

Investigation of the variability of circulation regimes and dangerous weather phenomena in Russia in the 21st century.

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Abstract. The variability of Northern Hemisphere circulation types from 1899-2018 are analyzed and the classification of atmospheric circulation types in the early 21st century are shown. These are associated with the frequency of dangerous weather phenomena, natural processes, and disasters within Russia during this time. Against this background, the synoptic conditions for the formation of extreme precipitation and floods, as well as natural fires in 2019 are considered. It is shown that an increase in the frequency of occurrence of stationary anticyclones and blocking flow regimes as well as an extension of the Mediterranean storm track was associated with an increase in the frequency of extreme precipitation and dangerous natural processes. Additionally, the occurrence of thunderstorms, often dry, led to the development of natural fires.

Key Words: atmospheric circulation, climate variability, Russia, natural disasters, 21st century.

1. Introduction.

At present, little attention is given to the nature of atmospheric general circulation, the long-term fluctuations, or the current trends in these fluctuations when analyzing the meteorological conditions associated with extreme natural hazards. Typically, the synoptic conditions during the specific days of occurrence and within the affected region are considered by examining meteorological characteristics such as temperature, rainfall, or wind speed. Using this approach, extremes are described often as unprecedented, unexpected, and difficult to predict. If these phenomena are considered in association with the long-term general circulation fluctuations, then it can be demonstrated that modern general circulation patterns are similar to those that have been observed earlier in the 20th century. These earlier flow regimes were associated with certain meteorological extremes as well. The goal of this work is to identify the general circulation flow regimes associated with extreme events within Russia and to demonstrate their relationship to long period fluctuations of the Northern Hemisphere general circulation.

2. Data and Methods.

In order to identify the character of atmospheric flow regimes, the classification scheme of daily atmospheric conditions developed by Dzerdzevsky et al. for either the entire Northern Hemisphere [1] or within six particular regions (sectors) were utilized [2]. The materials used, a description of the atmospheric classifications, and the frequency of occurrence data are archived on a website [3] hosted by the Institute of Geography at the Russian Academy of Sciences.

Information regarding the number and occurrence of extreme events is gathered from websites such as Weather News [4] and Weather and Climate [5]. The recurrence of hazardous hydrometeorological phenomena that cause economic and societal disruption as well as human casualties was quantified using data available via the All-Russian Scientific Research Institute of Hydrometeorological Information – World Center website [6]. Additionally, the duration of the hazard was considered. The analysis here was performed comprehensively including; the character of the general circulation, the synoptic situation, the occurrences of meteorological extremes, and the consequences of the extreme event occurrences.

3. Atmospheric Circulation Flow Regime Types

The atmospheric classification scheme used here was developed specifically for the analysis of long-term flow regime variations, and the associated variations in temperature and precipitation regimes. Based on the analysis of daily maps for the Northern Hemisphere, [1] (and subsequent publications) classified these conditions using four circulation groups, which are comprised of 13 different synoptic types, or 41 subtypes. These 13 types, referred to by [1] as elementary circulation mechanisms (ECM) (Table 1), were classified based on the number, amplitude, and phase of wave activity in the Northern Hemisphere jet stream.

The ECM designation includes the type number and a letter indicating the season or the particular number/location of amplified trough(s). Firstly, the association of a, b, c, or d (a, б, в, г in the Cyrillic Alphabet) with the ECM type indicating the location of these amplified troughs. Then, the letter w or s (з or л in the Cyrillic Alphabet) indicates the cold/winter or warm/summer season, respectively. The differences are typically that the pressure center is of the opposite sense over either the oceans or continental regions. However, Types 4a, 9b, and 10a winter ECM are indicated only by a letter.

Table 1 The character of atmospheric circulation groups for Northern Hemisphere flows using the scheme developed by Dzerdzeevsky et al. [1].

Circulation Group (number)	ECM types included.	Pressure in the Arctic Region	Number of amplified waves or blocking	Number of troughs / cyclones
Zonal (1)	1 and 2	High	0	2–3
Zonal breaking (2)	3 - 7	High	1	2–3
Meridional NH Circulation (3)	8–12	High	2–4	2–4
Equatorward troughs (4)	13	Low	0	3–4

The year was partitioned into six seasons; pre-spring, spring, summer, fall, pre-winter, and winter. The ECM that were dominant during these seasons and their duration are shown in Table 2.

Table 2. Seasonal Circulation Groups.

Season	Dates	Dominant ECMs
Winter	26 Nov – 8 Mar	5a, 5b, 5c, 7aw, 7bw, 11a, 11b, 11c, 12bw, 12cw, 13w
Summer	24 May – 31 Aug	2a, 2b, 2c, 3, 4b, 4b, 6, 7as, 7bs, 8bs, 8cs, 8ds, 9a, 10b, 13s
Spring / Fall	9 Apr – 23 May / 1 Sept – 7 Oct	10a, 12a, 12bs, 12cs
Pre-winter / pre-spring	9 Mar – 8 Apr / 8 Oct – 25 Nov	1a, 1b, 4a, 5c, 8a, 8bw, 8cw, 8dw, 9b, 11d, 12d

Diagrams for each ECM showing the geographic position and general direction of motion for cyclones and anticyclones was developed by [7, 8]. Thus, each of the diagrams is characterizing the Northern Hemisphere atmospheric circulation as well as the regional synoptic situations regardless of horizontal extent.

The zonal group (Group 1 - Table 1) includes two ECMs that are typical of the pre-winter and spring seasons (1a, 1b) and three that are predominant in the summer season (2a, 2b, 2c). The characteristics of this group is the dominance of high pressure in the polar region and a mid-latitude jet stream with no amplified wave activity. During the warm part of the year, the wave number tends to be larger than during the cold season. During the cold part of the year, relatively expansive anticyclones form over Eurasia and/or North America and are associated with clear cold weather. During the warm part of the year, these stationary anticyclones are often the cause of drought conditions.

The zonal breaking group (Group 2 - Table 1) are associated with one amplified ridge or ridge / trough couplet in the Northern Hemisphere flow or even a blocking anticyclone. Blocking events disrupt the regular progression of synoptic-scale cyclones in any sector. In this group, ECM 3 is associated with amplified ridging in the Atlantic, while for ECM 4, 5, 6, and 7 this ridging is located within the European, Siberian, Pacific, and North American sectors, respectively.

The meridional Northern Hemisphere group (Group 3 - Table 1) contains the greatest number of ECM subtypes (21). This group includes Type 8 and Types 9-11 ECMs, which are associated with two amplified waves located close together or in opposite sectors of the Northern Hemisphere, respectively. Additionally, the ECM Type 12, is associated with three or four amplified waves across the Northern Hemisphere. This includes subtype 12a which is predominant during the spring and fall and associated with four amplified Northern Hemisphere waves. These conditions result in warm and cold air masses being located in close proximity and as such are associated with strong fronts, heavy precipitation events, and strong winds. In this case, hazardous conditions may occur simultaneously across different sectors within the Northern Hemisphere.

Group 4 (Equatorward troughs – Table 1) is characterized by cyclonic conditions in the polar region. During the winter season, the Atlantic, Pacific, and Mediterranean storm tracks are very active along the polar front and strong anticyclones persist over Eurasia and North America. During the summer season, the hemispheric wave number is four. Strong high pressure or blocking occurs over European Russia and western Siberia allowing the Mediterranean storm track to extend into western Siberia. This is often the cause of flooding events within the Altai Region of Russia. If these associated

cyclones penetrate into the North Caucasus, their progression is blocked and the result is a period of persistent heavy rainfall, which causes flooding and other natural disasters (e.g. mudslides). Alternatively, cyclones that form on the polar front in the Mongolian region as well as those even further to the east will contribute to heavy rainfall and flooding in the Baikal, Yakutia, and Magadan regions. These regions are located across the southern periphery of Russia (the Transbaikalia and Far East).

4. Northern Hemisphere Atmospheric Flow Variability for the 20th and 21st Centuries.

An analysis of the total annual duration for the circulation groups revealed decadal periods in which certain group(s) were dominant (Fig. 1), and these are called circulation eras or epochs. Since 1899, there have been three such epochs in the Northern Hemisphere flow, two of which were dominated by meridional (1899 – 1915 and from 1957 – present) and one by zonal (1916-1956) flows.

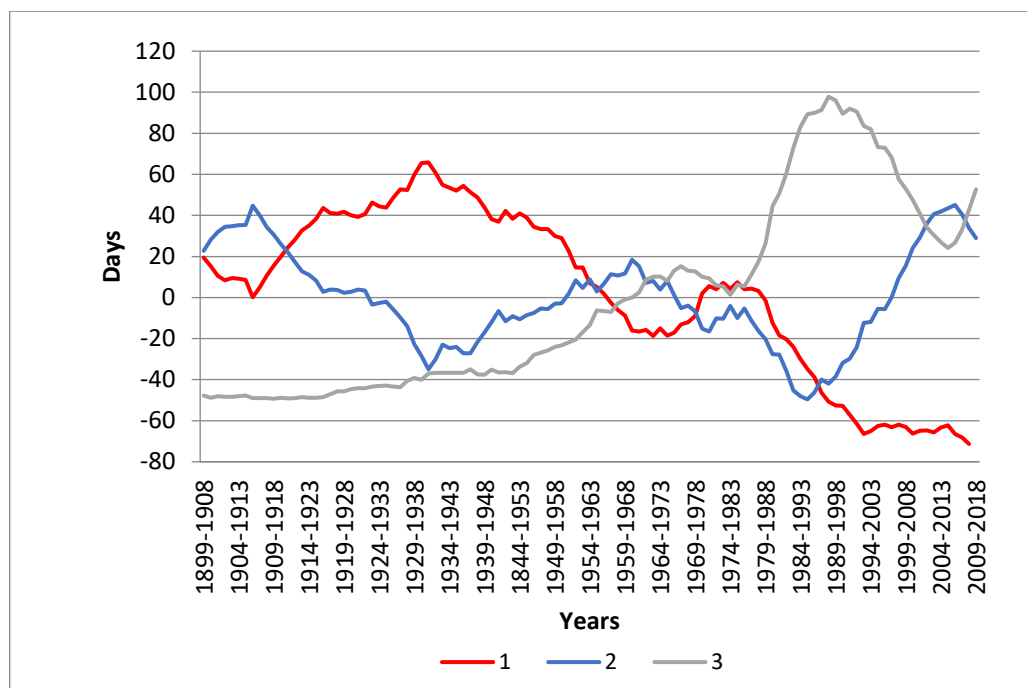


Figure 1. Deviations from the period mean in the duration of Northern Hemisphere (10-year running averages) circulation groups for 1899-2018. The red line is circulation groups one and two (zonal and zonal breaking), the blue line is circulation group three (meridional), and the grey line is group four (equatorward troughs).

During the zonal era (Figs. 1, 2), ECMs 1-7 (Groups 1 and 2) prevailed and these represented the Northern Hemisphere flow regimes that were characterized predominantly by at most one amplified ridge. Note that this does not mean that circulations represented by the other groups (Groups 3 and 4) did not occur, those groups just occurred less frequently. During this era, the Atlantic region storm track was located along coast of Eurasia. This period was associated with a warming of the Arctic. Over continental regions of Eurasia and North America, anticyclones dominated and, thus, severe frosts were noted during the cold season, while severe droughts characterized the warm seasons. During this period, a book chapter appeared in “Climate and Life” (L.S. Berg) discussing a lowering of the Caspian Sea levels due to the lack of precipitation in the Volga River watershed basin [10].

The two meridional epochs differ between the predominance of various circulation groups. At the beginning of the 20th century, the first meridional Northern Hemisphere flow regime group was dominant (1899- 1915) (Figs. 1, 2) and characterized by amplified troughs and ridges in the mid-latitudes. Since 1957, the second meridional epoch has dominated (Groups 3 and 4), and has been characterized by storm tracks located further equatorward. The occurrence of circulation Group 4 has occurred about 2.5 times more frequently than the long-term average during this era. Since the total annual occurrence of circulation Group 4 was below average from 1899 – 1963, the first two eras differed primarily by the occurrences of circulation Groups 1 and 2 versus circulation Group 3.

The current era (1957 – present) has been characterized by several sub-periods (Fig. 1). From 1957-1969, both meridional circulation groups showed positive anomalies, while from 1970 – 1980 the occurrence of the generalized zonal group occurred nearly as frequently as the meridional groups. From 1981 – 1997 the frequency of circulation group four increased very rapidly. Since 1998, the occurrence of Group 4 circulation types has decreased. Although during 2018, 117 days could be characterized as circulation Group 4, which is higher than the 1899-present mean occurrence. After a minimum in 1992 (91 days), the occurrence of circulation Group 3 began to increase and, by 2009, there were 68 days more than the mean that year. Since this year, the occurrence of circulation Group 3 decreased again, and, in 2018, there were 12 fewer circulation Group 3 days than average.

The recent increases and decreases of the meridional flow groups has been associated with more unstable weather and more frequent intrusions of warm (cold) air at high (lower) latitudes (Fig. 2). This period has been associated with strong fronts, increases in strong wind, and heavy precipitation events.



Figure 2. As in Fig. 1, except for the generalized zonal (dotted) and meridional (solid) circulation groups in the Northern Hemisphere.

5. Recurrence of Hazardous Hydrometeorological Phenomena

A change in the nature of the hemispheric or regional circulation will be associated naturally with a change in the occurrence of dangerous or hazardous weather [11]. Since 1991, the All-Russian Scientific Research Institute of Hydrometeorological Information – the World Data Center has created a

specialized body of information, including an archive of all adverse and dangerous weather phenomena that have caused economic or societal damage [6]. We present an analysis of the occurrence frequency for dangerous hydrometeorological phenomena within Russia as recorded in the cited data archive from 2000-2018 (Figs. 3 and 4).

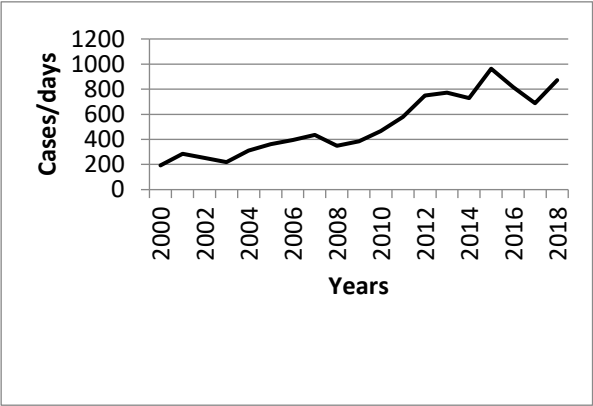


Figure 3. The total annual number of cases of dangerous hydrometeorological phenomena or adverse weather conditions that caused social and economic losses (in days).

The annual increase in dangerous hydrometeorological phenomena and adverse weather conditions was anywhere from 30 to 200 cases or days year⁻¹. Flooding events in southern Russia during 2002, 2009 and 2012, in Far East Russia during 2013, and in the Altai region during 2014 made significant contributions to the increase in the number of hazardous events. Regarding flood events, it is known that there were 14, 35, and 57 events within Russia during 1990, 2000, and 2010, respectively.

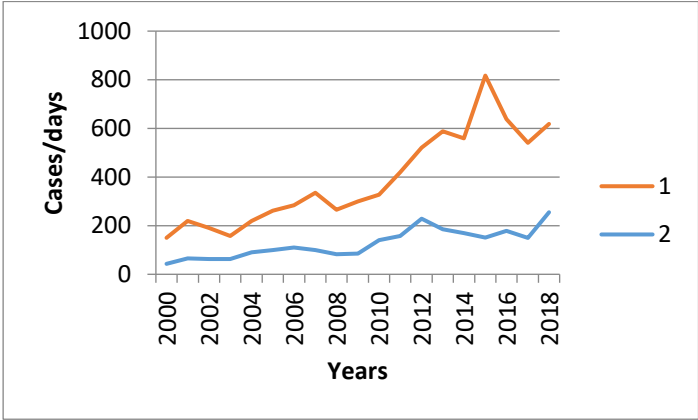


Figure 4. As in Fig. 3, except for the warm period (April – October, orange) and cold period (November – March, blue) of the year.

The warm season was associated with 70% or more of the hazardous weather phenomena that cause societal and economic damage that occurred annually. This season is associated with a higher frequency of convectively driven phenomena.

In Russia, especially during the warm part of the year, natural disasters such as drought and fires also occur. At the start of the 21st century, a change in the nature of atmospheric circulations gave rise to the more frequent occurrence of these phenomena as well. Unprecedented drought and natural fires within European Russia during 2010 arose due to the occurrence of prolonged ridging events including blocking anticyclones. These were associated with ECM 4b, 9a, 12a, 13s [12]. In Siberia, natural fires occurred during dry thunderstorms and were associated most often with ECMs 9a and 13s [13]. An

increase in the combined frequency of anticyclonic weather regimes over European Russia and the extension of the Mediterranean storm track into the North Caucasus has led to an increased frequency of extreme precipitation, flooding, landslides, and mudflows within the larger region [14]. In the Far East, heavy rains caused hazardous and dangerous natural processes to occur during ECMs 9a, 12a, and 13s [15, 16].

Given the current nature of the atmospheric circulation (predominance of circulation Groups 3 and 4 especially ECMs 12a and 13s), the occurrence of simultaneous extreme flooding events was noted in different parts of the Northern Hemisphere [4, 5]. On 28 May 2014, heavy rains in the Stavropol Territory triggered emergency declarations, and similar hazards occurred simultaneously within the Altai Region and China. Then during 3-4 June 2014, heavy showers across southern Russia occurred simultaneously with heavy showers in Kamchatka. In early June, there was also a destructive mudflow in Dagestan. Additionally, showers were noted in the southern part of Far East Russia. Then on 16 June 2019, within the central Krasnoyarsk Territory, 80 mm of precipitation fell in 12 hours, as well as 56 mm in the Kuril Islands over 12 hours. On 23 July 2014, it rained simultaneously in the mountains of Europe from Germany to Slovenia, the mountains of the Caucasus Region, the southern Krasnodar Territory, and in Siberia. [17].

In comparison with the earlier eras, the location of the regional storm tracks has changed. In Vladivostok during the winter of 1918/19, less than 1 mm of precipitation fell and no snow cover formed during that year. The duration of ECMs 12a and 13s have increased in the first part of the 21st century about four-fold relative to the average for 1899 - 2018 [3]. In this regard, the recurrence of natural disasters is growing. In the current year (2019), three periods of catastrophic floods and natural fires were noted in Siberia.

5.1 Natural Fires in 2019

Information about the growing fire hazard in southern Siberia and the Far East was noted during the second half of April. This was caused by the lack of precipitation and the occurrence of strong winds across the region. As of 26 July, the area burned in forest fires within the Krasnoyarsk Territory, Irkutsk Region, Buryatia, Transbaikalia and Yakutia exceeded 3.5 million hectares. Smoke from the Siberian forest fires reached the western Ulyanovsk region and even to Alaska further east.

5.2 Floods in 2019

The first flooding events in the Novosibirsk region were reported on 4 April. A second wave of flooding occurred in May over the Far East. Then, floods in June and July swept the Irkutsk and Amur regions. From 25 – 29 June, a powerful cyclone passed over the watersheds of the Uda, Oia, Oka and Belaya rivers. Typically, these cyclones do not persist over a region for more than several hours to one day. However, this cyclone remained over the region for five days due to the presence of stationary anticyclones persisting over the northern and southern parts of the region further east. The situation was aggravated since the heavy rains coincided with the late snowmelt within the eastern Sayans Region. In only five days, 3.7 times the normal monthly rainfall was measured across the region. The preliminary cost of flood damage is estimated to be 35.152 billion rubles.

At the end of June, 109 settlements were flooded in 10 districts within the Irkutsk Region, and the cities of Tulun and Nizhneudinsk were the most affected. At the end of July, the same region experienced a second wave of flooding during which another 58 settlements were damaged. As of 26 July, 10,900 residential buildings were destroyed completely and 25 people were killed.

On 21-22 July 22, a cyclone that moved into the Amur Region from China caused heavy rains and thunderstorms resulting in 86 mm precipitation. Then on 23 July, within the northern Amur and Selezhdzhinsky regions the rivers overflowed their banks and the Norsky Reserve was under water. People and pets were evacuated, and the damage to the reservation is still unknown [4, 5].

In November, flooding began in northwestern Russia. From 1-10 November, the Novgorod Region experienced about 220% of the normal monthly rainfall. The Volkov River flooded the lower tier of the embankment and covered villages across the Novgorod region. From 6 November forward, an emergency declaration has been in effect [4, 5].

In addition, heavy snowfall led to a blackout in four districts of the Vologda Oblast, where 171 settlements are located. Then rains followed which overflowed regional rivers and flooding the homes of the local population. According to weather forecasts and at the time of this writing, these rains are projected to continue [5].

6. Conclusions

The results of this study allowed us to draw the following conclusions.

- The occurrence of extreme weather conditions (temperature and precipitation) continues to increase in the first part of the 21st century. Negative precipitation extremes in combination with positive temperature anomalies has led to droughts and natural fires, while positive precipitation extremes have led to catastrophic flooding events.
- The increases in the occurrence these phenomena have been associated with the changing nature of atmospheric circulation regimes across the Northern Hemisphere as well as regionally, and in particular the occurrence of meridional circulation types including blocking.

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