Russian Journal of Earth Sciences

Special Issue: "Fundamental and Applied Aspects of Geology, Geophysics and Geoecology"

Histograms of the Caspian Sea Hydrometeorological Parameters

Andrey G. Kostianoy[1,2,3], Sergey A. Lebedev[4,3,5], Alexandr V. Bocharov[1,6], Ilya A. Kosolapov[1], Ilya D. Tretiyak[1], Daniil S. Volkov[7], Dmitry A. Grebenikov[1,8], Pavel N. Kravchenko[1,2,6]

[1]Shirshov Institute of Oceanology of RAS, Moscow, Russia
[2]S. Yu. Witte Moscow University, Moscow, Russia
[3]Maykop State Technological University, Maykop, Russia
[4]Geophysical Center of RAS, Moscow, Russia
[5]National Research University of Electronic Technology (MIET), Moscow, Zelenograd, Russia
[6]Tver State University, Tver, Russia
[7]Skolkovo Institute of Science and Technology (Skoltech), Moscow, Russia
[8]Sirius University of Science and Technology, Sochi, Sirius, Russia
* **Correspondence to:** Andrey Kostianoy, Kostianoy@gmail.com

Abstract: The article analyzes histograms of the distribution of the main hydrometeorological parameters of the Caspian Sea for 1980–2021 – air temperature, atmospheric pressure, absolute humidity, atmospheric precipitation and wind speed according to the MERRA-2 atmospheric reanalysis. Histograms were constructed for the entire study region of the Caspian Sea (36°–48°N, 45.625°–55°E), as well as separately for land and sea areas. The extremeness criteria were calculated based on the normal distribution and the real histogram for all 5 main meteorological parameters. A comparison was made of histograms obtained from MERRA-2 data and from weather station at Derbent located on the coast of the Caspian Sea. Distributions of average monthly wind speed, integral water vapor content and water vapor content in clouds over the Caspian Sea were also constructed according to microwave radiometry (SMMR, SSM/I) data for the time interval 1980–2021.

Keywords: Caspian Sea, climate, extreme weather events, meteo parameters, weather stations, MERRA-2, SMMR, SSM/I.

Citation: Kostianoy A., Lebedev S., Bocharov A., Kosolapov I., Tretiyak I., Volkov D., Grebenikov D., Kravchenko P. (2023), Histograms of the Caspian Sea Hydrometeorological Parameters, *Russian Journal of Earth Sciences*, Vol. 23, ES0211, https://doi.org/10.2205/2023ES02SI11

Research Article

Received: 20 October 2023
Accepted: 27 November 2023
Published: 15 December 2023

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) assessment reports [*IPCC*, 2007, 2014, 2021] indicate that in the 21st century, climate change will be accompanied by an increase in the frequency, intensity and duration of extreme natural events such as extreme precipitation and extremely high and low air temperatures. All this will lead to floods, droughts, fires, shallowing of rivers, lakes and reservoirs, desertification, dust storms, melting of glaciers and permafrost, blooming of seas and freshwater bodies. In turn, these phenomena will lead to chemical and biological pollution of water, land and air. The end result of these events is a deterioration in the quality of life of the population, significant financial losses associated with damage to housing, businesses, roads, agriculture and forestry, tourism, and in many cases they result in loss of life.

The same forecasts are confirmed by the results of studies presented in the Roshydromet Assessment Reports on climate change and its consequences on the territory of the Russian Federation [*Roshydromet*, 2008, 2014, 2022]. Scientists' forecasts have been repeatedly confirmed over the past 20 years – these are floods, droughts, fires, heat and cold waves in various regions of the Russian Federation.

Climate change leads to changes in the frequency, intensity, spatial extent, and duration of extreme weather and climate events, leading to the occurrence of hazardous hydrometeorological events. More than 30 types of dangerous hydrometeorological phenomena are observed in Russia. Their total number per year increased on average at the end of the 20th and beginning of the 21st centuries. Of these, 52% were observed in the European territory of Russia. The North Caucasus and Southern Federal districts are most susceptible to various extreme weather and climate phenomena. In this regard, the analysis and forecasting of extreme climatic events associated with regional climate change on the coast of the Caspian Sea and its waters is an extremely important task.

The state of the ecosystems of the Caspian Sea and its coast is of serious concern, due not only to anthropogenic, but also natural causes (climate changes, extreme meteorological and hydrological phenomena, dangerous natural phenomena, as well as the frequency of their recurrence, etc.). In this regard, there is a need for a comprehensive analysis of both climate change and all phenomena associated with them [*Kostianoy and Kosarev*, 2005; *Lavrova et al.*, 2011, 2016, 2022; *Zonn et al.*, 2010].

The Caspian Sea has important economic (fishing, shipping, offshore production and transportation of oil and gas, international transportation, and tourism) and military-strategic significance, especially in connection with the real narrowing of the boundaries of Russian influence in the Caspian Sea after the collapse of the USSR. Characteristic features of the Caspian Sea are the absence of water exchange with other seas and World Ocean, the reduced salt content (compared to the ocean), and the fact that its water balance is largely determined by the runoff of the rivers flowing into the sea and evaporation. The lack of water exchange makes it extremely sensitive to both changes in global and regional climate, as well as to anthropogenic impacts caused by river flow and its regulation, waste from resort areas and industrial centers on the shore, offshore oil and gas production and transportation, etc., which can lead to changes at the ecosystem level. The consequence of climate change is changes in sea surface temperature, its salinity and sea level, the onset of formation and duration of ice cover, associated with climate-related changes in air temperature, wind speed and direction, runoff of rivers flowing into the sea, atmospheric precipitation and evaporation from the sea surface. Environmental objectives and the maintenance of coastal infrastructure require constant monitoring of changes in these hydrological and meteorological parameters.

From April 2023 at the Shirshov Institute of Oceanology of Russian Academy of Sciences (Moscow), with the support of the Russian Science Foundation Grant N 23-77-00027, the project «Investigation of the climate variability of thermo-hydrodynamic regime of the Caspian Sea based on remote sensing data» (https://rscf.ru/en/project/23-77-00027) is being carried out. The main fundamental objectives of the project are:

1. Analysis of climatic variability of the main physical parameters of the sea state (sea surface temperature, sea level, wind waves, sea ice, etc.) and meteorological parameters (air temperature, atmospheric pressure, surface wind speed, humidity, integral water vapor content, water vapor content in clouds, atmospheric precipitation) over the waters of the Caspian Sea;
2. Application of the analysis of "extremeness" (i.e., phenomena that stand out sharply against the background of the "norm") to the study of the variability of the main parameters of the state of the Caspian Sea and the atmosphere over its water area. Analysis of extreme hydrological and meteorological events will be carried out using remote sensing data and reanalysis data. This will make it possible to give scientifically based recommendations for the implementation of the "Strategy for the development of Russian sea ports in the Caspian Basin, railway and road approaches to them in the period until 2030", adopted by Order of the Government of the Russian Federation of November 8, 2017 No. 2469-r.

The aim of this paper is: (1) to analyze histograms of the distribution of the main hydrometeorological parameters of the Caspian Sea for 1980–2021 – air temperature, atmospheric pressure, absolute humidity, atmospheric precipitation and wind speed according to the MERRA-2 atmospheric reanalysis; (2) to construct and compare histograms for the entire study region of the Caspian Sea (36°–48°N, 45.625°–55°E), as well as separately for land and sea areas; (3) to calculate the extremeness criteria based on the normal distribution and the real histogram for all 5 main meteorological parameters; (4) to compare the histograms obtained from MERRA-2 data and from Derbent weather station located on the Caspian Sea coast; and (5) to analyze histograms of average monthly wind speed, integral water vapor content and water vapor content in clouds over the Caspian Sea constructed according to microwave radiometry (SMMR, SSM/I) data for the time interval 1980–2021.

2. Extreme and dangerous events, emergency situations

Extreme hydrological and meteorological phenomena are usually understood as those phenomena that stand out sharply in their characteristics against the background of "normal" phenomena in the climate system. As a rule, such phenomena have a special, often negative impact on natural systems and lead to the emergence of dangerous natural consequences, which should be understood as a spontaneous event of natural origin, which, in its intensity, scale of distribution and duration, can cause negative consequences for the life of people, as well as economy and natural environment. Depending on the mechanism and nature of origin, hazardous natural phenomena are divided into the following groups (classes):

1. Geophysical hazards: earthquakes; volcanic eruptions; tsunami.
2. Geological hazards (exogenous geological phenomena): landslides, mudflows, screes, avalanches, subsidence of the earth's surface, abrasion, erosion, dust storms, etc.
3. Meteorological and agrometeorological hazards: storms, hurricanes, tornadoes, squalls, vertical vortices (flows), large hail, heavy rain, heavy snowfall, heavy ice, severe frost, severe snowstorm, heat wave, cold wave, heavy fog, drought, dry wind, frosts.
4. Marine hydrological hazards: tropical cyclones (typhoons), strong waves, strong fluctuations in sea level, strong currents in ports, early ice cover or fast ice, ice pressure, intense ice drift, impassable (difficult to pass) ice, icing of ships, detachment of coastal ice.
5. Hydrological hazards: high water level, flood, rain floods, wind surge, low water level, early freeze-up and appearance of ice on navigable reservoirs and rivers, rising groundwater levels (flooding).
6. Natural fires: extreme fire danger, forest fires, fires of steppe and grain massifs, peat fires, underground fossil fuel fires.

Not every dangerous natural phenomenon leads to an emergency situation, especially if there is no threat to human life at the place of its occurrence. For example, an annual flood is not counted as a flood if it does not threaten anyone. There is no reason to consider storms, avalanches, freeze-ups, and volcanic eruptions as emergencies in places where people do not live or do any work. An emergency occurs only when, as a result of a dangerous natural phenomenon, a real threat arises to people and their environment. Many dangerous natural phenomena are closely related to each other. An earthquake can cause landslides, mudflows, floods, tsunamis, avalanches, and increased volcanic activity. Many storms, hurricanes, and tornadoes are accompanied by showers, thunderstorms, and hail. Extreme heat waves are accompanied by drought, low groundwater, fires, epidemics, and pest infestations.

3. Norm and extremeness

Climatic norms can be calculated for a wide range of parameters. While some parameters, such as temperature and precipitation, have significance for all parts of the world, others, such as snowfall or the exceedance of certain thresholds (for example, maximum temperatures below 0°C in the tropics), have little or no significance. meanings for some parts of the world.

According to [*WMO*, 2007], the period from 1961 to 1990 was adopted as the standard reference period for long-term climate change assessment. The Seventeenth World

Meteorological Congress [*WMO*, 2015] approved a number of changes that are reflected in the "*WMO Guidelines on the Calculation of Climate Normals*" in the definitions relating to climate norms [*WMO*, 2017]. The most significant of these changes was the redefinition of climatological standard normals so that they now apply to the most recent 30-year period ending with a year ending in 0 (for example, periods 1901–1930, 1931–1960, 1961–1990, and 1991–2020).

With the development of methods for remote sensing of the Earth from space at the end of the 20th century, the time interval 1961–1990 as the standard reference period or "norm" for long-term climate change assessments cannot be applied due to lack of data. Since the 1980s, active monitoring of the characteristics of the land and atmosphere (air and surface temperature, wind speed, humidity, atmospheric precipitation, integral content of water vapor, water in clouds, etc.) and the World Ocean (sea surface temperature, ocean color, sea level anomaly, sea surface state) has been carried out in the infrared, optical, and microwave ranges [*Kopelevich and Kostianoy*, 2018; *Kostianoy*, 2017a,b; *Kostianoy et al.*, 2018]. This makes it possible to determine the time intervals 1991–2020 as a reference period for long-term assessment of climate change in both the atmosphere, ocean and inland seas and calculate the "norm" of the state of individual parameters, relative to which "extreme" values will be determined.

Extreme meteorological phenomena are usually understood as statistics of "extreme", i.e., phenomena in the climate system that stand out sharply against the background of the "norm". As a rule, such phenomena have a special (usually negative) impact on natural systems, which are therefore especially sensitive to changes in their frequency and intensity [*IPCC*, 2007, 2014, 2021; *Roshydromet*, 2008, 2014, 2022; *Shkol'nik et al.*, 2012]. Various types of extreme events can be distinguished:

1. Values of meteorological parameters that differ greatly from the norm at points of regular observation (meteorological stations): anomalies exceeding certain threshold values (extreme heat/cold, rain, etc.); for this group the most reliable statistics can be obtained from observational data;
2. Long-term episodes during which a meteorological variable or set of variables exceeds a given level: heat and cold waves, droughts (it should be noted that in this case the levels are not necessarily "extreme": drought can be the result of a prolonged combination of above-normal temperature and precipitation below normal);
3. Large-scale phenomena associated with atmospheric circulation: the most intense cyclones/anticyclones, blockings, tropical hurricanes (typhoons); for these phenomena (at least for repeatability) fairly reliable statistics can also be obtained;
4. Dangerous or unfavorable natural phenomena of a local nature; this includes tornadoes, floods, severe ice, etc.: the peculiarity of this group is that, according to the observation network, it is difficult to obtain sufficiently adequate statistics for them; however, a qualitative analysis of regional generalizations on a fairly large scale is possible for them.

Definitions of extreme events in the first two groups depend on the choice of threshold values. One approach to the selection of threshold values is directly related to the understanding of extreme events as rare: in other words, belonging to the extreme regions of the distribution of a meteorological parameter, the probability of occurrence in which is low. Many researchers a priori accept the distribution of hydrometeorological parameters to correspond to the Gaussian distribution or normal distribution, and take the three-sigma law as threshold values, for example, [*Coumou and Robinson*, 2013].

A more reasonable criterion for determining "extremeness" is whether a value falls into a given percentile of the distribution function, for example, 10, 5, or 1 percentile for extreme negative anomalies (respectively, 90, 95, 99 percentile for positive ones).

Another approach is based on critical values, determined based on the thresholds of a certain (usually adverse) impact on natural or technical systems. The simplest example is frosts during the growing season; a more complex example is the adverse impact of prolonged heat on people's health (here 2 thresholds must be assigned simultaneously, for example, temperatures above 30 °C for 5 days or more).

Changes in the statistics of extreme values inevitably occur with climate change, which for a given meteorological parameter is described by a change in the distribution function. In the simplest case, when the distribution is close to Gaussian, these changes are completely described by changes in the mean value and standard deviation. Changes in extremes can be described as changes in the probability (recurrence) of values exceeding a fixed threshold, or as changes in threshold values (if they are assigned according to the percentile of the distribution).

Thus, for example, if the average value increases and the overall variability remains constant, the frequency of positive extremes increases and the frequency of negative extremes decreases (Figure 1a). In terms of changes in the quantiles of the distribution, this means an increase in the threshold quantile in both cases (as the average decreases, the changes in the extrema are the opposite of those described). An increase in the variability of standard deviations with a constant average value leads to an increase in the frequency of both positive and negative extremes, or to an increase in the "upper" (P_e^+) thresholds and a decrease in the "lower" (P_e^-) (Figure 1b). Simultaneous changes in the mean value and standard deviation can lead to different results depending on the ratio of the magnitudes of these changes (Figure 1c). In the case of multimodal distribution, the picture becomes more complex (Figure 1d).

To describe extremes, the WMO Joint Working Group on Climate Change proposed a set of 27 extremeness indices [*Karl et al.*, 1999]. Most indices refer to the number of days on which the values of a meteorological parameter fall outside some specified threshold. Initially, the indices were defined for the whole year, but such definitions in many cases did not make much sense for the extratropical zone, where the seasonal variation of meteorological variables is large, so they were reformulated for seasons or months. The threshold for various locations may be fixed or variable (e.g., a specific percentile). The most commonly used extremity indices are:

1. FD – total number of days with frost (days). The indicator is important for agriculture. It is calculated as the number of days in a calendar year (season) with a daily minimum air temperature below 0 °C. In extratropical latitudes, the index in annual generalization is one of the possible characteristics of the duration of the cold period of the year.
2. R10 – number of days with precipitation of at least 10 mm (days). On the territory of Russia, the index mainly characterizes the frequency of significant precipitation, since in mid-latitudes a daily amount of 10 mm corresponds mainly to heavy precipitation.
3. CDD – maximum duration of the "dry" period per year (days). A "dry" period is defined as a sequence of days without precipitation or with traces of precipitation (<1 mm); can serve as an indicator of droughts. Changing the duration of such a phenomenon and shifting its boundaries affects vegetation and ecosystems as a whole.
4. TXx, TNn – annual maximum of maximum daily air temperature and annual minimum of minimum daily air temperature. Naturally, on the territory of Russia, the first of the indices characterizes the summer season, and the second - the winter season.
5. TX95p, TN5p – number of days per season (year) with extreme (above the 95th percentile/below the 5th percentile) values of maximum/minimum daily temperature.
6. RR95p – number of days per season (year) with extreme (above 95th percentile/below 5th percentile) precipitation.
7. Indices of "moderate" extremes (TX90p, TN10p, etc.)
8. Duration of stable frosty and frost-free periods, number of days with thaws, etc.

The disadvantage of the ongoing research is the averaging of the studied parameters and the generalization of the findings for very large territories and water areas comparable to the size of individual countries. This project proposes to detail the variability of various hydrometeorological parameters and characteristics of extreme climatic events with a

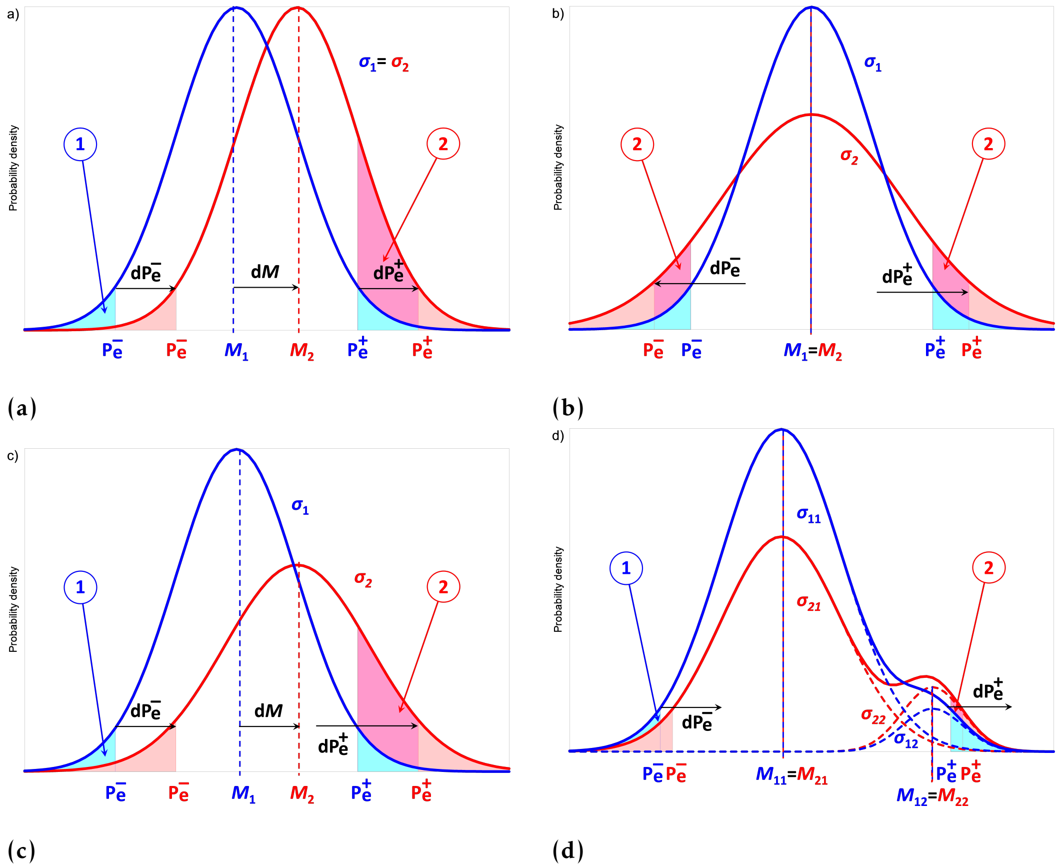


Figure 1. Scheme of possible changes in the frequency of extrema relative to unchanged percentiles of the distribution when changing the mean (a), dispersion (b), mean and dispersion (c), dispersion in the case of a multimodal distribution (d). The distribution of the previous climate is shown in blue, and the distribution of the new climate in red. P_e^- and P_e^+ are threshold values for minimum and maximum values. M_i and M_{ij} are the mean, and σ_i and σ_{ij} are the standard deviation of the distributions. Numbers 1 and 2 show areas of decrease and increase in the frequency of events while maintaining threshold values.

spatial scale of about 0.5 degrees (and for some hydrological parameters of the state of the water surface – a quarter of a degree) in the Caspian Sea and its coast.

For the coast of the Caspian Sea and its waters, there is not enough data from field measurements to statistically describe the main parameters of the state of the atmosphere and sea water and identify extreme meteorological and/or hydrological phenomena. This is also true for mountainous or foothill areas, where instrumental measurements of meteorological parameters are clearly insufficient.

4. Data

For the study, regional databases of basic meteorological parameters for 1980–2021 were created:

1. Atmospheric pressure at sea level, atmospheric pressure at station level, air temperature, relative air humidity, water vapor pressure, amount of cloud cover, precipitation amounts, number of days with precipitation more than 1 mm, etc. according to data from coastal weather stations located on the coast of the Caspian Sea (Makhachkala, Baku, Fort Shevchenko, Turkmenbashi (formerly Krasnovodsk), etc.) [*Volkov et al.*, 2023a];
2. Air temperature, water temperature, atmospheric pressure at sea level, wind speed, humidity, precipitation, sea ice, state of vegetation cover – based on the global at-

mospheric reanalysis database MERRA-2 (Modern-Era Retrospective analysis for Research and Applications) [*Kostianoy and Lebedev*, 2023];

3. Surface wind speed, integral water vapor content and water vapor content in clouds according to microwave radiometers SMMR (Scanning Multichannel Microwave Radiometer) and SSM/I (Special Sensor Microwave Imager) [*Volkov et al.*, 2023b].

There are a huge number of databases on weather stations included in the network of the World Meteorological Organization, which exchanges data between its members. Thus, the All-Russian Scientific Research Institute of Hydrometeorological Information – World Data Center (VNIIGMI-MCD) provides urgent, daily and average monthly data from 521 meteorological stations in the territory of the former USSR from the moment the stations were founded to present, in some places with breaks for wars, etc. [*Bulygina et al.*, 2014; *Kuznetsova et al.*, 2019; *Shvets et al.*, 2018]. The main parameters of these data are: the number of days with precipitation more than 1 mm, air temperature, water vapor pressure, atmospheric pressure at the station level, average monthly cloudiness, precipitation amounts, relative air humidity, atmospheric pressure at sea level, etc.

Among the foreign sources of information on weather stations is the GSOD (Global Surface Summary of the Day) average daily data base [*NCDC NESDIS NOAA*, 2021; *Sparks et al.*, 2017] of the National Centers for Environmental Information. This database contains average daily data for the following parameters: average dew point, average sea level pressure, average wind speed (in knots), maximum sustained wind speed, snow depth (in inches). Historical data is generally available from 1929 to the present, with data from 1973 being the most complete. Since the data is converted to constant units (such as nodes), there may be a slight rounding error from the original data [*Lavigne and Liu*, 2022].

MERRA-2 (US National Aeronautics and Space Administration, NASA) is a global atmospheric reanalysis covering the era of satellite observations from 1980 to the present. It provides an organized, regularly referenced record of global atmospheric parameters and includes additional information about the climate system: trace gases (stratospheric ozone), an improved representation of the Earth's surface, and cryosphere processes. MERRA-2 is the first global reanalysis of the satellite era, assimilating space-based observations of aerosols and representing their interaction with other physical processes in the climate system [*Gelaro et al.*, 2017].

Application of microwave radiometry for climate studies of surface wind speed [*Atlas et al.*, 1996; *Chang and Li*, 1998], integral water vapor content [*Jackson and Stephens*, 1995; *Tjemkes et al.*, 1991] and cloud water vapor content [*Greenwald et al.*, 1993] became possible after the launch of the SMMR multichannel scanning radiometer on the Nimbus-7 satellite in 1978, which operated for about 9 years. With a short break, since 1987, operational meteorological satellites DMSP (Defense Meteorological Satellite Program) with microwave radiometers SSM/I have been constantly operating. The SSM/I multichannel scanning radiometer is the most prominent representative of satellite microwave radiometric systems operated in recent years as part of the US Department of Defense meteorological program designed for long-term monitoring of the Earth in order to provide global meteorological, oceanographic and solar geophysical operational information. In December 1992 the data was declassified and became available to the civil and scientific community. In the future, this series of observations may be expanded both by DMSP satellites and by satellites planned for launch. Thus, at present, a unique opportunity has arisen to assess changes in climate-significant parameters of the state of the atmosphere using satellite microwave radiometry methods.

5. Methods

To analyze extremality, at the first stage, distributions (probability density) were constructed for all parameters included in the created databases. For the parameters of the atmospheric state of the MERRA-2 reanalysis, the data of which exist both over land and over the sea: atmospheric pressure at sea level, air temperature (at a height of 2 m), absolute humidity (at a height of 2 m), precipitation and wind speed (at a height of

10 m) – three distributions were constructed for data over land, over the sea and over the whole Caspian Sea region (36°–48°N, 45.625°–55°E) for the time interval 1980–2021. A significant difference in distributions over land, over sea and over the region as a whole is observed for air temperature at a height of 2 m according to the MERRA-2 reanalysis data (Figure 2).

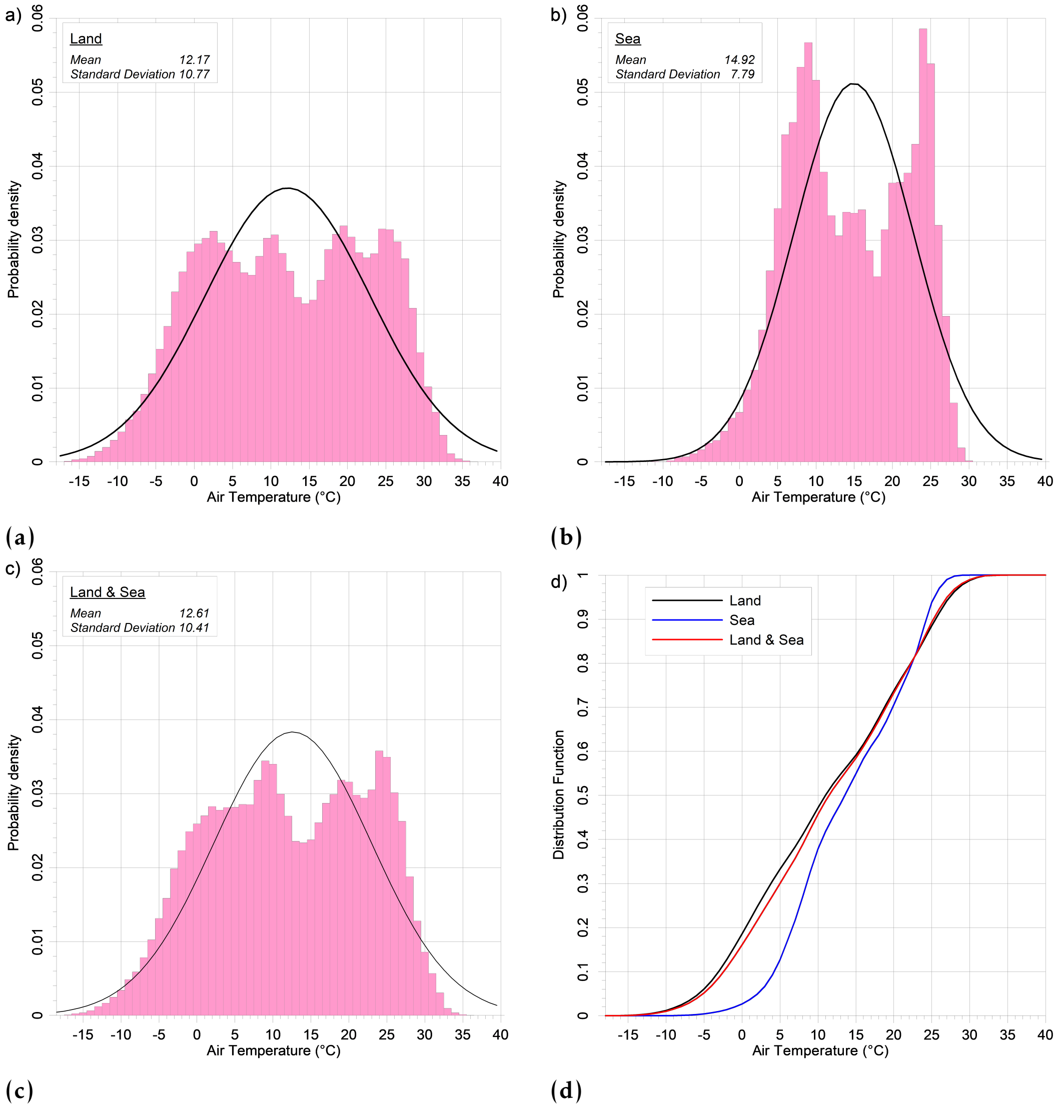
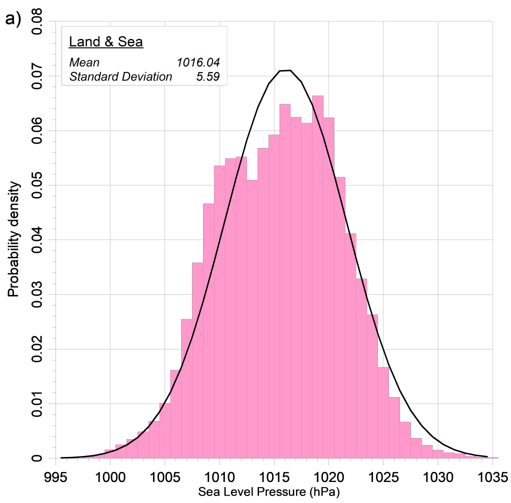
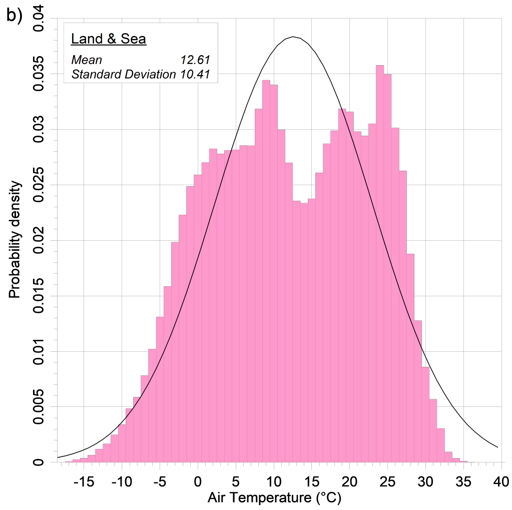


Figure 2. Probability density of air temperature at a height of 2 m above land (a), over the sea (b) and over the Caspian Sea region (36°–48°N, 45.625°–55°E) as a whole (c) and distribution function (d) according to MERRA-2 reanalysis data for 1980–2021. The solid line shows the corresponding Gaussian distributions. Each figure shows the mean value and standard deviation.

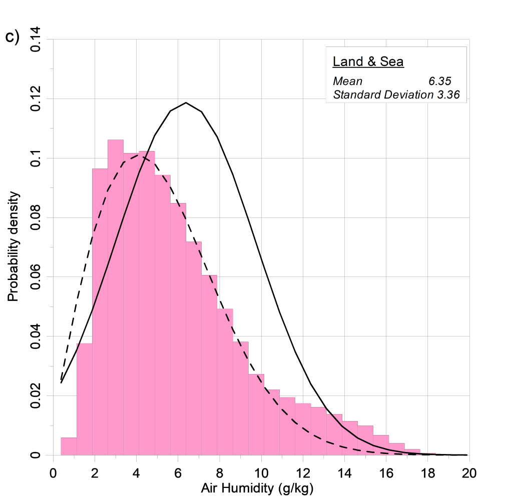
According to the MERRA-2 reanalysis, the probability density distribution of not a single parameter corresponds to a normal distribution (Figure 3). The distribution of atmospheric pressure at sea level is closest to it (Figure 3a). To analyze the probability density of wind speed (at a height of 10 m), the most optimal is the Rayleigh distribution (Figure 3e), and for atmospheric precipitation, the exponential distribution (Figure 3d).


a)
Land & Sea
Mean 1016.04
Standard Deviation 5.59
Probability density
Sea Level Pressure (hPa)

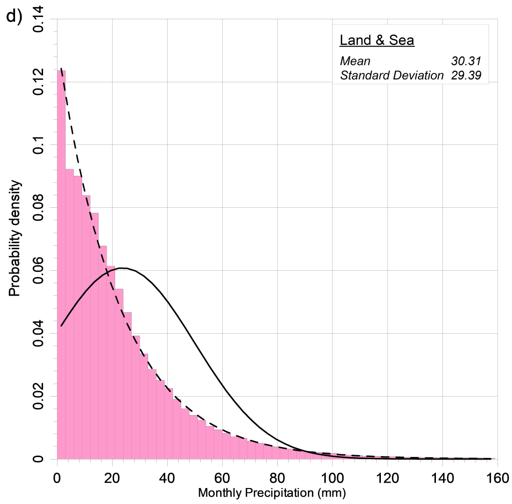
(a)


b)
Land & Sea
Mean 12.61
Standard Deviation 10.41
Probability density
Air Temperature (°C)

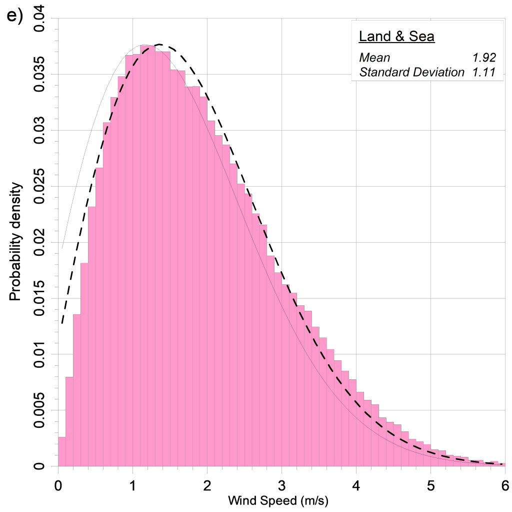
(b)


c)
Land & Sea
Mean 6.35
Standard Deviation 3.36
Probability density
Air Humidity (g/kg)

(c)


d)
Land & Sea
Mean 30.31
Standard Deviation 29.39
Probability density
Monthly Precipitation (mm)

(d)



(e)

Figure 3. Probability density distribution of atmospheric pressure at sea level (a), air temperature (at a height of 2 m) (b), absolute humidity (at a height of 2 m) (c), atmospheric precipitation (d) and wind speed (at a height of 10 m) (e) over the Caspian Sea region (36°–48°N, 45.625°–55°E) according to MERRA-2 reanalysis data for the time interval 1980–2021. The solid line shows the corresponding Gaussian distributions (a–e), the dashed line shows exponential distribution (d) and Rayleigh distribution (c, e). Each figure shows the mean value and standard deviation.

6. Results and Discussion

The distributions of air temperature and absolute humidity at a height of 2 m can be considered multimodal or a combination of several Gaussian distributions (Figure 3b) or Gaussian and Rayleigh distributions (Figure 3c). Assuming that these probability densities of these values correspond to the Gaussian distribution, we compare the limits of extremity based on the 2 and 3 sigma rule with the limits determined from the 1, 5 and 10 percentiles for the minimum values and 99, 95 and 90 percentiles for the maximum values (Table 1).

Table 1. Extremeness criteria calculated from the normal distribution and a real histogram for five main meteorological parameters according to the MERRA-2 reanalysis data for 1980–2021.

Criteria	Land		Sea		Land & Sea	
			Sea level pressure (hPa)			
2 sigma (4.56%)	< 1010.25	> 1021.62	< 1011.43	> 1021.52	< 1010.44	> 1021.64
3 sigma (0.28%)	< 1007.41	> 1024.46	< 1008.91	> 1024.04	< 1007.65	> 1024.44
1 and 99 percentile (2%)	< 1002.49	> 1027.92	< 1006.30	> 1026.57	< 1002.79	> 1027.76
5 and 95 percentile (10%)	< 1006.35	> 1024.41	< 1007.93	> 1023.81	< 1006.64	> 1024.33
10 and 90 percentile (20%)	< 1008.10	> 1022.68	< 1009.06	> 1022.42	< 1008.28	> 1022.64
			Air temperature (ºC)			
2 sigma (4.56%)	< 1.41	> 22.94	< 7.12	> 22.71	< 2.20	> 23.01
3 sigma (0.28%)	< −3.98	> 28.33	< 3.23	> 26.61	< −3.01	> 28.22
1 and 99 percentile (2%)	< −10.00	> 30.81	< −2.45	> 27.50	< −9.55	> 30.53
5 and 95 percentile (10%)	< −5.22	> 27.88	< 2.57	> 25.86	< −4.66	> 27.52

Continued on next page

Table 1. Extremeness criteria calculated from the normal distribution and a real histogram for five main meteorological parameters according to the MERRA-2 reanalysis data for 1980–2021. (Continued)

Criteria	Land		Sea		Land & Sea	
10 and 90 percentile (20%)	< −2.60	> 26.01	< 4.72	> 24.79	< −1.95	> 25.72
Air humidity (g/kg)						
2 sigma (4.56%)	< 2.88	> 8.86	< 4.93	> 12.95	< 2.90	> 9.72
3 sigma (0.28%)	< 1.39	> 10.36	< 2.93	> 14.95	< 1.31	> 11.40
1 and 99 percentile (2%)	< 1.18	> 14.55	< 2.31	> 17.13	< 1.21	> 13.97
5 and 95 percentile (10%)	< 1.86	> 11.50	< 3.44	> 15.63	< 1.93	> 13.67
10 and 90 percentile (20%)	< 2.20	> 9.58	< 4.03	> 14.60	< 2.31	> 10.94
Monthly Precipitation (mm)						
2 sigma (4.56%)		> 48.02		> 59.70		> 50.05
3 sigma (0.28%)		> 60.74	< 0.92	> 74.40		> 63.17
1 and 99 percentile (2%)	< 22.59	> 105.12	< 30.31	> 118.33	< 23.81	> 107.73
5 and 95 percentile (10%)	< 47.66	> 79.87	< 62.29	> 93.77	< 50.52	> 137.24
10 and 90 percentile (20%)	< 54.52	> 64.62	< 73.45	> 79.31	< 57.49	> 67.53
Wind speed (m/s)						
2 sigma (4.56%)	< 0.76	>2.88	<1.32	> 3.68	< 0.81	> 3.03
3 sigma (0.28%)	< 0.22	>3.41	< 0.72	> 4.27	< 0.26	> 3.58
1 and 99 percentile (2%)	<0.36	>4.80	< 0.24	> 5.39	< 0.58	> 4.92
5 and 95 percentile (10%)	< 0.55	>3.79	< 0.61	> 4.45	< 0.38	> 3.94
10 and 90 percentile (20%)	< 1.82	>3.25	< 0.91	> 4.00	< 1.92	> 3.43

For sea level pressure at land 3 sigma approximately corresponds to a value between 5 and 10 percentile for minimum values and 95 percentile for maximum values. For air temperature at land 3 sigma approximately corresponds to a value between 5–10 percentile for minimum values and between 95–99 percentile for maximum values. For air humidity at land 3 sigma approximately corresponds to a value between 1–5 percentile for minimum values and between 90–95 percentile for maximum values. For atmospheric precipitation at land 3 sigma approximately corresponds to a value of 90 percentile for maximum values. For wind speed at land 3 sigma approximately corresponds to values less than 1 percentile for minimum values and between 90–95 percentile for maximum values. For all five parameters the same relationships are valid for the sea area only as well as for the whole region of investigation.

Many real histograms are multimodal (Figure 3a, 3b). To develop an extremeness criterion, we present them as a superposition of several Gaussian distributions. For example, let's solve this problem for a histogram of air temperature over land (Figure 4a), which is decomposed into 4 Gaussian distributions. The probability density $p(x,I)$ in this case is written as:

$$p(x,I) = \frac{1}{\sum_{i=1}^{4} k_i} \sum_{i=1}^{I=4} \frac{k_i}{\sigma_i \sqrt{2\pi}} \exp\left(-\frac{(x-m_i)^2}{2\sigma_i^2}\right), \tag{1}$$

where m_i is a mean value of a parameter x, σ_i is a standard deviation, k_i is a proportionality factor, $i = 1,2,3,4$ is an index of the corresponding Gaussian distribution. Values of coefficients m_i, σ_i and k_i were calculated by minimizing the error functional

$$J(x, k_i, m_i, \sigma_i) = p(x, k_i, m_i, \sigma_i) - P(x),$$

where $P(x)$ – is a real histogram of distribution of parameter x.

The resulting system of linear equations was solved by the gradient descent method [*Korn and Korn*, 2000]. The resulting coefficient values for the air temperature histogram over land are presented in Table 2, and the corresponding distributions and their superposition in Figure 4b.

Table 2. Values of Gaussian distributions for air temperature over land are presented according to MERRA-2 reanalysis data for 1980–2021 time period.

Distribution	Mean value of the parameter (m), °C	Standard deviation (σ), °C	Proportionality factor (k)
One distribution	12.17	10.71	1.00
Distribution 1 from 4	1.43	5.27	0.41
Distribution 2 from 4	11.27	2.70	0.17
Distribution 3 from 4	18.90	2.51	0.19
Distribution 4 from 4	26.07	2.97	0.23

To identify the boundaries of extremity according to the 2 and 3 sigma rule, the average air temperature values and standard deviations of the first distribution for minimum values and the fourth distribution for maximum values were used according to Table 2. The results obtained are presented in Table 3.

Figure 4 shows that a superposition of four Gaussian distributions perfectly describes a real histogram of air temperature above land in the Caspian Sea region based on MERRA-2 data. The complexity of the real shape of the histogram of air temperature over land suggests that deviations from the norm calculated for 1980–2021 can be observed not only at the “tails” of the distribution, but also inside the distribution. Thus, Figure 5 shows the deviations of the annual distribution density from the climate norm.

Table 3. Extremeness criteria calculated from the normal distribution and a real histogram for air temperature over land (°C) according to the MERRA-2 reanalysis data for 1980–2021 time period.

Criteria	Land	
One distribution		
2 sigma (4.56%)	< 1.41	> 22.94
3 sigma (0.28%)	< −3.98	> 28.33
Distribution 1 and 4 from 4		
2 sigma (4.56%)	< −2,43	> 29.04
3 sigma (0.28%)	< −3.84	> 30.53
Histogram		
1 and 99 percentile (2%)	< −10.00	> 30.81
5 and 95 percentile (10%)	< −5.22	> 27.88
10 and 90 percentile (20%)	< −2.60	> 26.01

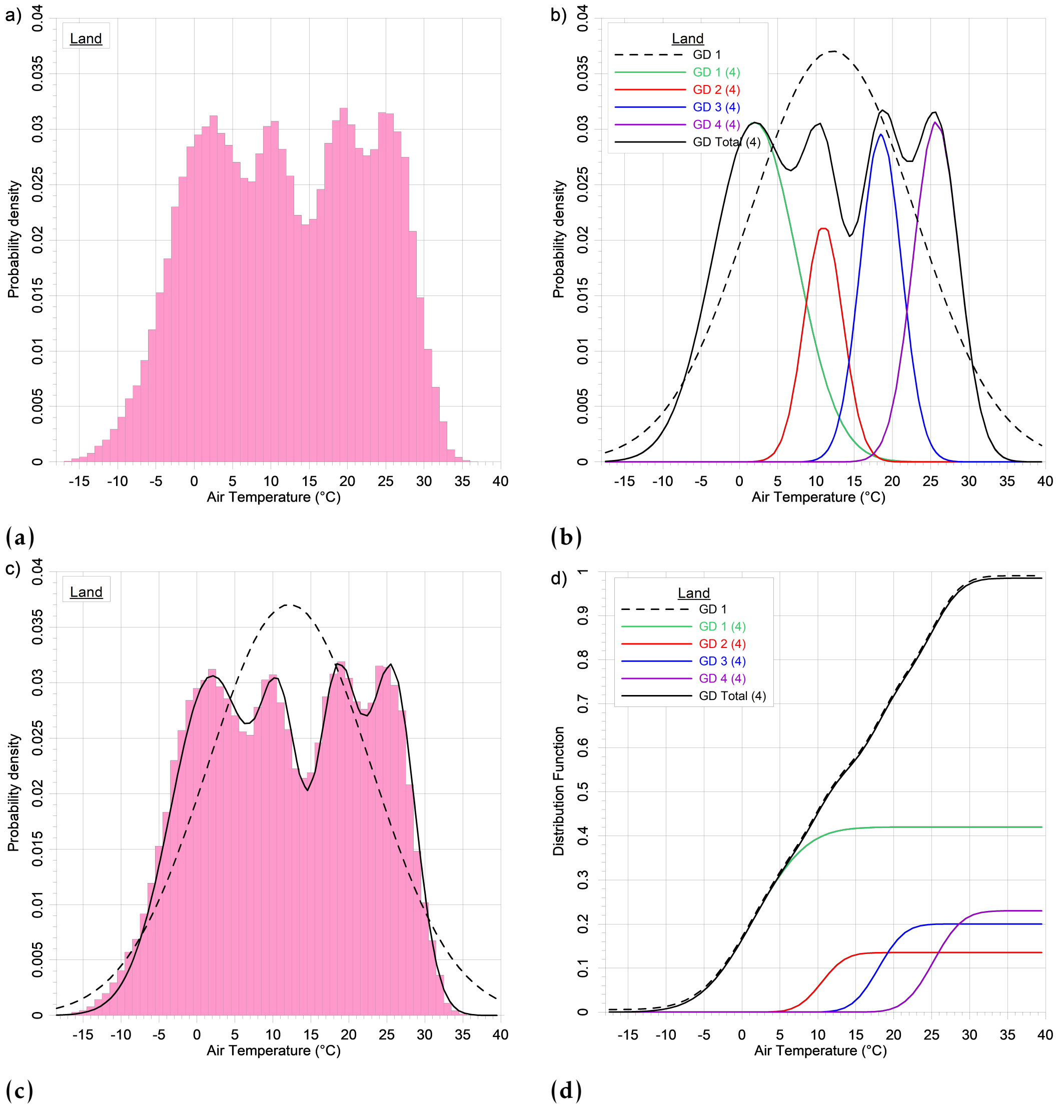


Figure 4. Probability density of air temperature at a height of 2 m above land (a), decomposition of the histogram into four Gaussian distributions (GD) (b), combined results (c) and distribution functions for each distribution (d) according to MERRA-2 reanalysis data for 1980–2021.

Analysis of the distribution of the main parameters according to data from weather stations located on the coast of the Caspian Sea (Figure 6) showed a relatively good agreement with the MERRA-2 reanalysis data at least for atmospheric pressure, air temperature and precipitation. The distribution of air temperature is considered multimodal or a combination of several Gaussian distributions (Figure 6b).

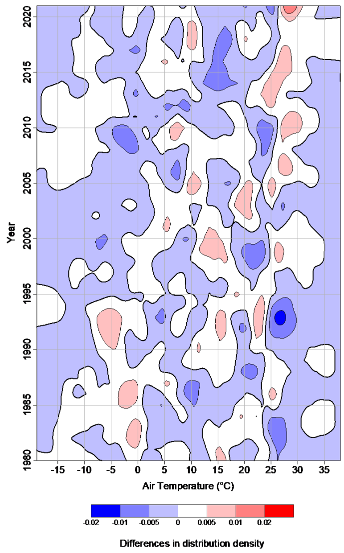
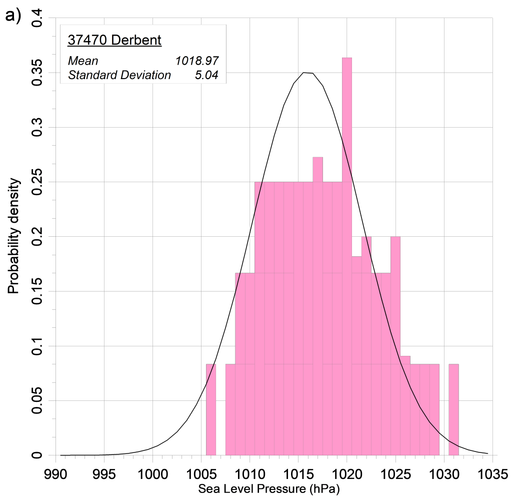
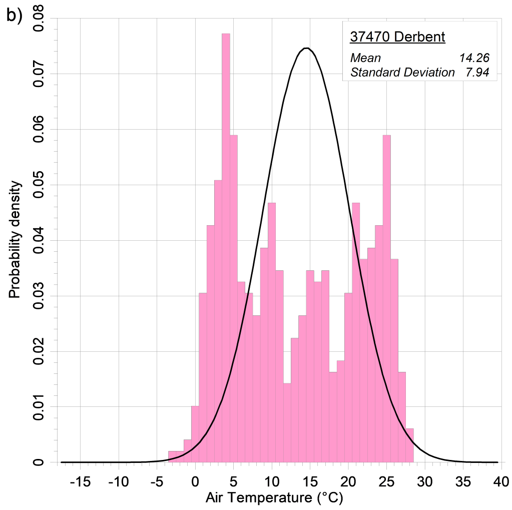


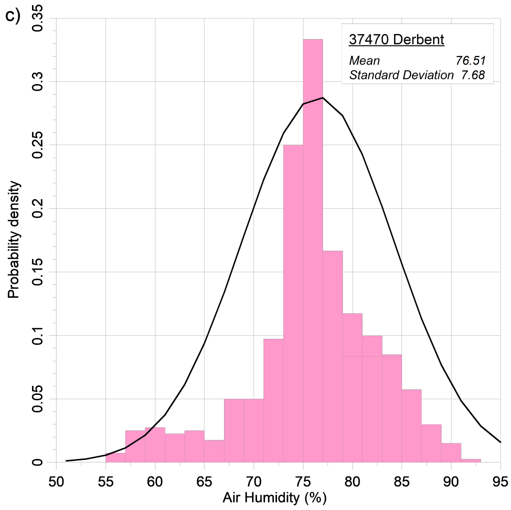
Figure 5. Deviations of the annual air temperature distribution density according to the MERRA-2 reanalysis data from the climate norm calculated for the time interval 1980–2021. The zero isoline is highlighted with a thick line.



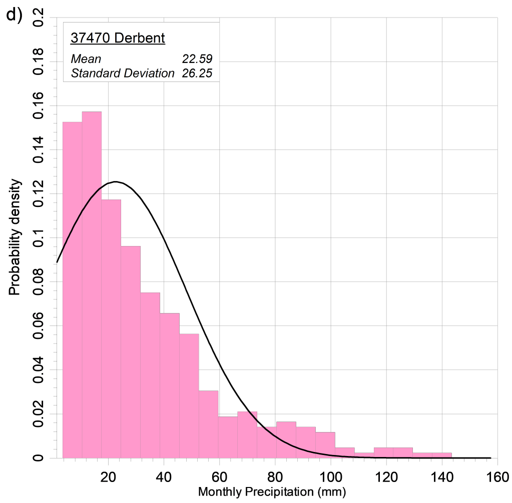
(a)



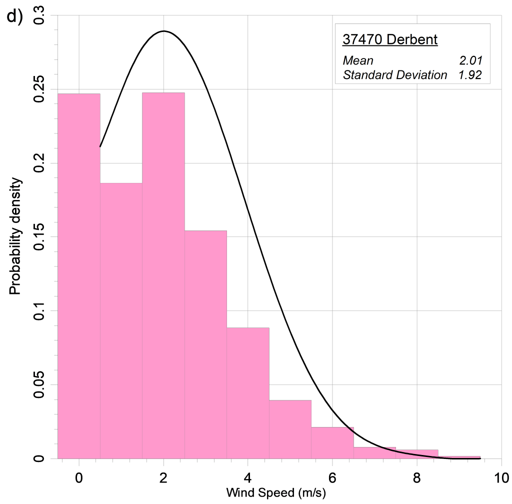
(b)



(c)



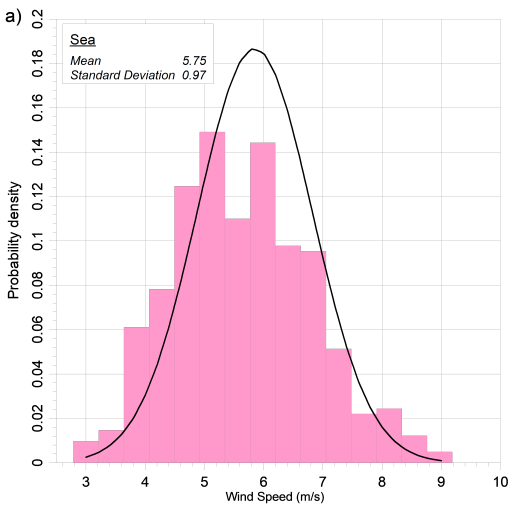
(d)



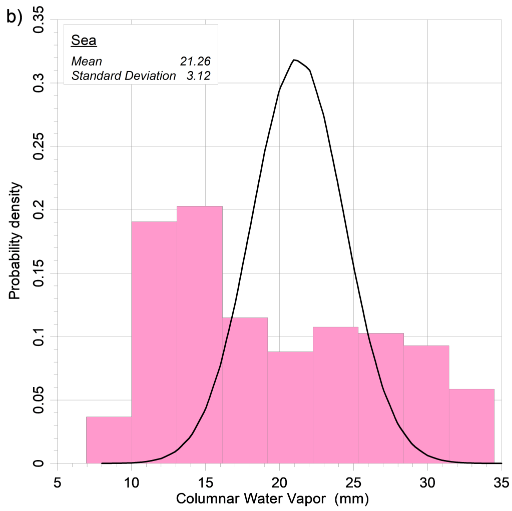
(e)

Figure 6. Probability density distribution of atmospheric pressure at sea level (a), air temperature (b), relative humidity (c), atmospheric precipitation (d) and wind speed (e) according to the Derbent weather station (WMO No. 37470) for the time interval 1980–2021. The solid line shows the corresponding Gaussian distributions. Each figure shows the mean value and standard deviation.

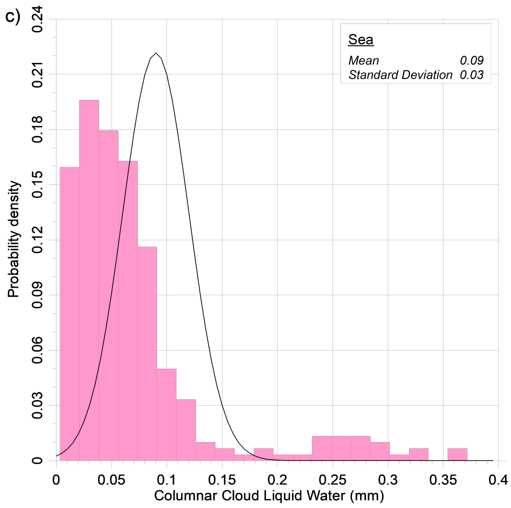
The distributions of average monthly wind speed (Figure 7a), integral water vapor content (Figure 7b) and water vapor content in clouds (Figure 7c) over the Caspian Sea were also constructed according to microwave radiometry data for the time interval 1980–2021.



(a)



(b)



(c)

Figure 7. Probability density of average monthly wind speed (a), integral water vapor content (b) and water vapor content in clouds (c) over the Caspian Sea according to microwave radiometry data for the time interval 1980–2021. The solid line shows the corresponding Gaussian distributions. Each figure shows the mean value and standard deviation.

7. Conclusions

We have examined histograms of the main hydrometeorological parameters of the Caspian Sea Region in the boundaries between 36°–48°N, 45.625°–55°E based on the MERRA-2 atmospheric reanalysis for 1980–2021. The histograms of air temperature, atmospheric pressure, absolute humidity, atmospheric precipitation and wind speed have been built based on monthly averaged data. The histograms were constructed for the whole area of investigation mentioned above, as well as separately for land and sea areas. All these three types of histograms have been used to calculate extreme values of the above mentioned meteo parameters based on two and three sigma criteria, and 1 and 99, 5 and 95, 10 and 90 percentiles for minimum and maximum values accordingly.

All histograms turned out to be far from normal (Gaussian) distribution. The distribution of atmospheric pressure at sea level was closest to the normal distribution. The histogram of air temperature showed a multimodal distribution which has four distinct peaks (local maxima) in the probability density function. The Rayleigh distribution is the most optimal do describe the probability density of wind speed and humidity. In case of atmospheric precipitation, the exponential distribution has the best fit. In this respect, we found that two and three sigma criteria do not work well for establishment of thresholds for extreme values, instead it is better to use a percentiles approach.

We could calculate a superposition of four Gaussian distributions which perfectly describes a real histogram of air temperature above land in the Caspian Sea region, as an example. This is a very promising methodology which can be used to understand the reasons of such a complex structure of the probability density function for air temperature. This will be one of the tasks for our future research – to understand the physical nature of this four-mode distribution. Potentially, we could expect three modes according to division of the Caspian Sea on the Northern, Middle and Southern Caspian.

A significant difference in distributions over land, over sea and over the region as a whole is observed for air temperature at a height of 2 m according to the MERRA-2 reanalysis data. For instance, for the land this is a four-mode distribution, and for the sea – two-mode distribution, as well as for the whole region where the sea plays the major role as a surface area.

Another interesting task is to follow interannual changes in thresholds of extreme values for different meteo parameters which will be displayed in the form of histograms. How will the tails change in the probability distributions, will they become longer or shorter, fat or thin?

A comparison was made of histograms obtained from MERRA-2 data and from weather station at Derbent located on the coast of the Caspian Sea. We found evident differences in the form of the obtained histograms for all five meteo parameters which is not surprising taking in mind a huge area of the Caspian Sea Region. Distributions of average monthly wind speed, integral water vapor content and water vapor content in clouds over the Caspian Sea were also constructed according to microwave radiometry (SMMR, SSM/I) data for the same time interval 1980–2021. If we compare histograms for wind speed constructed from MERRA-2, microwave radiometry and Derbent weather station, we also find significant discrepancies.

Finally, we have to note that we have analyzed general probability distributions constructed on the base of monthly averaged data for the 1980–2021 time period. Thus, the obtained characteristics of the extremes are seriously smoothed. This will be improved in the future research by using daily data. In case of air temperature the obtained characteristics of the negative and positive extremes correspond to minimal temperature in winter and maximal temperature in summer accordingly. But air temperature extremes can be observed at any point in the region under study on any day of the year, they will vary greatly and need to be calculated, which is of great importance for natural and socio-economic systems in the Caspian Sea Region.

Acknowledgements

The research was done with the support of the RSF Grant N 23-77-00027 "Investigation of the climate variability of thermo-hydrodynamic regime of the Caspian Sea based on remote sensing data", https://rscf.ru/en/project/23-77-00027.

References

Atlas, R., R. N. Hoffman, S. C. Bloom, J. C. Jusem, and J. Ardizzone (1996), A Multiyear Global Surface Wind Velocity Dataset Using SSM/I Wind Observations, *Bulletin of the American Meteorological Society*, *77*(5), 869–882, https://doi.org/10.1175/1520-0477(1996)077<0869:AMGSWV>2.0.CO;2.

Bulygina, O. N., V. M. Veselov, V. N. Razuvaev, and T. M. Aleksandrova (2014), Description of an array of urgent data on the main meteorological parameters at Russian stations. Certificate of state registration of the database No 2014620549, http://meteo.ru/data/163-basic-parameters#%D0%BE%D0%BF%D0%B8%D1%81%D0%B0%D0%BD%D0%B8%D0%B5-%D0%BC%D0%B0%D1%81%D1%81%D0%B8%D0%B2%D0%B0-%D0%B4%D0%B0%D0%BD%D0%BD%D1%8B%D1%85 (in Russian).

Chang, P. S., and L. Li (1998), Ocean surface wind speed and direction retrievals from the SSM/I, *IEEE Transactions on Geoscience and Remote Sensing*, *36*(6), 1866–1871, https://doi.org/10.1109/36.729357.

Coumou, D., and A. Robinson (2013), Historic and future increase in the global land area affected by monthly heat extremes, *Environmental Research Letters*, *8*(3), 034,018, https://doi.org/10.1088/1748-9326/8/3/034018.

Gelaro, R., W. McCarty, M. J. Suárez, R. Todling, A. Molod, L. Takacs, C. A. Randles, A. Darmenov, M. G. Bosilovich, R. Reichle, K. Wargan, L. Coy, R. Cullather, C. Draper, S. Akella, V. Buchard, A. Conaty, A. M. da Silva, W. Gu, G.-K. Kim, R. Koster, R. Lucchesi, D. Merkova, J. E. Nielsen, G. Partyka, S. Pawson, W. Putman, M. Rienecker, S. D. Schubert, M. Sienkiewicz, and B. Zhao (2017), The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), *Journal of Climate*, *30*(14), 5419–5454, https://doi.org/10.1175/JCLI-D-16-0758.1.

Greenwald, T. J., G. L. Stephens, T. H. V. Haar, and D. L. Jackson (1993), A physical retrieval of cloud liquid water over the global oceans using special sensor microwave/imager (SSM/I) observations, *Journal of Geophysical Research: Atmospheres*, *98*(D10), 18,471–18,488, https://doi.org/10.1029/93JD00339.

IPCC (2007), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, 996 pp., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2014), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 1132 pp., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2021), *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, 1132 pp., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, https://doi.org/10.1017/9781009157896.

Jackson, D. L., and G. L. Stephens (1995), A Study of SSM/I-Derived Columnar Water Vapor over the Global Oceans, *Journal of Climate*, *8*(8), 2025–2038, https://doi.org/10.1175/1520-0442(1995)008<2025:ASOSDC>2.0.CO;2.

Karl, T. R., N. Nicholls, and A. Ghazi (1999), CLIVAR/GCOS/WMO Workshop on Indices and Indicators for Climate Extremes Workshop Summary, in *Weather and Climate Extremes*, pp. 3–7, Springer Netherlands, https://doi.org/10.1007/978-94-015-9265-9_2.

Kopelevich, O. V., and A. G. Kostianoy (2018), The use of bio-optical parameters of the ocean, derived from satellite data as essential climate variables, *Fundamental and Applied Climatology*, *3*, 8–29, https://doi.org/10.21513/2410-8758-2018-3-8-29 (in Russian).

Korn, G., and T. Korn (2000), *Mathematical Handbook for Scientists and Engineers: Definitions, Theorems, and Formulas for Reference and Review*, 1152 pp., Dover Publications.

Kostianoy, A. G. (2017a), Satellite monitoring of the ocean climate parameters. Part 1, *Fundamental and Applied Climatology*, *2*, 63–85, https://doi.org/10.21513/2410-8758-2017-2-63-85 (in Russian).

Kostianoy, A. G. (2017b), Satellite monitoring of the ocean climate parameters. Part 2, *Fundamental and Applied Climatology*, *3*, 57–64, https://doi.org/10.21513/2410-8758-2017-3-57-64 (in Russian).

Kostianoy, A. G., and A. N. Kosarev (Eds.) (2005), *The Caspian Sea Environment*, Springer Berlin Heidelberg, https://doi.org/10.1007/b138238.

Kostianoy, A. G., and S. A. Lebedev (2023), Creation of a regional database of main meteorological parameters of the Caspian Sea for 1980–2022. according to the data of atmospheric reanalysis, in *Fundamental and applied aspects of geology, geophysics and geoecology using modern information technologies. VII International Scientific and Practical Conference. Part 1*, pp. 196–206, Maykop State Technological University, Republic of Adygeya, Maykop (in Russian).

Kostianoy, A. G., A. I. Ginzburg, O. V. Kopelevich, V. N. Kudryavtsev, O. Y. Lavrova, S. A. Lebedev, L. M. Mitnik, M. I. Mityagina, V. G. Smirnov, S. V. Stanichny, and Y. I. Troitskaya (2018), Ocean Remote Sensing in Russia, in *Comprehensive Remote Sensing*, pp. 284–325, Elsevier, https://doi.org/10.1016/B978-0-12-409548-9.10412-9.

Kuznetsova, V. N., S. G. Davletshin, and N. V. Shvets (2019), Description of the database "Average monthly relative air humidity at meteorological stations in Russia", Certificate of state registration of the database No 2019621537, http://meteo.ru/data/790-srednemesyachnaya-otnositelnaya-vlazhnost-vozdukha#%D0%BE%D0%BF%D0%B8%D1%81%D0%B0%D0%BD%D0%B8%D0%B5-%D0%BC%D0%B0%D1%81%D1%81%D0%B8%D0%B2%D0%B0-%D0%B4%D0%B0%D0%BD%D0%BD%D1%8B%D1%85 (in Russian).

Lavigne, T., and C. Liu (2022), Validity of Global Fog-Day Trends Indicated by the Global Surface Summary of the Day (GSOD) Data Set, *Journal of Geophysical Research: Atmospheres*, *127*(10), https://doi.org/10.1029/2021jd035881.

Lavrova, O. Y., A. G. Kostianoy, S. A. Lebedev, V. I. Mityagina, A. I. Ginzburg, and N. A. Sheremet (2011), *Complex Satellite Monitoring of the Russian Seas*, 470 pp., IKI RAS, Moscow (in Russian).

Lavrova, O. Y., M. I. Mityagina, and A. G. Kostianoy (2016), *Satellite Methods for Detecting and Monitoring Marine Zones of Ecological Risk*, 336 pp., IKI RAS, Moscow (in Russian).

Lavrova, O. Y., M. I. Mityagina, and A. G. Kostianoy (2022), *Satellite methods in the study of the Caspian Sea variability*, 250 pp., IKI RAS, Moscow (in Russian).

NCDC NESDIS NOAA (2021), Global Surface Summary of the Day (GSOD), https://www.ncei.noaa.gov/access/metadata/landing-page/bin/iso?id=gov.noaa.ncdc:C00516, (date of access: 20.08.2023).

Roshydromet (2008), *Assessment Report on Climate Change and its Consequences on the Territory of the Russian Federation. V. 1. Climate Change*, 227 pp., Roshydromet, Moscow (in Russian).

Roshydromet (2014), *Second Roshydromet Assessment Report on Climate Change and its Consequences in Russian Federation*, 1008 pp., Roshydromet, Moscow (in Russian).

Roshydromet (2022), *The Third Assessment Report on Climate Change and its Consequences on the Territory of the Russian Federation*, 227 pp., Roshydromet, St.-Petersburg (in Russian).

Shkol'nik, I. M., V. P. Meleshko, S. V. Efimov, and E. N. Stafeeva (2012), Changes in climate extremes on the territory of Siberia by the middle of the 21st century: An ensemble forecast based on the MGO regional climate model, *Russian Meteorology and Hydrology*, (2), 5–23 (in Russian).

Shvets, N. V., V. N. Razuvaev, and L. T. Trofimenko (2018), Description of the data array "Average monthly air pressure at sea level at meteorological stations in Russia", Certificate of state registration of the database No 2018621521, http://meteo.ru/data/746-srednemesyachnoe-davlenie-vozdukha-na-urovne-morya#%D0%BE%D0%BF%D0%B8%D1%81%D0%B0%D0%BD%D0%B8%D0%B5-%D0%BC%D0%B0%D1%81%D1%81%D0%B8%D0%B2%D0%B0-%D0%B4%D0%B0%D0%BD%D0%BD%D1%8B%D1%85 (in Russian).

Sparks, A. H., T. Hengl, and A. Nelson (2017), GSODR: Global Summary Daily Weather Data in R, *The Journal of Open Source Software*, *2*(10), 177, https://doi.org/10.21105/joss.00177.

Tjemkes, S. A., G. L. Stephens, and D. L. Jackson (1991), Spaceborne observation of columnar water vapor: SSMI observations and algorithm, *Journal of Geophysical Research: Atmospheres*, *96*(D6), 10,941–10,954, https://doi.org/10.1029/91JD00272.

Volkov, D. S., I. A. Kosolapov, D. A. Grebenikov, and S. A. Lebedev (2023a), Creation of the main meteorological parameters Caspian Sea regional database based on weather station data, in *Fundamental and applied aspects of geology, geophysics and geoecology using modern information technologies. VII International Scientific and Practical Conference. Part 1*, pp. 58–62, Maykop State Technological University, Republic of Adygeya, Maykop (in Russian).

Volkov, D. S., I. A. Kosolapov, D. A. Grebenikov, and S. A. Lebedev (2023b), Creation of the main meteorological parameters Caspian Sea regional database based on satellite microwave radiometry data, in *Fundamental and applied aspects of geology, geophysics and geoecology using modern information technologies. VII International Scientific and Practical Conference. Part 1*, pp. 63–68, Maykop State Technological University, Republic of Adygeya, Maykop (in Russian).

WMO (2007), *The role of Climatological Normals in a Changing Climate. WCDMP-No. 61. WMO-TD No. 1377*, 130 pp., World Meteorological Organization, Geneva.

WMO (2015), *Cg-17 Seventeenth World Meteorological Congress. Abridged final report with resolutions. Geneva. 25 May–12 June 2015. WMO-No. 1157*, 1171 pp., World Meteorological Organization, Geneva.

WMO (2017), *WMO Guidelines on the Calculation of Climate Normals. WMO-No. 1203*, 29 pp., World Meteorological Organization, Geneva.

Zonn, I. S., A. G. Kostianoy, A. N. Kosarev, and M. H. Glantz (2010), *The Caspian Sea Encyclopedia*, Springer Berlin Heidelberg, https://doi.org/10.1007/978-3-642-11524-0.