temperature is rather uniform with freezing rains in the Middle Urals. Fluctuations in the air temperature are in the range from −7 to 0°C, and the average value is −2.3°C. If we consider the average air temperature during ice rains by months, then only December is characterized by a reduced background (−3.7°C on average); for the remaining months of the cold period the average air temperature is at a level of −1.0 ... −1.5°C. Isolated cases of ice rain are observed at air temperatures below −5°C. The ice rain event is observed most often at air temperatures of −3°C (23% of cases) and −2°C (20% of cases).

A comparison of ice rainfalls on both sides of the Ural Mountains showed that the Trans-Urals are characterized by a longer duration of the event; the accompanying phenomenon is always ice and a lower temperature background.

The frontal process dominates over the intramass process (66 and 34% of cases, respectively) during ice rains. For frontal ice rains, the average duration is 35 minutes, and the average air temperature is −2.2°C. 52% of the ice rainfalls are accompanied by the formation of ice up to 6 mm in diameter. Rarely, with a repeatability of 5%, ice rain falls under the influence of a cold front, and extremely rarely (1 case) under the influence of a sedentary front. 43% of the ice rain events were caused by a warm front. The periphery of an anticyclone with a warm front belongs to the classical synoptic situation. With such a synoptic position, when a warm front was located along the western periphery of the anticyclone, 16% of cases of freezing rain were formed in the Middle Urals (Figure 2A). Their duration was from 7 to 32 minutes in general; the duration was more than 1 hour in two cases. At the time of the ice rain, the air temperature near the Earth's surface was at a level of −3 ... 0°C, and the formation of ice up to 1 mm in diameter was noted in 3 cases out of 7.

Figure 1. The number of cases of ice rain in the Middle Ural by months.
It is interesting to note that in the warm sector of the cyclone in a homogeneous air mass more than 30% of cases of ice rain were formed (Figure 2 B). Their average duration is 25 minutes. The average air temperature is $-2.5^\circ$C. 53% of cases of freezing rainfall is accompanied by the formation of ice up to 2 mm in diameter. Moreover, the intramass process of ice rain formation is noted only in the Urals. For the Trans-Urals, the main synoptic position during ice rains is the presence of a warm front.

Let us consider the physical conditions of the formation and the features of the development of the ice rain event in the Middle Urals. The data of radio sounding close to the time of ice rain at the meteorological stations of Perm region and Sverdlovsk region were taken into account. At the same time, the radio sounding points were selected as close as possible to the place of fixation of this phenomenon. In total, 31 cases of radio sounding at the upper-air stations Perm, Verkhnyaya Dubrova, Ivel, Kirov, and Syktyvkar from November 2019 to March 2020 inclusive were considered. In addition, the aerological data for the periods closest to the time of the ice rain, but when the event either has not yet begun or has already ended, were considered separately. In general, we can say that the vertical distribution of the meteorological quantities during ice rain and freezing rain is very similar (see the table).

However, the development of the processes occurs differently in each case. The “classical” and “non-classical” conditions are distinguished. Thus, in the “classical” case the temperature at the earth's surface is close to $0^\circ$C. An elevated temperature inversion is noted. There are small values of the total dew point deficit in the layer from the earth's surface to the isobaric surface of 850 hPa and increased values of the wind velocity in the boundary layer of the atmosphere. “Nonclassical” cases of ice rain occur at negative temperatures near the earth's surface and at altitudes, without temperature inversion, and sometimes with a large total dew point deficit. For example, on December 23, 2019, according to data for 00 h UTC, the temperature at the Earth's surface was $-12.3^\circ$C, and the maximum temperature was $-3.5^\circ$C at the upper boundary of the inversion. The number of cases when the temperature in the entire layer is negative is 41.9% (13 cases) of the total number of radio sounding cases. In 44.5% (14 cases), the surface temperature was in the range from $+2$ to $-2^\circ$C.

Another feature of the processes considered is the presence of cases with a surface temperature ($T_s$) above $+6^\circ$C (9.7% or 3 cases). Thus, on November 7, 2019 the maximum value of $T_s$ was $+7.4$ ºC. This is higher than the surface temperature values, which can be observed during ice precipitation (about 0ºC). The minimum values of the surface temperature are also higher with ice rain than with freezing precipitation and amount to $-12.3^\circ$C ($-20^\circ$C with freezing precipitation). When considering situations without the phenomena but close to the time of registration of ice rain, the temperature near the Earth's surface is close to the values observed during freezing precipitation. The distribution

![Figure 2. Synoptic position over the Middle Urals: A – Anticyclone periphery with a warm front, B – Warm sector of the cyclone.](image-url)
patterns of the surface dew point temperature (Tdₘ) values are close to those for the surface temperature values. A similar feature is noted for an isobaric surface temperature of 850 hPa (Tₘ₈₅₀). Accordingly, the height of the isotherm minus 10°C (the level of crystallization) is higher in freezing rain than in other cases presented by us.

**Table.** Distribution of meteorological parameters in the atmosphere with ice rain, freezing rain, and in the absence of phenomena in the Middle Urals.

| Parameter | Ice rain | Freezing rain | No weather phenomena |
|-----------|----------|---------------|---------------------|
|           | average  | minimal | maximum | average  | minimal | maximum | average  | minimal | maximum |
| Tₛ       | -0.5     | -12.3   | 7.4      | -4.3     | -20     | 0       | -3.5     | -20.9   | 4.6      |
| Tdₛ      | -4.1     | -13.3   | 7.1      | -5.4     | -22     | 0       | -5.9     | -23.9   | 4.2      |
| Tₘ₈₅₀    | -0.9     | -7.9    | 3.2      | -5.8     | -13     | 4       | -2.1     | -7.1    | 4        |
| Tdₘ₈₅₀   | -6.2     | -28.6   | 3.2      | -        | -       | -7      | -25.3    | 4       |
| H₁₀      | 3494     | 2555    | 4000     | 2619     | 600     | 4400    | 2996     | 2050    | 3800     |
| Hcb      | 769      | -       | 1331     | 765      | -       | 2250    | 615      | -       | 1150     |
| Tcb      | -4       | -12     | 5        | -8.5     | -25     | -1      | -6       | -21     | 1        |
| Htc      | 1247     | 285     | 2018     | 1277     | 180     | 2650    | 1245     | 802     | 1800     |
| Ttc      | 0.2      | -7.9    | 6.2      | -4.4     | -13     | 4       | -0.6     | -7.1    | 4        |
| ΔH       | 477      | 9       | 1298     | 510      | 9       | 1500    | 630      | 87      | 1425     |
| Σd       | 8.9      | 0.3     | 41       | 3.9      | 1       | 19      | 7.3      | 0.4     | 22.5     |
| Hmax     | 1044     | 218     | 2231     | 1002     | 450     | 2200    | 781      | 350     | 1037     |
| Dₘₐₓ     | 246      | 20      | 325      | 246      | 15      | 350     | 236      | 165     | 280      |
| Vₘₐₓ     | 19       | 5       | 30       | 17       | 6       | 35      | 15       | 8       | 27       |

The average height of the lower boundary of the inversion is about 760 m above sea level. It is approximately the same both for cases with freezing precipitation and for cases without these phenomena. The maximum height of the cloud base (Hcb) in cases with ice rain is 1331 m, which has values similar to observations when there were no such phenomena (1150 m). In the case of freezing precipitation, the maximum height is almost 2 times higher, 2250 m. The temperature at the lower and upper boundaries of the inversion during ice precipitation is recorded higher than in other cases. The average height of the upper boundary of the inversion (Htb) is about 1250 m with and without the phenomena. The minimum height of the upper boundary with the phenomena is 285 m in case of ice rain, 180 m in case of freezing precipitation, and 800 m in the absence of the phenomena, which is about 3–4 times higher. The inversion power (ΔH) in the boundary layer for different variants of upper-air data is approximately the same and is about 500–600 m on average.

The average total dew point deficit (Σd) in the layer from the earth's surface to the isobaric surface of 850 hPa has the highest values for cases of ice rain (8.9°C), and the lowest values of this indicator are characteristic of freezing precipitation (3.9°C).

A strong wind at altitude indicates the presence of large baric gradients and promotes the removal of warm humid air. The altitude at which the maximum wind speeds are observed in the boundary layer (Hmax) is for cases with phenomena of about 1000 m on average and about 780 m when no phenomena were observed. The prevailing direction of the maximum wind is southwest. At the same time, the maximum speeds are higher in cases of ice rain and freezing precipitation on average.
Let us consider the results of studying the radar characteristics of cloudiness during supercooled precipitation [3, 4]. The values of radar reflectivity (Z) in the cloud during the period of the highest precipitation intensity, the maximum height of the cloud radio echo, the phenomenon type, as well as the change in these characteristics during the front passage are presented. The evaluated data were from DMRL Vologda, Kotlas, Izhевск, N. Novgorod, and Kirov. The assessment of the synoptic situation and weather conditions was carried out on the basis of data from the network of meteorological stations and weather maps provided by the Perm Center for Hydrometeorology and Environmental Monitoring.

Since the radar data is essentially a signal reflected from a meteorological target, converted into a phenomenon based on physical regularities, to increase the reliability of the processed data only those radar sounding times were used that coincided with the time of ice rain fixation at meteorological stations. The following assumptions were made: the radar period may differ from the registration time of a phenomenon by no more than 5 minutes, and the cells with the phenomenon are located at a distance of no more than 30 km from the meteorological station. During the study period, a number of cases of ice rain were recorded in the European territory of Russia, two of which formed the basis of this study: November 10–11, 2019 and December 23-24, 2019. These cases caused severe ice slicker and resulted in significant material damage. In the first case the phenomenon mainly covered Perm region, and in the second one Udmurtia, Kirov Region, and the south-west of Perm region were most severely affected.

On November 11, 2019, a warm front passed through Perm. On the morning of November 11, overcooled rain began in the central and southern regions of Perm region and in Perm. During the day the precipitation zone spread to the northern regions. In Perm, 5 mm of precipitation fell in the form of supercooled rain, which led to the formation of severe icing. More precipitation fell in the north of the edge than in the south (12 mm in Nyrob, 8 mm in Kochevo, and 9 mm in Berezniki). In the afternoon the air temperature crossed 0°C, and part of the precipitation fell in the form of ordinary rain. The maximum diameter of glaze deposits (4 mm) was noted in Nyrob, Berezniki, and Kochevo. As the front approached, the thickness of the clouds of the Ns–Cb system increased, and the intensity of precipitation increased. The main cloud and precipitation system has moved forward relative to the surface front line. During the passage of the atmospheric front the state of the atmosphere and weather conditions changed. These changes were reflected in the microphysical properties of the cloud and, consequently, in its radar characteristics (the radar reflectivity at different levels within the cloud). In the period from 00:00 to 01:50 UTC, the average height of the radio echo was 8 km, and the radar reflectivity in the lower kilometer layer (near the Earth's surface) was 30 dBZ, which corresponds to heavy rainfall of low and moderate intensity or heavy overburden. The maximum values of radar reflectivity (24–30 dBZ) were recorded up to an altitude of 4 km, in the cloud layer from 5 to 7 km there was a gradual decrease in reflectivity to 12 dBZ, and above 7 km there was a sharp drop in Z to zero values (Figure 3 A). Such a distribution of reflectivity with height is a sign of the development of convection in the fields of stratus clouds and heavy rainfall against the background of overburden. Immediately before, on and behind the front line near the ground, a decrease in the height of the radio echo and the cessation of heavy rainfall are noted (01: 30–06: 00 UTC). In the fields of average characteristics the following values are

![Figure 3. Average profile of radar reflectivity of clouds for 00.00–01.50 UTC (A), 02.00–06.00 UTC (B) (2019.11.11).](image-url)
noted: the average height of the radio echo is 5-6 km, the radar reflectivity at the Earth is 24 dBZ, the maximum reflectivity is observed up to an altitude of 3 km, above 3 km to the top of the cloud the reflectivity sharply decreases to zero. Such a radar reflectivity profile is typical for Ns-As clouds with strong and moderate precipitation (Figure 3 B). At the end of December 2019, the thaw was the result of heat removal at the exit of the southern cyclone and the displacement of the inactive warm front. On December 23–25, rain was observed on the territory of several regions of the Russian Federation. Kirov region (Kirov), the Republic of Udmurtia (Izhevsk, Glazov, Game), and Perm region (Vereshchagino, Nozhovka, Perm) suffered from ice. During this period the most difficult weather conditions were observed in Kirov on December 23, 2019 from 00:00 UTC. In the lower layer of the cloud, a radar reflectivity of 40 dBZ was noted, which corresponds to heavy and moderate heavy rainfall. Above there is a rather sharp drop in reflectivity which, near the upper boundary of the radio echo at an altitude of 7 km, retains a value of 15 dBZ. This distribution of reflectivity is a sign of the development of convection and stratus cloud fields. The distribution of radar characteristics in the territories, to one degree or another, exposed to supercooled precipitation with the formation of ice on December 23-25, 2019 is shown in Figure 4. It shows the average radar reflectivity profile with height, as well as the height distribution of the minimum and maximum reflectivity values in the vertical profile. In general, it can be noted that supercooled precipitation, causing ice deposits and the formation of ice during the transitional periods of the year, fall out of the cloudiness with reflectivity values in the radar core corresponding to weak rainfall and heavy and moderate overburden precipitation (respectively, clouds and cloud systems Cb and As–Ns) during the warm period.

Figure 4. Average profile of radar reflectivity in the ice rain for 23–25 Dec 2019.

4. Conclusions
Despite the presence of some general physical and synoptic conditions for the formation and development of a freezing rain event, each event has its own characteristics of the process.

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