

# Upper-air climate monitoring: data sources, technological aspects, and some results

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**Abstract.** Monitoring and analysis of upper-air climate variations are performed regularly at the Russian Research Institute for Hydrometeorological Information – World Data Center (RIHMI-WDC). This paper describes a data source for upper-air climate monitoring that is based on radiosonde observations from a global network and further steps in space-time generalization of original temperature and wind observational data for the troposphere and the lower stratosphere. Technological elements of monitoring of these climate parameters are described. A comparison of the RIHMI-WDC time series with those from other independent sources demonstrates good agreement between them. Some features of recent tropospheric and lower stratospheric climate variations for 2015, 2016, and 2017 temperature and for 2017 wind parameters are shown and discussed.

## 1 Introduction

Climate anomalies observed in the 21<sup>st</sup> century, most evident in the last few years, are the subject of detailed studies by various research groups. According to the World Meteorological Organization (WMO), 2015, 2016, and 2017 were the warmest years since the start of instrumental surface temperature observations [1-3]. The year 2016 was the warmest on record. The global surface temperature anomaly in 2016 was 0.52 °C above the norm of 1981-2010. Several other climate records were also registered in 2017. They include:

- The highest on record change in the global ocean heat content in the 0-700 m layer ( $1.581 \cdot 10^{23}$ J);
- The highest global averaged near-surface mole fraction of CO<sub>2</sub> (403.3 parts per million);
- The highest change in the global mean sea level since 1993 (8.0 cm).

Climate monitoring is performed by many international organizations, agencies, and large centres with main focus on the surface climate characteristics, particularly on the air temperature, clouds, precipitation, and droughts. However, the upper air is an equally important component of the climate system [4-9]. The annual “Report on Specific Features of Climate in the Russian Federation” includes sections on the upper air temperature and wind. Information for these sections is prepared and relevant analysis is performed by RIHMI-WDC. For such monitoring and analysis, radiosonde observations from the global network accumulated and processed by RIHMI-WDC are used.

This paper:

- Describes the data processing and generalization technology being used;
- Provides and discusses results of the upper air temperature and wind monitoring, in particular, specific features of temperature anomalies of the troposphere and lower stratosphere in 2015, 2016, and 2017;
- Provides characteristics of the upper air temperature anomaly time series computed by the RIHMI-WDC;
- Compares these characteristics with similar characteristic independently computed on the basis of other radiosonde data, satellite data, and reanalyses;
- Provides some of the maps of the wind characteristics in the troposphere and lower stratosphere in 2017.



## 2 Data

Data used by RIHMI-WDC for monitoring of the upper air temperature and wind are the current radiosonde observations from the global network of upper air stations. On a monthly basis, RIHMI-WDC collects current data of radiosonde observations from more than 900 stations. These data are accumulated into the AEROSTAS data archive. All data undergo a complex quality control procedure. After that a quality flag is assigned to every value of the upper air meteorological parameters. RIHMI-WDC's data set of radiosonde data contains data from 1958 to the present day.

To affirm the results of temperature and wind monitoring they are compared with data from other independent and regularly updated sources [10-16]:

- Radiosonde observations (temperature data):
  - RATPAC (National Climatic Data Centre, USA - <https://www.ncdc.noaa.gov/>);
- Satellite data (temperature data):
  - RSS (Remote Sensing Systems, Inc. - <http://www.remss.com/>);
  - UAH (University of Alabama in Huntsville, USA - <https://www.nsstc.uah.edu/>)
- Reanalyses:
  - ERA-Interim (European Centre for Medium Range Weather Forecasts - <https://www.ecmwf.int/>);
  - JRA-55 (Japan Meteorological Agency - <http://jra.kishou.go.jp/>);
  - NCEP/DOE (National Centers for Environmental Prediction, USA - <http://www.ncep.noaa.gov/>);
  - NCEP/CFSR (National Centers for Environmental Prediction, USA - <http://www.ncep.noaa.gov/>);

Results of upper air temperature monitoring are compared with all above-mentioned sources. Results of upper air wind monitoring are compared with the ERA-Interim reanalysis data set.

Results of temperature monitoring for publications and for comparisons are averaged within six latitude zones:

- Globe (GLOBE): 90S-90N (70S-82.5N for RSS);
- Northern Hemisphere (NH): 0-90N (0-82.5N for RSS);
- Northern Extratropic Zone (Noext): 20N-90N (20-82.5N for RSS);
- Southern Hemisphere (SH): 90S-0 (70S-0 for RSS);
- Southern Extratropic Zone (Soext): 90S-20S (70S-20S for RSS);
- Tropics (Trpcs): 20S-20N.

## 3 Elements of monitoring technology

The general scheme of the upper air temperature and wind climate characteristics monitoring consists of several steps. They are:

- Obtaining of long-term mean monthly seasonal and annual statistical characteristics for each station on standard isobaric surfaces (norms for stations);
- Obtaining of the same characteristics for a relevant month or season of the year being analyzed;
- Computation of anomalies, trends, and other characteristics;
- Spatial generalization;
- Analysis of specific features of the year being analyzed;
- Presentation of results.

On the basis of current observations, a station-by-station data set of mean monthly statistical characteristics of temperature, wind speed and direction, zonal and meridional wind is computed. Values of the characteristics are chosen at 15 standard pressure levels from 1000 to 10 hPa. On the basis of these computations, the values of characteristics are computed for the main vertical layers of the atmosphere: 850-300 hPa (troposphere), 100-50 hPa (lower stratosphere), 300-100 hPa (transitional layer characterized by considerable instability; not used for monitoring).

Generalization is made by the formula

$$x = \frac{1}{z} \sum_{i=1}^n \frac{x_i - x_{i-1}}{2} (z_i - z_{i-1}),$$

where  $z$  is the layer height;  $n$  is the number of isobaric surfaces being analyzed;  $x_i$  is the value of characteristic at the  $i$ -th pressure level;  $z_i$  is the  $i$ -th pressure level.

Anomalies of temperature, wind speed, zonal and meridional components of wind speed are computed at each standard pressure level and in each vertical layer. Anomalies are computed as a deviation from 1981-2010 norms (for temperature) and 1985-2014 norms (for wind parameters).

Upper air temperature fields have a pronounced zonal character. Therefore, spatial generalization is used. Generalization is made by 5-degree and 30-degree latitude belts 0-30N, 30-60N, 60-90N, as well as for the whole of the Northern Hemisphere with weighing by the formula

$$T_a = \frac{\sum_{i=1}^k T_{ai} N_i \cos \varphi_i}{\sum_{i=1}^k N_i \cos \varphi_i},$$

where  $k$  is the number of station in a latitude belt,  $T_{ai}$  is the temperature anomaly at the  $i$ -th station,  $N_i$  is the number of observations at the  $i$ -th station, and  $\varphi_i$  is the geographical latitude of the  $i$ -th station.

Assessments of wind speed and wind speed anomalies characterized by inhomogeneity along latitude circles do not undergo spatial generalization and are currently performed only over the territory of the Russian Federation. Special features of wind conditions are analyzed on the basis of wind speed and direction anomalies distribution maps.

On the basis of the computed characteristics, the relevant sections of the “Reports on Specific Features of Climate” produced by Roshydromet are prepared. They include tables, graphics, and detailed analysis of the results. The Reports contain a description of specific features of the upper air climate over the past year. The section of the report on the temperature conditions includes the mean monthly, mean seasonal and mean annual temperature anomalies and trends in the troposphere, lower stratosphere, and at separate standard pressure levels. The anomalies are provided for three latitude belts of the Northern Hemisphere and for the whole of the Northern Hemisphere. Also, ranks in the climate records for the warmest years in the troposphere and the coldest years in the lower stratosphere are computed and presented. Graphs are constructed and presented showing seasonal and annual vertical-latitude profiles of the fields for the Northern Hemisphere.

The section of the report on the upper air wind conditions includes mean monthly, mean seasonal and mean annual values of the wind speed and its components, as well as their anomalies in the troposphere and lower stratosphere. The maps of the Russian Federation territory are used as the basic graphic material to prepare wind characteristics.

## 4 Results of upper air temperature monitoring

### 4.1. Troposphere temperature

According to WMO, 2015, 2016, and 2017 are the years with the highest surface temperatures on record. Therefore, the results of the upper air tropospheric temperature monitoring for 2015, 2016, and 2017 are of special interest, since they are needed for better understanding of global warming processes.

According to RIHMI-WDC, record high temperature anomalies were observed in the autumn of 2015 and in winter, spring, and in the whole of 2016 (see Table 1). The record high annual temperature anomaly in 2016 (as in 2015) was 0.65 °C. In 2017 no record high temperatures were registered in the whole of the Northern Hemisphere, but 2017 appeared to be among the top five warmest years across all seasons. In the high latitudes, 2016 appeared to be among the top four warmest years across all

seasons with a record spring anomaly of 1,13 °C. On the other hand, tropospheric anomalies for 2015 and for 2017 in the high latitudes did not appear even among the top ten warmest years.

**Table 1.** Seasonal and annual troposphere temperature anomalies in 2015-2017 and their reversal ranks –**R** (according to RIHMI-WDC).

SEASON		0-30 N		30-60 N		60-90 N		Northern Hemisphere	
2015		$\Delta T_{2015}$	-R	$\Delta T_{2015}$	-R	$\Delta T_{2015}$	-R	$\Delta T_{2015}$	-R
	WINTER	0.23	18	0.72	3	0.48	10	0.56	4
	SPRING	0.29	9	0.70	3	0.28	17	0.55	3
	SUMMER	0.27	9	0.49	7	-0.03	28	0.39	8
	AUTUMN	0.60	3	0.83	1	0.40	12	0.73	1
	YEAR	0.39	8	0.83	1	0.26	17	0.65	1-2
2016		$\Delta T_{2016}$	-R	$\Delta T_{2016}$	-R	$\Delta T_{2016}$	-R	$\Delta T_{2016}$	-R
	WINTER	0.73	1	0.84	2	0.94	3	0.81	1
	SPRING	0.69	2	0.82	2	1.13	1	0.80	1
	SUMMER	0.46	1	0.86	2	0.75	3	0.71	2
	AUTUMN	0.77	2	0.33	17	0.83	4	0.51	3
	YEAR	0.68	1	0.61	2	0.86	2	0.65	1-2
2017		$\Delta T_{2017}$	-R	$\Delta T_{2017}$	-R	$\Delta T_{2017}$	-R	$\Delta T_{2017}$	-R
	WINTER	0.71	2	0.70	4	0.32	14	0.68	2
	SPRING	0.27	11	0.59	5	-0.03	28	0.44	5
	SUMMER	0.37	3	0.56	5	0.27	18	0.48	3
	AUTUMN	0.79	1	0.47	7	0.41	11	0.57	2
	YEAR	0.50	3	0.54	3	0.37	11	0.52	3

For the troposphere, similar results are obtained on the basis of other independent data sources. Table 2 presents five warmest years in the troposphere on the basis of RATPAC radiosonde data, RSS satellite data and ERA-Interim reanalysis data for various latitude belts. Assessments of the warmest years based on other data sources are similar to those presented.

**Table 2.** Five warmest years for the troposphere temperature in various latitude zones on the basis of data from various data sets. T – annual anomalies (°C).

Rank	Globe		NH		Noext		SH		Trpcs	
	T	year	T	year	T	year	T	year	T	year
RATPAC										
1	0.97	2016	1.07	2016	1.08	2016	0.78	2016	1.03	2016
2	0.81	2017	0.89	2015	0.95	2017	0.69	1998	0.76	1998
3	0.77	2015	0.88	2017	0.94	2015	0.69	2017	0.76	2010
4	0.73	2010	0.82	2010	0.83	2010	0.59	2010	0.71	2015
5	0.70	1998	0.73	2005	0.74	2005	0.53	2015	0.70	2017
ERA-Interim										
1	0.66	2016	0.78	2016	0.77	2016	0.56	2016	0.78	2016
2	0.47	2017	0.50	2015	0.53	2017	0.44	2017	0.60	1998
3	0.43	2010	0.50	2017	0.52	2010	0.37	2010	0.50	2015
4	0.42	1998	0.50	2010	0.50	2015	0.36	1998	0.45	2010
5	0.38	2015	0.48	1998	0.42	1998	0.27	2015	0.43	2017

RSS										
1	0.75	2016	0.90	2016	1.00	2016	0.59	2016	0.73	2016
2	0.64	2017	0.72	2017	0.87	2017	0.54	2017	0.68	1998
3	0.58	1998	0.69	2015	0.79	2015	0.49	2010	0.50	2015
4	0.58	2010	0.67	1998	0.76	2010	0.48	1998	0.49	2010
5	0.55	2015	0.66	2010	0.68	1998	0.41	2015	0.46	2017

2015, 2016, and 2017 appeared among the top five warmest years in the troposphere according to all data sources including those not included in Table 2. The year 2016 appeared to be record warm in the troposphere almost in all latitude zones according to all data sources. According to almost all data sources, 1998 and 2010 are also among the top five warmest years in the troposphere.

#### 4.2. Lower stratosphere temperature

According to RIHMI-WDC data (Table 3), 2017 was record cold over the whole of the Northern Hemisphere in the lower stratosphere (temperature anomaly was  $-1.14^{\circ}\text{C}$ ). The same was true for the winter in the equatorial latitudes and the summer in the high latitudes in 2017 ( $-2.29$  and  $-0.92^{\circ}\text{C}$ , respectively). In the middle latitudes, no record low temperatures were observed in individual seasons of 2017, but low temperatures persisted throughout the year. Due to such persistence, 2017 became record cold in the middle latitudes, with the temperature anomaly being  $-0.99^{\circ}\text{C}$ .

The year 2016 has become the coldest one since 1958 throughout the Northern Hemisphere, with the temperature anomaly being  $-1.10^{\circ}\text{C}$ . In individual summer and autumn seasons, record low temperatures were observed throughout the Northern Hemisphere ( $-1.34$  and  $-1.68^{\circ}\text{C}$ , respectively). As for the low latitudes, record low temperatures were observed in all seasons of 2016, except for winter. In the middle latitudes, record low temperatures were observed in summer and autumn.

In 2015, no record low temperatures were observed in the lower stratosphere.

**Table 3.** Seasonal and annual temperature anomalies and their ranks R in the lower stratosphere for the thirty-degree latitude zones and the entire Northern Hemisphere in 2016 and 2017 (from RIHMI-WDC data).

SEASON		0-30 N		30-60 N		60-90 N		Northern Hemisphere	
2016 year		$\Delta T_{2016}$	R	$\Delta T_{2016}$	R	$\Delta T_{2016}$	R	$\Delta T_{2016}$	R
	WINTER	-0.62	15	0.06	22	-3.00	3	-0.35	13
	SPRING	-1.60	1	-0.27	20	1.16	41	-0.60	9
	SUMMER	-2.03	1	-1.07	1	-0.66	4	-1.34	1
	AUTUMN	-2.74	1	-1.32	1	-0.06	23	-1.68	1
	YEAR	-1.96	1	-0.75	5	-0.35	14	-1.10	3
2017 year		$\Delta T_{2017}$	R	$\Delta T_{2017}$	R	$\Delta T_{2017}$	R	$\Delta T_{2017}$	R
	WINTER	-2.29	1	-1.37	3	-0.42	24	-1.61	1
	SPRING	-1.33	3	-1.19	4	-0.73	11	-1.20	2
	SUMMER	-1.11	5	-0.83	5	-0.92	1	-0.92	3
	AUTUMN	-1.83	3	-0.60	8	-0.38	9	-0.95	4
	YEAR	-1.51	2	-0.99	1	-0.74	7	-1.14	1

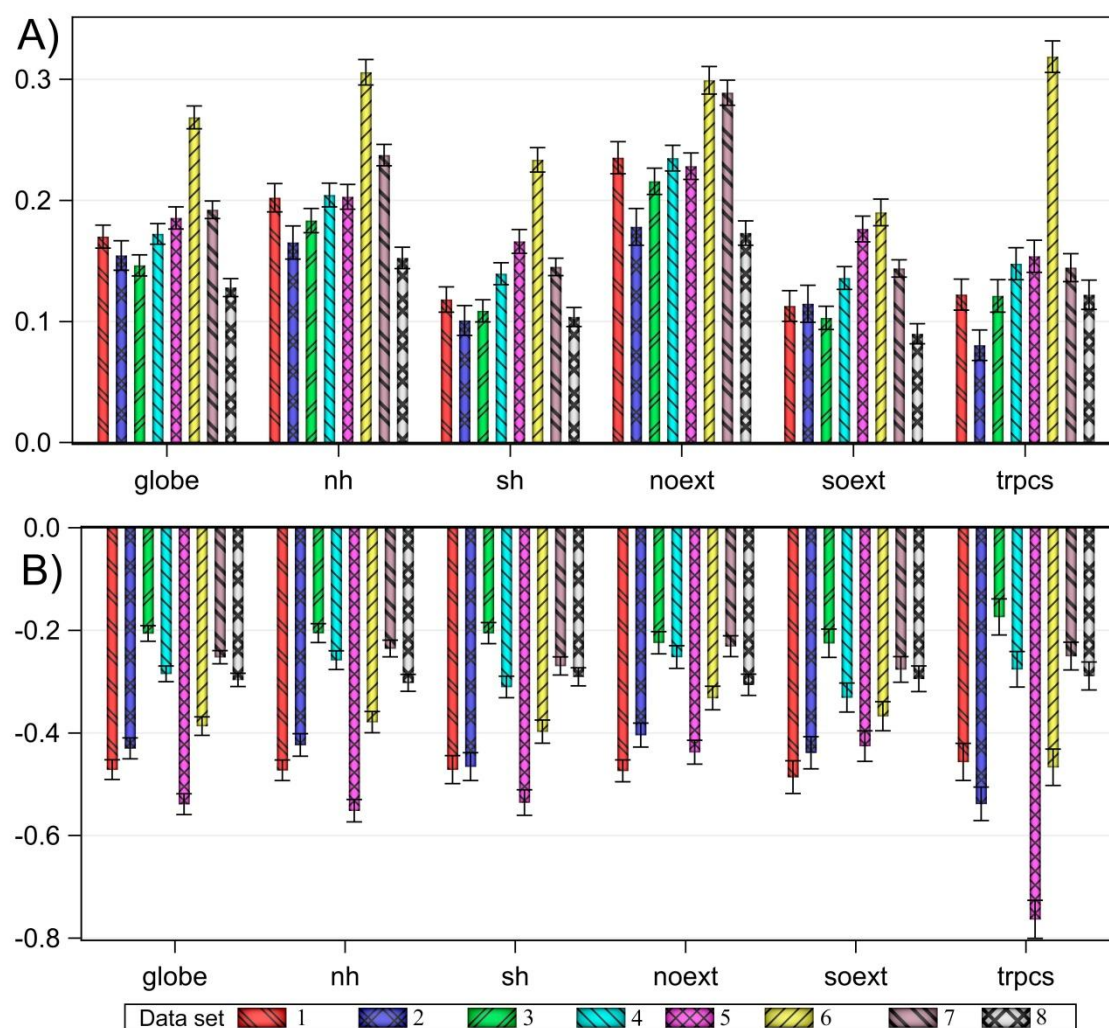
## 5 Comparison of statistical characteristics of temperature series

Figure 1 shows trends in temperature anomaly series in the troposphere and the lower stratosphere in different latitudes. These estimates are obtained from different sources. All estimates of the trends are statistically significant with a probability of 0.95.

According to different data sources, the global trends in the temperature anomalies in the troposphere all over the globe for 1979-2017 are estimated at 0.13 to 0.27°C/decade. Warming in the Southern Hemisphere latitudes takes place more slowly than that in the Northern Hemisphere latitudes. According to RIHMI-WDC data, for the Northern Hemisphere warming in the high-latitude troposphere is more intensive than that in the low-latitude troposphere (0.2 and 0.12°C/decade, respectively). The NCEP/CFSR reanalysis demonstrates higher positive temperature trends in the troposphere, especially in the tropics. This can be accounted for by the fact that since October 1998, ATOVS satellite measurements have been added to the data assimilation scheme. This contributed to higher consistency with data of other reanalyses. On the other hand, before 1998, temperature in the troposphere, according to NCEP/CFSR data, was underestimated, as compared with other reanalyses.

As for the lower stratosphere, based on different data sources, the global trends are estimated at -0.21 to -0.54°C/decade and the Northern Hemisphere trends are estimated at -0.21 to -0.55°C/decade. The trend estimates for the Southern Hemisphere latitudes are slightly higher than those for the Northern Hemisphere latitudes. From RIHMI-WDC data, for the Northern Hemisphere cooling in the equatorial latitudes is more intensive than that in the high latitudes (-0.58 and -0.23°C/decade, respectively).

In addition to comparison between the trend estimates, this was also made for pair correlations between anomaly series, root-mean-square deviations, and autocorrelations of data series from different sources after detrending. The least pair correlations in the troposphere are observed between series of monthly anomalies in the RIHMI-WDC dataset and the NCEP/CFSR reanalysis dataset (0.61). In the lower stratosphere, the same is observed between series of monthly anomalies in the RIHMI-WDC dataset and the NCEP/DOE reanalysis dataset (0.68). Nevertheless, in general anomaly series from all data sources are in good agreement.



**Figure 1.** Trends of temperature anomaly series ( $^{\circ}\text{C}$  per decade) in the troposphere (A) and the lower stratosphere (B) for 1979-2017 from different data sources 1 – RATPAC; 2 – RIHMI; 3 – ERA-Interim; 4 – JRA-55; 5 – NCEP/DOE; 6 – NCEP/CFSR; 7 – RSS; 8 – UAH.

## 6 Results of upper-air wind monitoring in 2017

Both maps for the annual wind speed anomalies and seasonal wind speed anomalies for the troposphere and lower stratosphere above the territory of the Russian Federation were prepared for the recent years and analyzed. Some results of such analysis for 2017 are provided below.

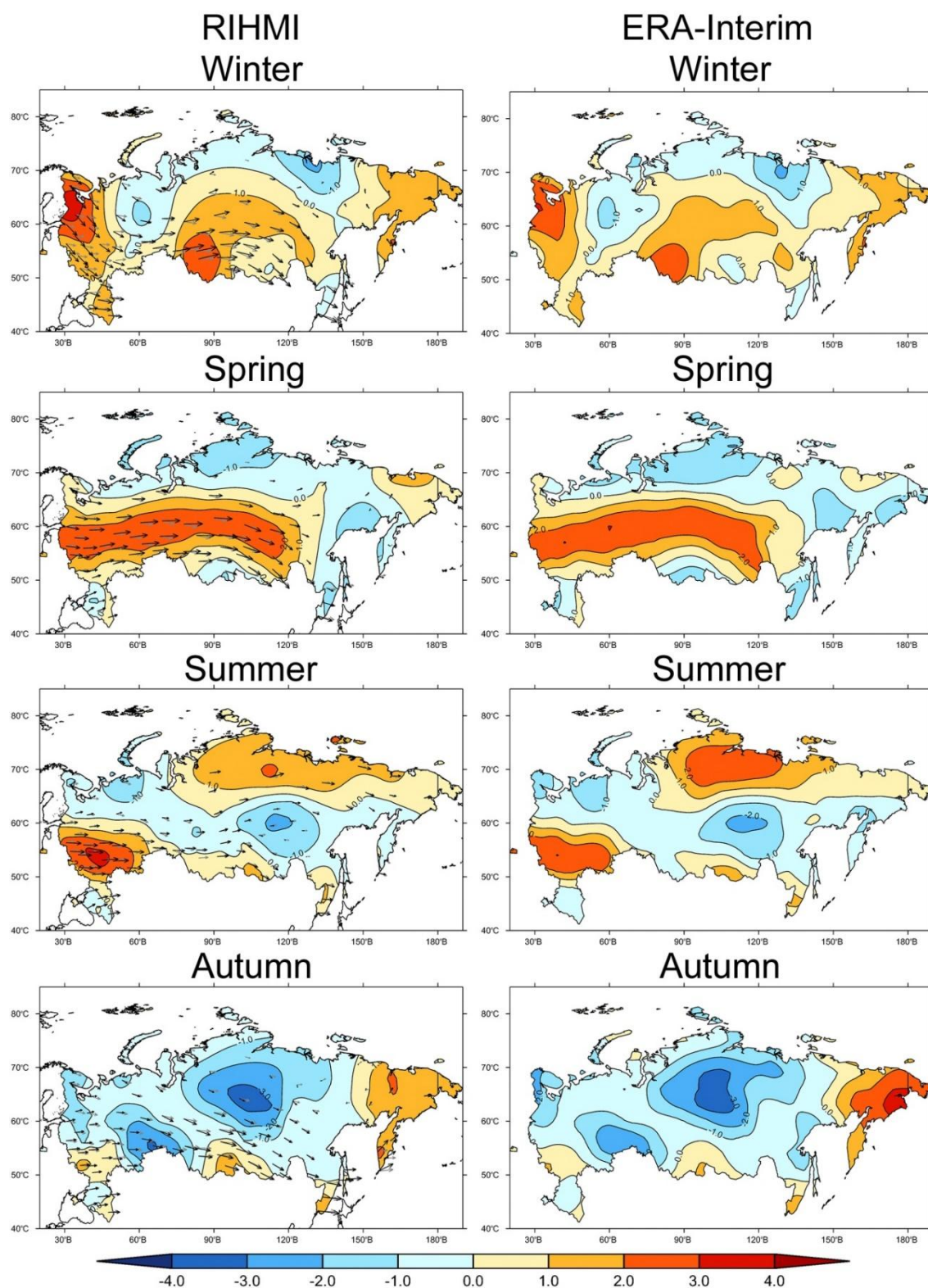
### 6.1. Troposphere wind speed anomalies in 2017

The map of 2017 annual troposphere wind speed anomalies (not shown in the figures here) allows noting only small anomalies: negative anomalies to  $-1$  m/s in the troposphere were recorded over Eastern Siberia and positive anomalies were observed over the rest of the territory, these attaining 2 m/s over European Russia and Chukotka.

The analysis of tropospheric wind speed anomalies for individual seasons of 2017 demonstrates essential anomalies: the largest positive anomalies of wind speed (to 4 m/s) were recorded in winter and in spring over European Russia and central Siberia (Figure 2). The largest negative anomalies of wind speed (to  $-4$  m/s) were recorded in autumn over central Siberia. In individual seasons of 2017 the



tropospheric wind direction was appropriate to normal, except that for the winter season. In the winter season of 2017, northwesterly winds were observed in the troposphere above European Russia.



**Figure 2.** Anomalies of tropospheric wind speed and wind direction in separate seasons of 2017. Left column - based on RIHMI-WDC radiosonde data, Right column – based on ERA Interim reanalysis.



### 6.2. Lower stratosphere wind speed anomalies in 2017

Similar maps constructed for the lower stratosphere (not given here either) allow noting that large 2017 annual anomalies of wind speed were not recorded. The largest positive seasonal anomalies of the lower stratospheric wind speed (more than 4 m/s) were observed in the winter of 2017 over the south of Western Siberia and the largest negative anomalies (to -4 m/s) were recorded in the winter of 2017 over northern Russia and in autumn over central Siberia.

### 6.3. Other upper-air wind parameters

The analysis of trend maps that was made for the troposphere and the lower stratosphere (not given here) allows us to note that the geographical distribution of estimates of the wind characteristics trends in the troposphere over the Russian Federation is generally appropriate to the distribution of the same characteristics in the lower stratosphere, but in the lower stratosphere absolute values of the trends are higher than those in the troposphere.

The analysis also confirms that the distribution of wind speed modulus trends is generally appropriate to the distribution of zonal wind component trends.

The results of wind monitoring were compared with similar estimates from ERA-Interim reanalyses. The comparison shows a good agreement both between the wind speed and wind direction anomalies and between the wind speed modulus trends and the trends in the zonal and meridional wind components. Figure 2 shows estimates of the wind speed anomalies in the troposphere in individual seasons of 2017 from RIHMI-WDC data and ERA-Interim reanalyses data; these estimates demonstrate their good agreement.

More detailed results of wind monitoring over the Russian Federation are to be provided by the authors in a separate paper that is now being prepared.

## 7 Conclusions

RIHMI-WDC conducts regular upper-air (troposphere and lower stratosphere) climate monitoring for temperature and wind. To this end, radiosonde observational data processing and analysis are performed with data from a global observation network.

The estimates of upper-air temperature anomalies over the Northern Hemisphere obtained from RIHMI-WDC data for recent years and partially given in this paper allowed us to make a number of temperature records both for the troposphere and the lower stratosphere in 2015, 2016, and 2017. The estimates of these records are in good agreement with estimates obtained from other independent sources, including estimates based on other radiosonde data sets, as well as on satellite data and on reanalyses. The trends and other statistical characteristics of climate series obtained at RIHMI-WDC are also in good agreement with statistical characteristics that are based on other independent sources. The good agreement between the record anomalies of tropospheric temperature and those of surface temperature is also worth noting.

This paper provided a small part of the wind monitoring results obtained at RIHMI-WDC from radiosonde data. A more detailed analysis of the results for upper-air wind shows good agreement with results obtained from ERA Interim reanalyses. The results of wind monitoring in the atmosphere will be provided in further publications.

Improving the systems and technologies of upper-air climate monitoring, along with monitoring of other parameters, and obtaining thereby reliable results on their basis need the development and updating of observation networks and higher integration of the data sources required for these investigations. This particularly refers to high-latitude regions of the Northern Hemisphere.

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