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Atmospheric Severe Convective Events in Russia: Changes Observed from Different Data

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Abstract—Changes in the frequency and intensity of atmospheric severe convective events, including heavy rainfall, thunderstorm, hailstorm, squall, and tornado, in the Russian regions during the warm season are analyzed using different independent sources of information. Based on observations at Russian weather stations in 1966–2020, the frequency of thunderstorm, hailstorm, and strong wind, the contribution of extreme showers to total precipitation, and the cumulonimbus cloud fraction are estimated. Based on satellite data, the frequency and intensity of tornado and squall events that caused windthrows for 1986–2021 and the height of the top of deep convective clouds for 2002–2021 are also evaluated. The ERA5 reanalysis data are used to analyze the frequency of conditions favorable for the development of moderate and intense severe convective events in 1979–2020. The results indicate a general intensification of severe convective events in most Russian regions, except for a number of regions in the south of the European part of Russia. The frequency of moderate hazards has a decreasing trend, and the frequency of the most intense severe hazards has an increasing trend. It is reasonable to take the results into account when developing plans for the adaptation of Russian regions and industries to climate change.

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INTRODUCTION

Since the second half of the 20th century, global surface air temperature has risen by 1.1 C [40]. Due to a number of positive feedbacks and local impacts [66], surface air temperature in the Northern Hemisphere high latitudes has increased more quickly than on average for the globe: in particular, in Russia, by 2.5 times since 1976 [8]. There is a change in the mid-tropospheric temperature pattern: in particular, the lapse rate increased over the Northern Hemisphere land with the increase in surface air temperature [18]. The warming leads to the increase both in atmospheric moisture capacity [71] and actual moisture content [31]. The rise in surface air temperature and air humidity, as well as the increase in the lapse rate intensify atmospheric convection and may lead to the strengthening and increased frequency of atmospheric severe convective events [16, 17].

The family of severe convective events (SCEs) usually includes large hail (with a diameter of >2 cm), squalls with a wind speed of >25 m/s, tornadoes (most often EF1) [30]. Some papers consider heavy showers [30] causing river floods as SCEs [44]. In overwhelming majority of cases, SCEs associated with multicell and supercell clouds, so called severe convective storms (see, for example, [26, 30]), which are also characterized by high lightning activity [46]. Considerable negative consequences are associated with SCEs, including the destruction of buildings and infrastructure facilities, human loss, continuous damage to the forest cover [49, 57], in particular, in Russia [37, 54, 65]. There is an increasing damage caused by SCEs [57], which, on the one hand, is associated with the increase in the exposure and vulnerability factors, but may also be partly associated with the increased frequency of SCEs.

The present paper analyzes changes in the frequency of SCEs and some indicators that indirectly characterize this frequency in Russia. The analysis is based on different sources of data, including ground-based and satellite observations and reanalysis data. The discussion of the results is complemented with the review of available studies in this research area.

DATA AND METHODS

Data of standard meteorological observations from 521 Russian stations [4] for 1966–2020 (for wind, from 1977) were used to estimate the frequency of SCEs. The warm season from April to September was analyzed. Based on these data, both directly SCEs (extreme showers, strong wind) and other variables characterizing the frequency of development of atmospheric convection (but not the intensity) were considered: total shower precipitation, daytime Cb cloud fraction, hail of any intensity (it is impossible to distinguish only large hail from the data of current observations since there is no information about the hail size), thunderstorm presence.

The frequency of days per warm season, when hailstorms, thunderstorms, and wind speed above 20 or 25 m/s were recorded, was assessed for every year. The frequency was calculated as the ratio of the number of such days (for example, thunderstorm or hailstorm days) to the total number of days from April to September. The Cb cloud fraction n_{Cb} was estimated from information on the morphological type of clouds and on the low-level cloud amount for the daylight hours (08:00 to 20:00 local time). If only Cb were observed at the moment of observation, n_{Cb} was equal to the low-level cloud amount (cumulus and cumulonimbus clouds are towering vertical ones but are coded as low-level clouds as their base is at the altitude of <2 km), regardless of the fact whether clouds from another level were observed synchronously with Cb (so called upper-bound estimate) [35]. If there were no Cb at the moment of observation, n_{Cb} was assumed equal to 0. For the whole warm season, n_{Cb} was calculated as the mean over all observations expressed in percent. Shower precipitation was found from the information about total precipitation, current and past weather, as well as the cloud type (more detail on the technique can be found in [23]). Extreme showers were defined as the 95th percentile of the empirical distribution of convective precipitation (heavy showers, according to the classical definition “events with precipitation 30 mm/hour” were not calculated in the study). The contribution of extreme showers to total precipitation for April–September was also computed [36].

The changes in all analyzed parameters at the stations with the absence of data for 5 and more years, as well as at mountain stations (the altitude of >1000 m) were considered insignificant. When evaluating shower precipitation and Cb cloud fraction, it is necessary to take into account subjectivity of weather and cloud type determination, as well as the jumps in the frequency of certain types of clouds at some stations, which are highly likely artefacts [47]. The uniformity of stations for such jumps was tested using the procedure described in detail in [36]. The changes in shower precipitation and Cb cloud fraction at the stations with the revealed nonuniformity were considered insignificant.

The information about windthrows in the forest zone of the European part of Russia (EPR) [65] for 1986–2021 based on their identification from the Landsat data and their subsequent testing using high-resolution imagery was used to evaluate the frequency of severe squalls and tornadoes (EF1 and higher categories). The more detailed description of the procedure for searching and verifying squall and tornado windthrows, as well as the characteristics of the windthrow database is given in [65], where the possible factors of temporal inhomogeneity of the series are also presented. However, the conclusion is made about the quasiuniformity of the series for continuous windthrows with an area above 1 km^2. Such windthrows were selected from the database [65] and were further analyzed (the database was complemented with the events for 2018–2021).

Satellite data on the height of the top deep convective clouds calculated from MODIS data for different cloud characteristics were used as an independent estimate of the total intensity of convective processes. The MOD_06_L2 product from the MODIS 6.1 collection was used [29], which is data for the cloud characteristics for the region within the satellite's field of view with a 5-minute step. The variable cloud_top_height_1km with a resolution of 1 km was used to estimate the cloud height. At the same time, to assess whether a cloud pixel belongs to the type of deep convective clouds, conditions were imposed on the optical thickness (23) and the mandatory presence of the ice phase, for which the variables Cloud_Optical_Thickness and Cloud_Phase_Optical_Properties, respectively, were used. The height of deep convective clouds was calculated for Northern Eurasia (45 –70 N, 30 –150 E) for a month as the mean height of all corresponding pixels in this region in a given month. The change in the height over the period of 2002–2021 was analyzed. The cloud height in the daytime and nighttime (from 08:00 to 20:00 and from 20:00 to 08:00, respectively) was considered separately. Due to the significant volume of initial data, the analysis was presented for July and was based on Terra satellite observations.

The ingredients-based approach was used to assess conditions favorable for the formation of SCEs [44]. In the framework of this approach, the values of convective instability indices and their critical values formalizing specific atmospheric conditions associated with the formation of SCEs were analyzed (see, for example, [45]). The calculation of the indices was based on the data of the modern ERA5 reanalysis [50] with a high horizontal (~30 km), vertical (20 levels from the ground to the level of 300 hPa), and temporal (1 hour) resolution. For Northern Eurasia for 1979–2020, more than 50 different convective instability indices (thermodynamic, dynamic, composite) were computed. The present study analyzed changes in the values only for some of them (which are more often used in the modern studies of SCEs and are the most informative in the framework of the ingredients-based approach (see [30, 69, 70]: convective available potential energy CAPE [55], convective inhibition energy CIN [41], and the WMAXSHEAR index. The latter is the product of wind shear (in the layer from the surface to 6 km) by the square root of the doubled CAPE and is a quite reliable predictor of intensive SCEs [70]. When calculating CAPE and CIN, initial temperature and humidity of the lifting air volume were calculated as the mean for the lower kilometer layer (so called Mixed Layer CAPE/CIN). The changes in the lightning activity index were also evaluated, which is the product of hourly values of CAPE and precipitation *P* (*P* CAPE) [62]. The changes in the mean values of the indices (over the period from April to September) and the frequency of the series of some critical values were computed.

The interannual variability of the analyzed variables was approximated by the linear trend calculated using the nonparametric median Theil–Sen estimator, which is less sensitive to outliers than the standard least-squares method [13]. The level of the trend significance was estimated using the Mann–Kendall rank correlation coefficient [13].

RESULTS AND DISCUSSION

According to observations at weather stations, there are consistent and significant positive changes for the characteristics of shower precipitation, namely, precipitation totals for all showers, precipitation accumulated during extreme showers (the 95th percentile), and the contribution of these showers to total precipitation (Figs. 1a, 1b, and 1c). A statistically significant increase in the analyzed characteristics of showers was registered at most stations, it was especially significant in the south of Siberia and the Far East (up to 8% per decade at some stations). The smallest changes (both in the magnitude and in the number of stations with a statistically significant trend of the same sign) were recorded in the southern EPR and southern Ural.

The statistically significant increase in extreme precipitation (of any type) in most of Russia and the decrease in southern Ural and the Lower Volga region were noted before in [12]. The increase in the amount of heavy summer precipitation in the EPR is also accompanied by the increase (although statistically insignificant) in river runoff during floods [52]. In the southern EPR, in particular, on the Black Sea coast during the warm season, there are differently directed trends in extreme precipitation at neighboring stations [12], which are registered against a background of the general reduction of precipitation in summer and its increase in the transition seasons [2].

The revealed increase in the frequency of extreme showers is generally consistent with an essential increase in the number of heavy precipitation events that caused significant damage to the economy and population [10] both due to heavy showers (30 mm/hour) and very heavy rains (50 mm/12 hours). However, the database of such events [15] (an important source of information for assessing vulnerability of regions to severe weather events) is characterized by temporal inhomogeneity. In particular, essentially the same events in different regions may be interpreted as one or as several events. For example, on July 9, 2011 at Kazan weather station (ID 27595), 68.7 mm of precipitation per 12 hours and 54 mm of precipitation per 1 hour were recorded (the values were retrieved from the pluviograph data [27]). One rain

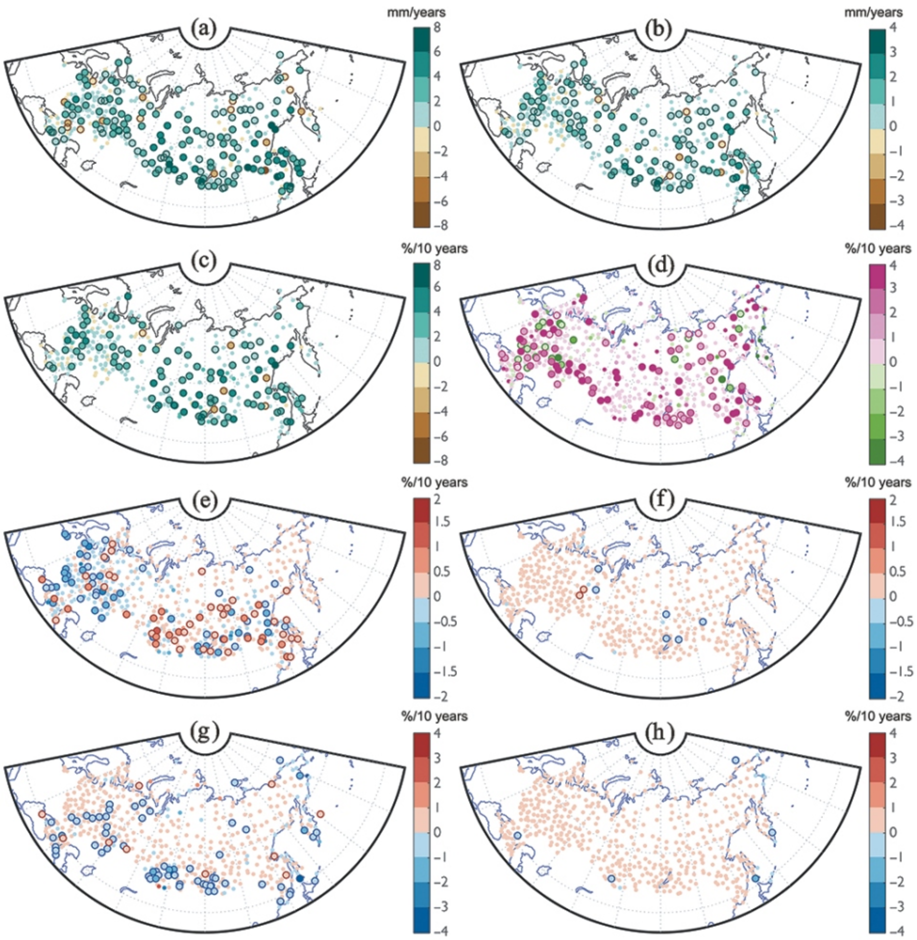

Fig. 1. The warm season (April–September) trends based on station observations for (a) total shower precipitation, (b) 95th percentile total shower precipitation, (c) contribution of the 95th percentile showers to total precipitation, (d) daytime Cb cloud fraction, (e) frequency of thunderstorm days, (f) frequency of hailstorm days, frequency of days with maximum wind speed above (g) 20 and (h) 25 m/s. The trends were calculated for 1966–2020 in figures (a–f) and for 1977–2020 in figures (g, h). The large circles show statistically significant trends at the level of 95%.

event on that day met two criteria (heavy shower and very heavy rain) and was recorded to the database [15] both as “very heavy rain” and “heavy shower.” At the same time, heavy precipitation in Kolomna (ID 27625) on June 15, 2012 with total precipitation of 87.2 mm/12 hours and 69.9 mm/1 hour was recorded to the database only as “very heavy rain,” while heavy precipitation in Ryazan (ID 27730) on July 25, 2001 (73.6 mm/12 hours and 57.5 mm/1 hour) was recorded only as “heavy shower.” Other similar examples of different interpretations of an event of the same type were also found, which indicates nonuniformity of the database and a need in a number of assumptions when using these data for assessing the interannual variability of SCEs.

The increase in the contribution of extreme showers to total precipitation observed in most Russian regions is accompanied by the lengthening of the dry period between precipitation events [75], with a positive trend of 3–6% per decade for 1966–2012 [12]. At the same time, the precipitation frequency reduction occurs primarily due to stratiform (large-scale) precipitation [36]. It should be noted that total precipitation varies at a lower rate than the intensity of precipitation and the contribution of extreme showers [36], in particular, the trend in annual total precipitation for Russia in 1976–2020 made up 2.2% per decade [9]. Based on the numerical convection-permitting modeling, it was shown for the territory of the USA that the decrease in the frequency of rains in the warm season expected due to global climate change is associated with the decreasing frequency of light precipitation (2 mm/day), while heavy precipitation (10 mm) becomes more frequent [42]. Evidently, similar trends may be expected for the regions in Northern Eurasia. For example, the results of global and regional model simulations demonstrate

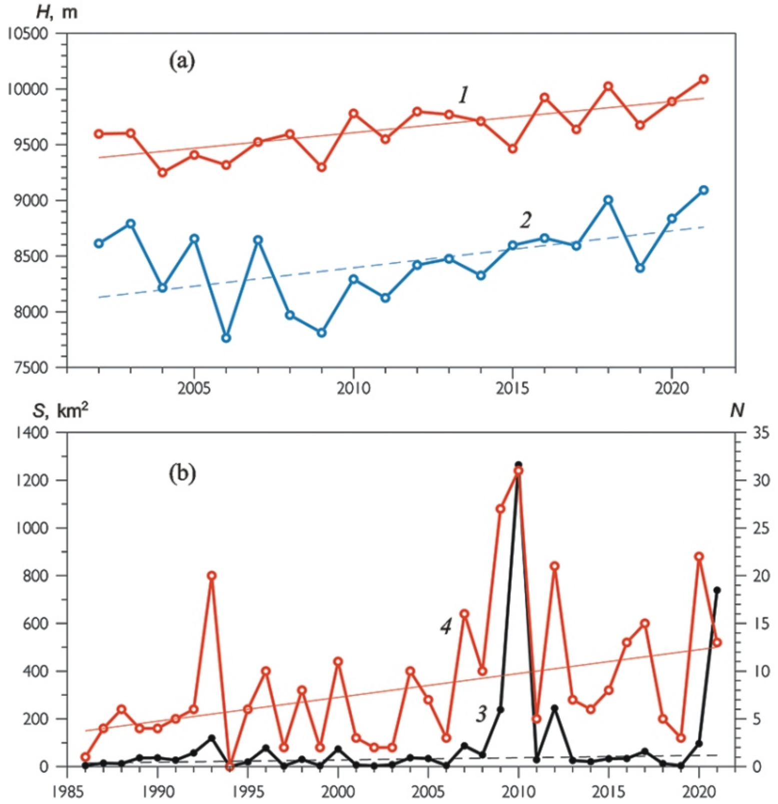

Fig. 2. (a) The interannual changes in the deep convective cloud top height over Northern Eurasia (*1*) by day and (*2*) at night in July according to Terra/MODIS satellite data and (b) interannual changes (*3*) in the area of squall and tornado windthrows (for windthrows with an area of 1 km^2) in the forest zone of the European part of Russia, as well as (*4*) in the number *N* of convective storms that caused them according to extended data [65]. The linear approximation of changes is shown, the solid and dotted lines show a statistically significant trend at the levels of 99 and 90%, respectively.

the persistence of trends towards an increase in extreme precipitation and precipitation intensity and a simultaneous extension of the dry period for the next decades [22, 43]. The extension of the dry period is expected south of 60 N, and its shortening is expected to the north [22], which is associated with a displacement of trajectories of extratropical cyclones to this region [19]. Air humidity also plays an important role in establishing a certain pattern of dependence of extreme precipitation on temperature in different regions of Northern Eurasia [28].

Along with the increase in the amount of shower precipitation in Russia, there is an increase in the Cb cloud fraction (Fig. 1d) and the number of thunderstorm days (Fig. 1e). It is more pronounced in the south of Siberia and the Far East, which is consistent with the earlier results [39]. High consistency of the number of thunderstorm days and convective precipitation was found before based on the local convective cloud model and reanalysis data [5]. Against a background of the general increase in the number of thunderstorm days, a number of regions with differently directed trends were identified, in particular, some stations in the EPR and the Far East demonstrate significant trends towards a decrease in the number of thunderstorm days. In general, there is the lengthening of the thunderstorm season [6, 39], mainly due to the earlier start of lightning activity in spring [6].

It should be noted that the frequency of thunderstorm days does not allow full evaluation of lightning activity (in particular, the number of lightning flashes per a certain area). A rather reliable indicator of convection intensity, in particular, of lightning activity, is the height of convective clouds [1, 11, 72]. For Northern Eurasia, there is a statistically significant increase in the height of the top of deep convective clouds retrieved from MODIS satellite data (Fig. 2a), whose rate is ~280 m/decade in the daytime and 330 m/decade at night. This more than twice exceeds the rate of the tropopause height growth retrieved over most regions of Northern Eurasia (except for northern Siberia) from radiosonde [14] and reanalysis data [73]. The increase in the height of convective clouds indicates a general intensification of lightning activity in the regions of Northern Eurasia. This is also confirmed by other data, in particular, by lightning detection data, based on which the increase in the lightning flash rate was found both in the high latitudes [51] and in separate Russian regions, for example, in Yakutia [67].

Available data sources do not allow any unambiguous conclusions about changes in hail activity on the territory of Russia: the overwhelming majority of stations demonstrate insignificant trends in the frequency of hail (Fig. 1f), both for the cases of small and large hail. The information about the hail size is fragmentary and inhomogeneous (in particular, it is transmitted in the form of "Storm" telegrams not for every phenomenon). Taking into account the limitation of available data, it is reasonable to estimate rather the frequency of atmospheric conditions typical of the generation of large hail than the frequency of hail events [57, 60].

Taking into account rare occurrence and a characteristic scale of severe squalls (>25 m/s) and tornados, the assessment of their long-period variability based on station data is difficult. Paper [25] shows a principal impossibility of using station observations for the correct simulation of even a typical number of tornadoes, not to mention their variability. At the same time, the increase in the number of tornados noted in [25, 37] is evidently instrumental and associated with an increase in the volume of information. According to uniform observations of the maximum wind speed at weather stations, there are quite small (mainly negative) changes in the frequency of days with wind speed of 20 m/s (Fig. 1g), significant changes were found in the eastern EPR, in the south of Siberia, and on the coast of the Pacific Ocean seas. The maximum consistency is observed for the stations in southern Siberia, where a negative significant trend in wind events during the warm season (to –2% per decade) was registered at most stations. At the same time, the trends for the events with storm wind (25 m/s) based on station data are insignificant (Fig. 1h).

A possible measure of intensity of squall and tornado events in the forest zone is the area of continuous windthrows that they caused [64]. There has been a significant increase both in the number of convective storms that caused tornado and squall windthrows (the trend value is 2.5 events per decade) and in the total area of windthrows (9.3 km^2/decade) for the forest zone of the EPR since the late 1980s (Fig. 2b). There is high interannual variability in the area of windthrows, in particular, the years 2010 and 2021 stand out, when so called "derecho" (long-lived squalls with a lifetime up to 8 hours) were formed on the western periphery of blocking anticyclones and caused windthrows with a length of above 500 km and a mean width of about 20 km [38]. Such events were registered on the territory of Russia for the first time.

It is reasonable to provide the further assessment of long-period variability of the area of windthrows and the number of convective storms that caused them for the forest regions of Siberia and the Far East. This will allow a more reliable estimation of trends in extreme events in these regions. However, such analysis would not be informative for the areas with the forest cover of <50% [63]. At the same time, it is essential to take into account an increase in vulnerability of the tree stand to wind impacts in a case when strong wind is accompanied by intense precipitation [48]. By the end of the 21st century, global climate models show an increase in the frequency of complex events with strong wind and heavy precipitation (both meet the 99th percentile) for Northern Eurasia, especially for a more aggressive scenario of anthropogenic emissions [61].

Recently, the diagnosis of observed and expected changes in the frequency of severe convective storms and accompanying SCEs has been carried out using convective instability indices based on the data of radiosondes (for example, [16, 70]), reanalysis systems (for example, [7, 69, 70]), and global and regional climate models (for example, [21, 24, 32, 53, 58]). In the latters both changes in different quantiles of the index distributions and in the frequency of exceeding certain thresholds are analyzed. For example, the possible threshold values are 150 J/kg for CAPE and 400 m^2/s^2 for WMAXSHEAR, their exceeding leads to the development of moderate or severe convective events, respectively [70].

The values of convective instability indices calculated from the ERA5 new generation reanalysis for 1979–2020 vary in different directions in different regions of Russia (Figs. 3 and 4). In particular, there is a decrease in convective activity in the south of the EPR and Ural, where a decrease was revealed both in the mean values of CAPE (and derived indices WMAXSHEAR and *P* CAPE) (Fig. 3) and in the frequency of critical values of the indices (Fig. 4). This reduction is consistent with the results of [68], where the convective instability indices were calculated from the ERA5 data with a higher vertical resolution (based on sigma levels). The decrease in *P* CAPE is in general agreement with the decrease in the frequency of thunderstorm days revealed from station data (Fig. 1e). At the same time, the further investigation is required to clarify the degree of consistency of small and differently directed changes in *P* CAPE registered in other regions with changes in the lightning flash rate according to the lightning detection data [51, 67] and with the height of deep convective clouds (Fig. 2a).

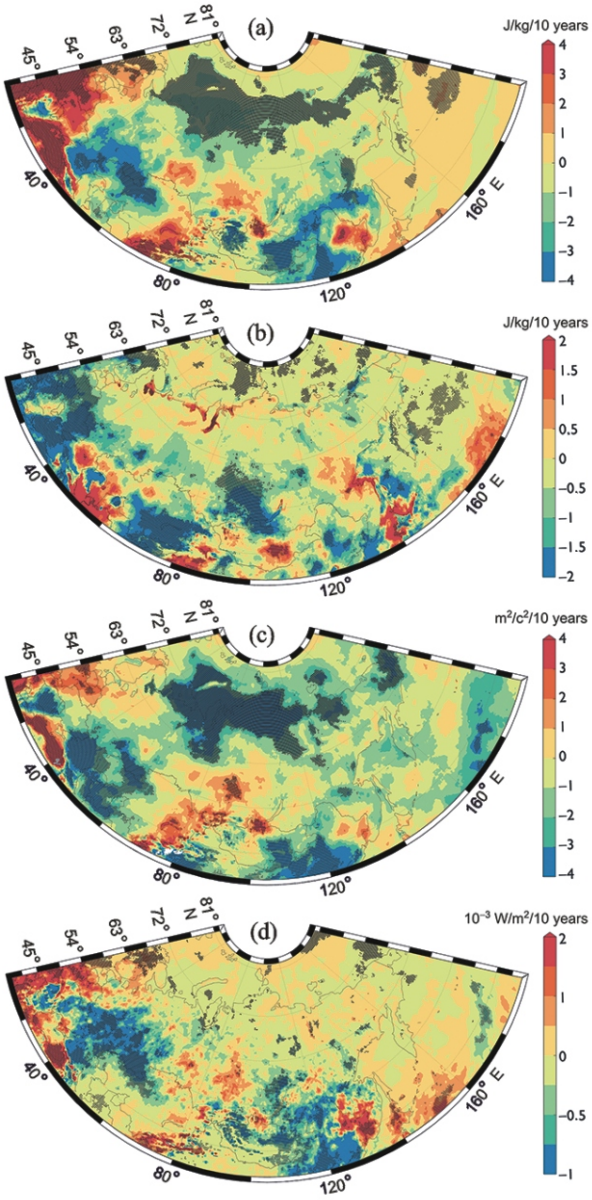

Fig. 3. The linear trend in the April–September mean values of convective instability indices: (a) CAPE, (b) CIN, (c) WMAXSHEAR, (d) *P* CAPE calculated from the ERA5 reanalysis data for 1979–2020. The dots show a statistically significant trend at the level of 95%.

In the polar regions, there is a small (in magnitude) but significant decrease in CAPE. It is evidently associated with the weakening of marine cold air outbreaks, in which convection develops in the Arctic [56]. A significant decrease in WMAXSHEAR is also observed here due to the wind shear reduction. In the south of the Far East, there are differently directed and mostly insignificant changes in the convective instability indices.

On the Black Sea coast and in southern Siberia, there are positive trends in CAPE and WMAXSHEAR and their critical values, which indicate an increase in the probability of development of SCEs, including intensive ones, in these regions. At the same time, the increase in CAPE is accompanied here by the increase in convective inhibition (CIN is usually expressed in negative values, so the negative trend means a general intensification of convective inhibition) (Fig. 3c), which may lead to the conditions for explosive convection. In particular, the combination of rather low absolute values of CIN (>–50 J/kg) and high values

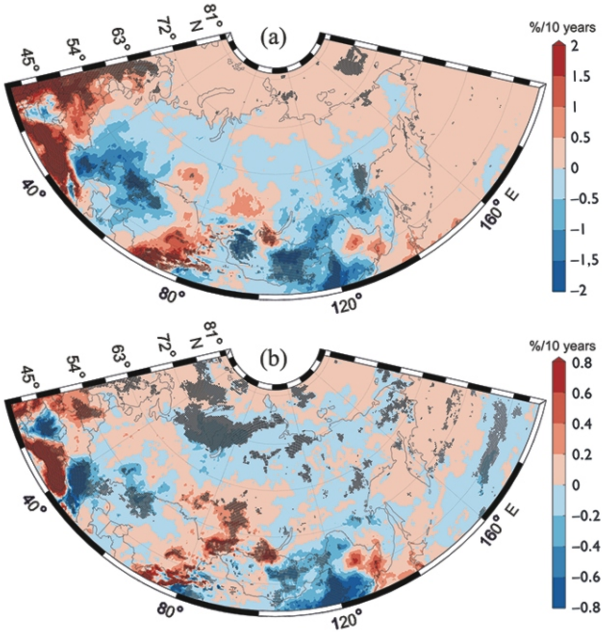

Fig. 4. The linear trend in the frequency of events with (a) CAPE > 150 J/kg, (b) WMAXSHEAR > 400 m^2/s^2 in the warm season (April–September) for 1979–2020. The dots show a statistically significant trend at the level of 95%.

of CAPE favors the development of convection but leads to the formation of moderate SCEs. However, high absolute values of CIN (corresponding to the values to –200 J/kg) in combination with high CAPE under certain conditions (when passing through the intercepting layer) lead to the explosive development of convection and the formation of especially intense SCEs [59]. In particular, such events may be implemented under certain circulation conditions, like, for example, in July 2012 in the area of Krymsk [54]. The idealized model experiments show that the main reason for the increase in CAPE and decrease in CIN in the Black Sea region is the warming of the Black Sea [3, 74]. The revelation of reasons for the convection intensity growth in southern Siberia (that was also noted in [6, 20]) requires further research.

The investigation of reasons for the weakening of convection in the southern EPR is also interesting, particularly because global climate models do not reveal such regional features and demonstrate an increase in the absolute values of CAPE and CIN with a further global temperature rise for entire Russia in the 21st century [32, 53]. In particular, the intensity of development of mesoscale convective systems generating intense SCEs is considerably affected by aerosol [33], whose regional trends are insufficiently correctly reproduced in global climate models [34].

CONCLUSIONS

The present paper analyzes changes in the frequency and intensity of atmospheric SCEs in Russian regions based on ground-based and satellite observations and reanalysis data for the recent decades. The analysis results indicate a general intensification of SCEs in most Russian regions. The weakening of SCEs was registered in southern Ural and the regions of the southern EPR (except for the Black Sea coast). The frequency of moderate SCEs has a decreasing trend, and the frequency of the severe ones has an increasing trend. This conclusion and a number of the revealed regional features of changes in the characteristics of SCEs require further refinement, in particular, based on numerical experiments with convection-permitting models, including the assessment of the role of local and global processes in these changes.

The results may be used for assessing climate change risks, in particular, those associated with the formation of SCEs, the expected changes in the intensity and frequency of which should be considered when developing plans for the adaptation of Russian regions and industries to climate change.

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