Verification of ERA5 reanalysis data for interpretation of radiosonde measurements in 2009–2023 in western Siberia

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Abstract

The article presents the joint analysis of vertical profiles obtained from radiosonde observations and the ERA5 data produced by the European Centre of Medium-Range Weather Forecasts. It is shown how accurately the ERA5 data can be used to interpret high-level clouds observations by the polarization-sensitive lidar.

Keywords Atmosphere · High-level clouds · Ice crystals · Polarization lidar · Meteorological conditions · Radiosonde observations · ERA5 reanalysis

Introduction

Radiation processes in the atmosphere affect weather and climate in different regions of the Earth. The climate depends on the state of cloud fields, which constantly cover a significant part of the globe's surface. The amount of solar radiation entering the Earth's surface, is associated with the cloud microstructure, i.e., optical properties, size, shape, and spatial orientation of aerosol particles [1, 2]. Different clouds have been intensively studied for more than two centuries (e.g. [3, 4]).

High-level clouds (HLCs) stand out from the variety of clouds. Their horizontal length reaches thousands of kilometers, and can therefore cover up to a half of the Earth's surface [5, 6]. These clouds significantly contribute to the greenhouse effect, despite their low optical thickness [7]. HLCs consist of ice particles of various size and shape. Their most commonly observed shape is hexagonal plates and columns. Under certain conditions, these particles are horizontally orientated, that leads to anomalous (specular) X-ray backscattering by high-level clouds [6, 8].

Radiation properties of contrails are similar to those of natural HLCs. They not only weaken the solar radiation flux, but also initiate the growth of cirrus. Contrail-induced cirrus contribute to the anthropogenic climate change. The lifetime of such clouds is determined by meteorological conditions. The World Meteorological Organization defines contrails remaining for more than 10 min as Cirrus Homogenitus, the only artificial type of ice clouds [9]. Long-term observations of ice clouds in northern latitudes show that the frequency of the cloud formation becomes higher with increasing intensity of air traffic [10].

Contemporary atmospheric models (SL-AV (semi-Lagrangian, based on the absolute vorticity equation) global hydrostatic atmospheric model, developed at the Institute of Computational Mathematics RAS, the European Centre of Medium-Range Weather Forecasts (ECMWF) model), do not consider the HLC microstructure. The parameter determination of the cloud microstructure is a non-trivial problem due to the different shape of ice particles and complexity of mathematical equations of their size distribution. The effective radius concept is usually used for the mathematical description. It is based on the equality of one of the particle properties and

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an ice spherical model [1]. This simplification allows using the Mi theory to calculate radiation properties of HLCs, although it is quite crude and leads to errors in numerical and climatic predictions.

An integral part of research into clouds, is a comparison of their properties with meteorological conditions at a certain height. Radiosonde observations (RAOB) is the most reliable source of these data. At the same time, weather stations conducting such measurements, are situated not in every city of Russia (114 stations in Russia and 3 stations in the Arctic and Antarctic regions). Radiosondes are launched only twice a day [11].

The purpose of this work is to test a hypothesis about a correct use of the ERA5 data produced by the ECMWF for interpretation of the experimental data. The ERA5 provides higher spatial (0.25×0.25°; approximately 28×28 km) and temporal (1 h) resolutions. Analytical results of vertical profiles obtained from radiosonde observations are combined with the ERA5 data.

Materials and methods

High-level clouds are almost entirely composed of ice particles. Their optical properties are determined by their microstructure parameters, namely shape, size, and spatial orientation of ice particles in clouds. In most cases, classical methods of local measurements allow to obtain a limited set (shape, mass, and electric charge) of data on atmospheric particles, but when sampling the atmospheric air, the orientation of non-spherical particles is disrupted, and there are no contact measurement techniques for the ice crystal orientation in clouds [12]. At the initial stage of formation, contrails cannot be distinguished from space platforms due to their small transverse dimensions. Contrails become available for spaceborne instruments 1 or 2 h after a release of combustion products from aircraft engines, which is unsatisfactorily long, since the average lifetime of a contrail is 1 to 6 h [13].

The spatial orientation of ice particles in clouds can be detected by the polarization transformation of probe radiation scattered over ice particles. Polarization measurements of sunlight reflected from the atmosphere, are widely used to study the planet composition [14]. This idea has been developed since the 1970s [15, 16] reporting on laser polarization sensing. The interest in this effect is explained by its sensitivity to the shape and orientation of aerosol particles. Van de Hulst [17] investigate the relationship between scattering matrices of particle ensembles and their symmetry. Rozenberg [18] for the first time pointed out the importance of studying scattering matrices in the atmosphere, showing that angular and spectral dependences provide maximum information about microphysical parameters of particles [12].

The advantage of the high-altitude matrix polarization lidar (HAMPL) developed in the National Research Tomsk State University (Tomsk, Russia), is its full measurement cycle necessary to obtain all 16 elements of the complete backscattering phase matrix. The lidar locates in Tomsk and is oriented toward the zenith. Since 2009, it has been regularly used in atmospheric sensing experiments [19]. Measurements are conducted at any time of day, when there are no precipitations, wind gusts, and low-level clouds. The second harmonic of the Nd:YAG Lotis TII LS-2137U laser operating at 532 nm, 400 mJ pulse energy, and 10 Hz frequency, is used as an optical radiation source. A Cassegrain mirror objective with a primary mirror diameter of 0.5 m and 5-m focal length, is used as a receiving antenna. A field stop, which determines the viewing field of the receiving system, is installed in its focal plane. A collecting lens is mounted such that its front focus is aligned with its back focus. After passing through the lens, the radiation beam becomes quasi-parallel and passes through an interference filter and Wollaston prism, forming two beams with mutually orthogonal polarization states. They are sent to Hamamatsu H5783P photoelectronic multipliers operating in the photon counting mode, the signal from which is digitized by a Becker & Hickl GmbH two-channel photon counter. Time signal adjustment provides the lidar altitude resolution of 37.5 to 150 m [12].

Measurement results are compared with the meteorological data corresponding to the date and time of the experiment and aerosol formation altitude recorded in experiments. Measurement results obtained from Kolpashevo and Novosibirsk weather stations, are used as the closest to the HAMPL location. According to the data from these stations, meteorological conditions at the HLC altitude formation are usually close to each other, despite the remoteness of these stations from Tomsk. At these stations, radiosondes are launched only twice a day. For Tomsk coordinates, it is advisable to choose a source of vertical profiles of meteorological variables with a higher temporal resolution. The ERA5 combines a series of meteorological data over a period of more than 40 years (from 1979 to the present). The time series of the air temperature and its derivatives in reanalysis of the family of ERA5 datasets, are homogeneous on the territory of Siberia and can therefore be used to identify spatial heterogeneity provided by the local factors.

In our recent research [20], the ERA5 data were verified by the joint analysis with radiosonde data for the coordinates of five weather stations located within a 500 km radius of Tomsk: Novosibirsk (WMO 29634, 210 km from the HAMPL), Kolpashevo (WMO 29231, 240 km), Barabinsk (WMO 29612, 430 km), Yemelyanovo (WMO 29572, 470 km), and Yeniseisk (WMO 29263, 480 km). We used each day's data for the period from 2017 to 2020, that demonstrated a correct use of several meteorological quantities according to the ERA5 for interpreting the lidar data. The present work effort is devoted to clarification of these results.

Results and discussion

We analyzed the meteorological data affecting the HLC growth and morphological properties (temperature, relative and absolute humidity) and the data used for calculation of drift parameters and contrails (wind direction and speed). The analysis was carried out for standard isobaric surfaces with a pressure of 1000 to 50 hPa, which approximately corresponded to a height of 0 to 20 km and included the HAMPL operating range (0 to 15 km). The meteorological data array included information from January 1, 2009 to April 12, 2023, two time points per day (corresponding to the measurement time 00:00 and 12:00 UTC at weather stations). The statistical analysis of the obtained data was performed as described in [20]. Then we obtained vertical profiles of the root mean square error (RMSE) of meteorological results from the ERA5 and RAOB and the average difference (bias) and correlation coefficient (Corr) for these values. The RMSE is calculated as

$$RMSE = \sqrt{\frac{1}{N_s}\sum\nolimits_{i=1}^{N_s}\left(X_{iRAOB} - X_{iERA5}\right)^2}.$$

The average bias of values showing the deviation sign, is calculated as follows:

$$Bias = \frac{1}{N_s}\sum\nolimits_{i=1}^{N_s}\left(X_{iERA5} - X_{iRAOB}\right).$$

The correlation coefficient is determined by the following equation:

$$Corr\,(ERA5, RAOB) = \frac{\sum\left(X_{ERA5} - \overline{X_{ERA5}}\right)\left(X_{RAOB} - \overline{X_{RAOB}}\right)}{\sqrt{\sum\left(X_{ERA5} - \overline{X_{ERA5}}\right)^2\sum\left(X_{RAOB} - \overline{X_{RAOB}}\right)^2}}.$$

Figure 1, 2, 3, 4 and 5 present vertical profiles of RMSE, bias, and correlation coefficient for the ERA5 and RAOB for absolute and relative air humidity, temperature, and wind velocity and direction. Figure 6 shows similar vertical profiles for these meteorological values obtained from five weather stations.

According to Fig. 1, the correlation coefficient varies from 0.8 to 1 at a pressure within 1000 to 650 hPa, that means good reliability of the ERA5 data. For example, at a pressure ranging between 1000 and 800 hPa, the relative humidity restores at an error of 0.5 to $0.7\cdot10^{-3}$ kg/kg. At 650 hPa, the RMSE decreases to approximately $0.1\cdot10^{-3}$ kg/kg, whereas at a pressure below 650 hPa (in some cases below 500 hPa), the data consistency

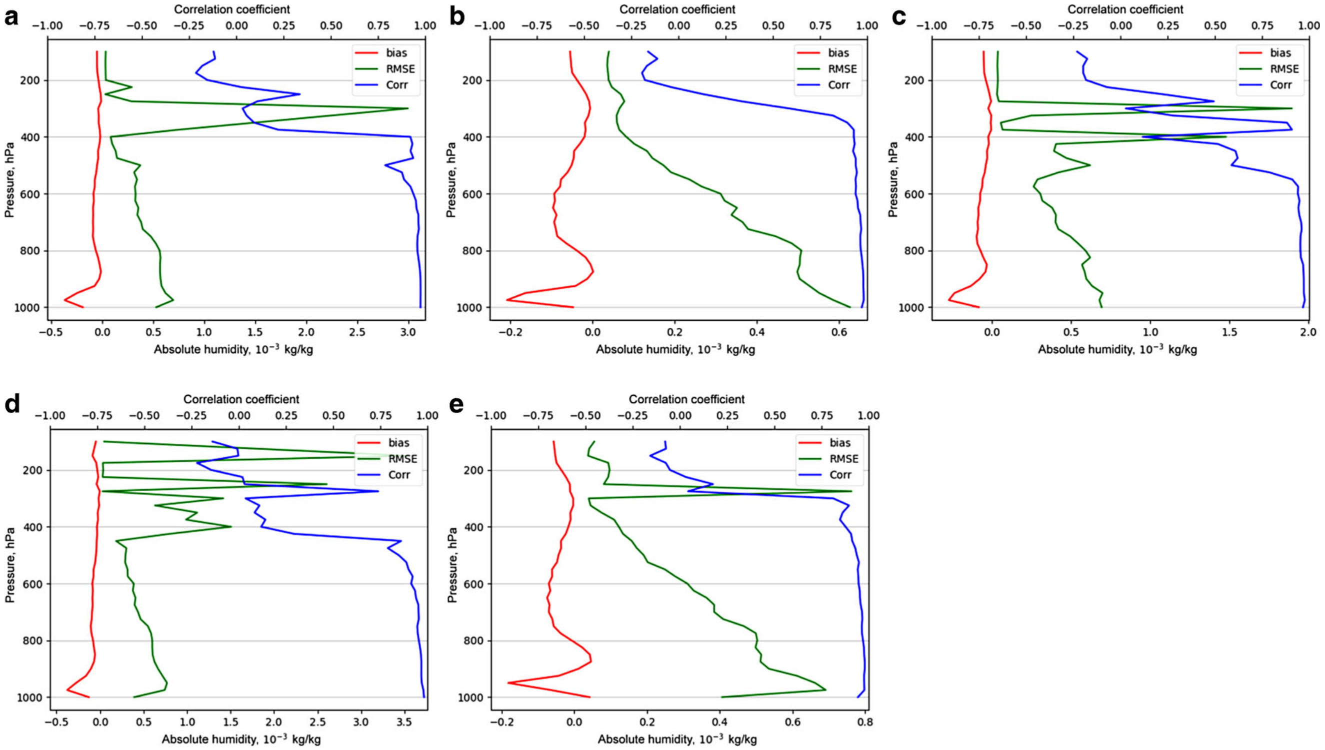

Fig. 1 RMSE, bias, correlation coefficient vertical profiles for ERA5 and RAOB absolute humidity based on 2009–2023 data obtained at different stations: **a** Barabinsk, **b** Yeniseisk, **c** Kolpashevo, **d** Novosibirsk, **e** Yemelyanovo

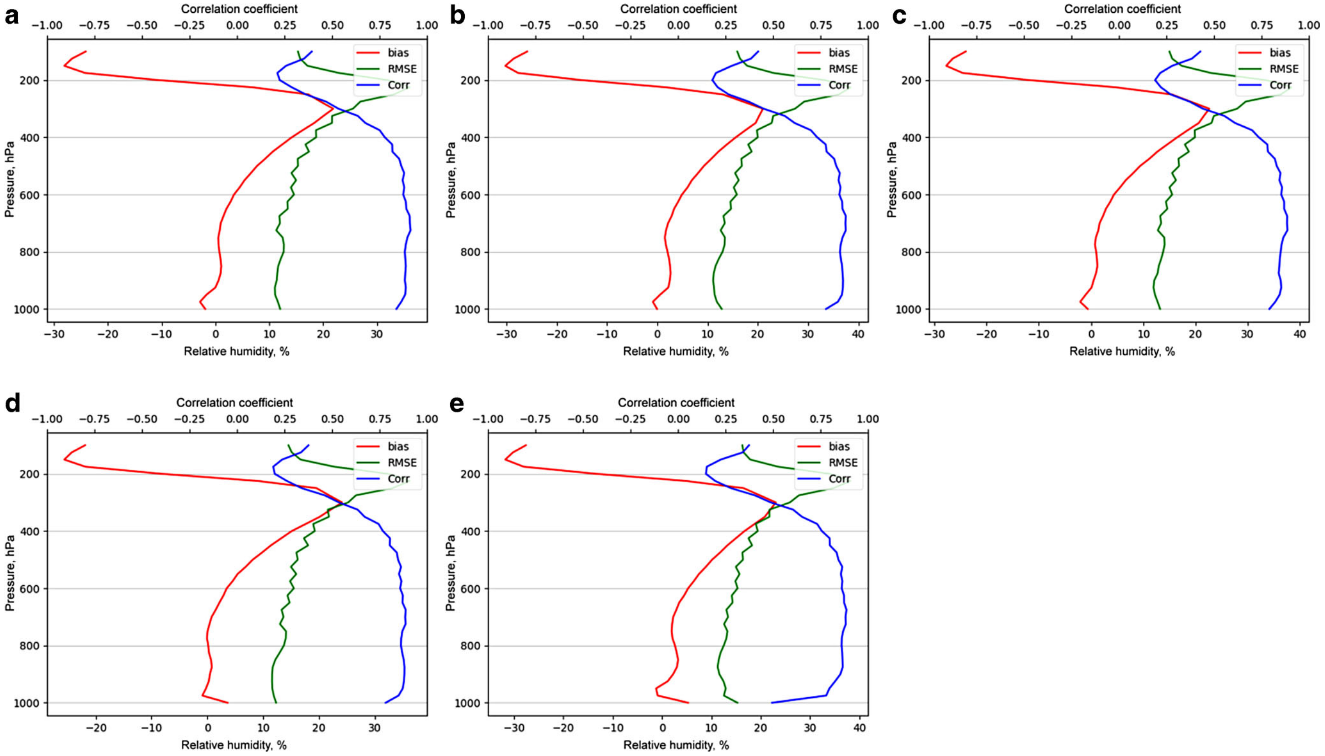

Fig. 2 RMSE, bias, correlation coefficient vertical profiles for ERA5 and RAOB relative humidity based on 2009–2023 data obtained at different stations: **a** Barabinsk, **b** Yeniseisk, **c** Kolpashevo, **d** Novosibirsk, **e** Yemelyanovo

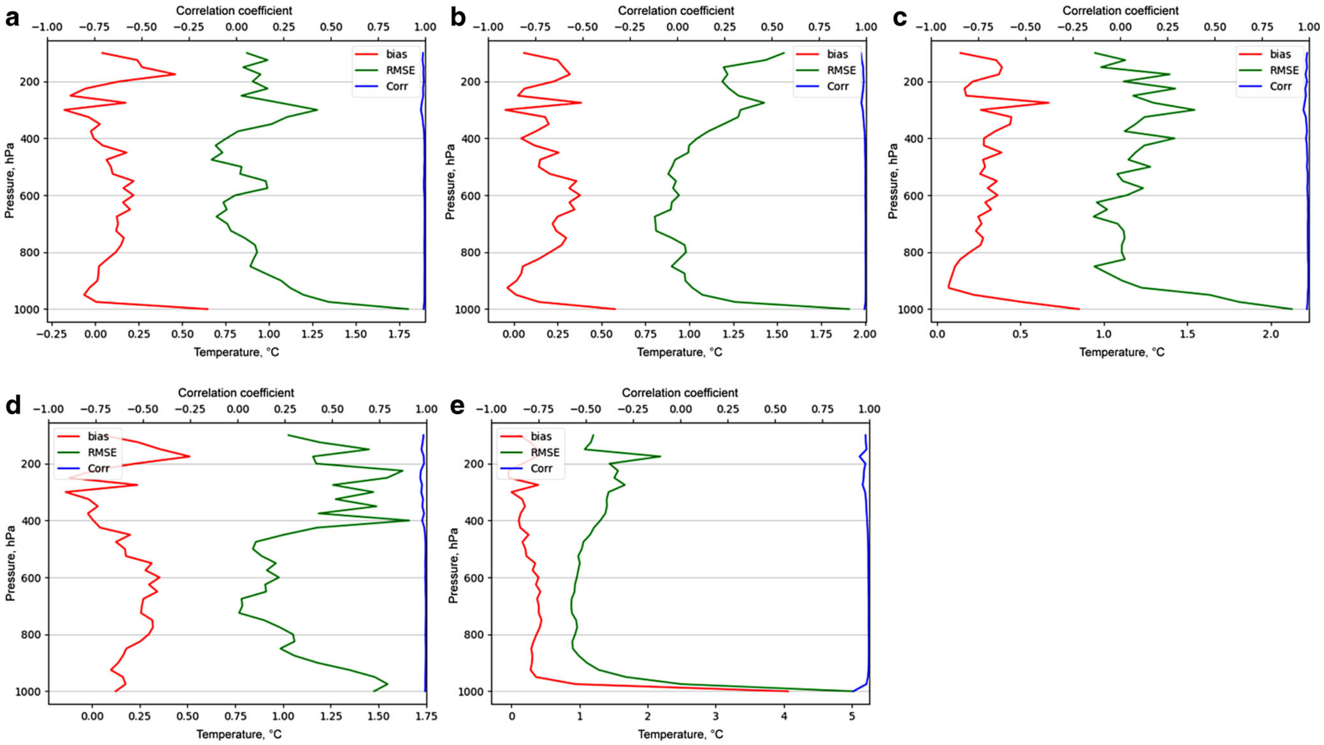

Fig. 3 RMSE, bias, correlation coefficient vertical profiles for ERA5 and RAOB temperature based on 2009–2023 data obtained at different stations: **a** Barabinsk, **b** Yeniseisk, **c** Kolpashevo, **d** Novosibirsk, **e** Yemelyanovo

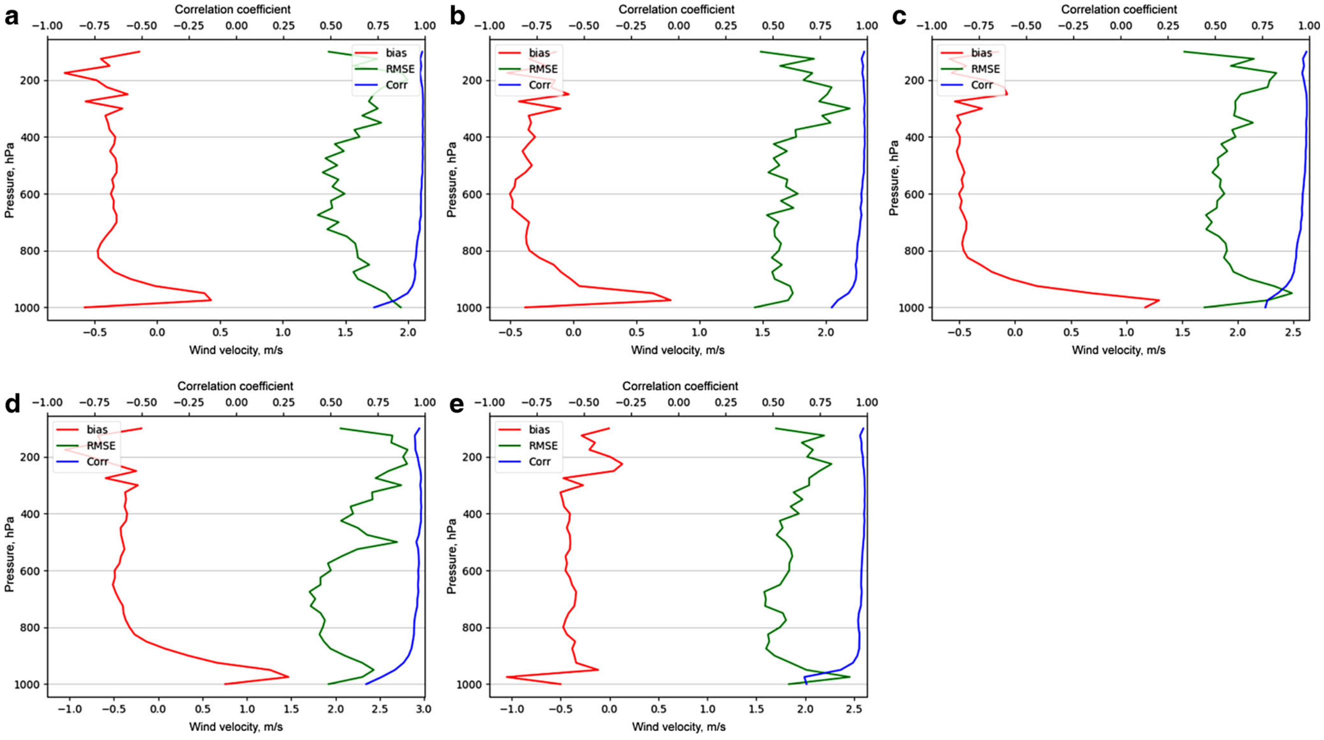

Fig. 4 RMSE, bias, correlation coefficient vertical profiles for ERA5 and RAOB wind velocity based on 2009–2023 data obtained at different stations: **a** Barabinsk, **b** Yeniseisk, **c** Kolpashevo, **d** Novosibirsk, **e** Yemelyanovo

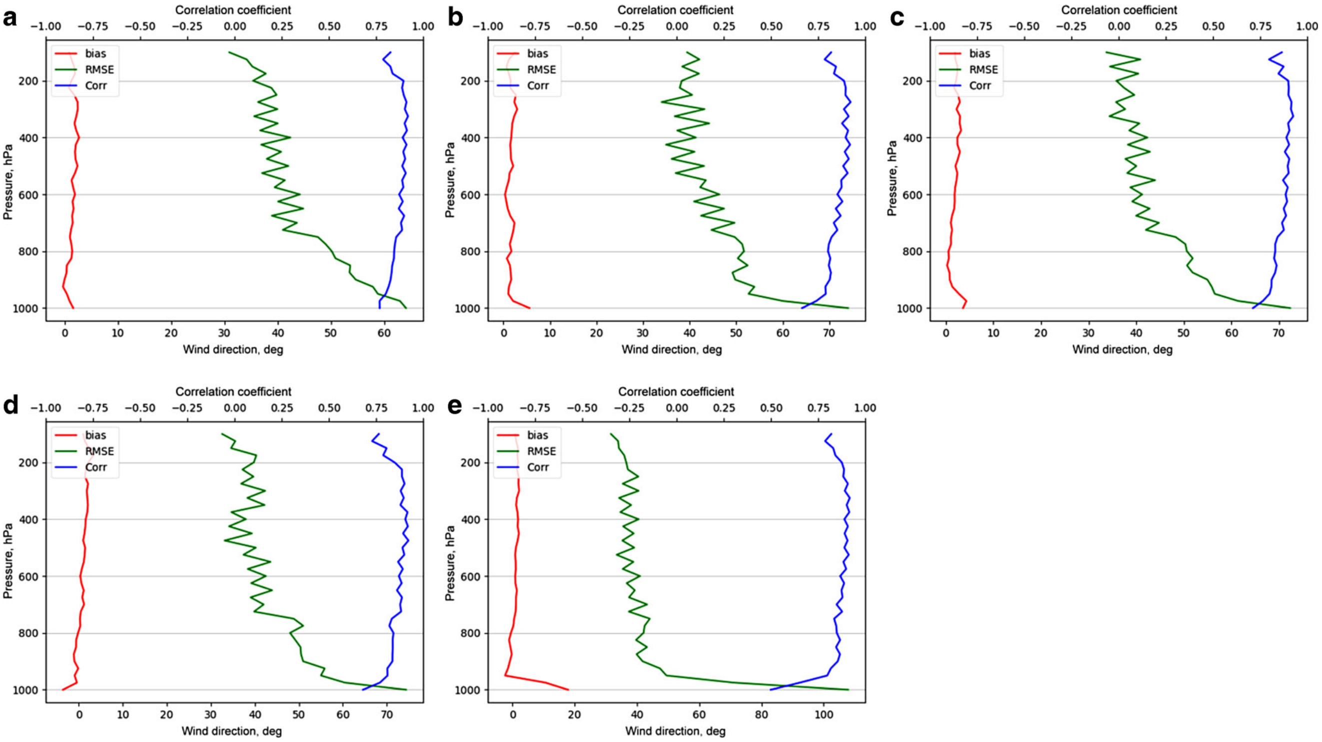

Fig. 5 RMSE, bias, correlation coefficient vertical profiles for ERA5 and RAOB wind direction based on 2009–2023 data obtained at different stations: **a** Barabinsk, **b** Yeniseisk, **c** Kolpashevo, **d** Novosibirsk, **e** Yemelyanovo

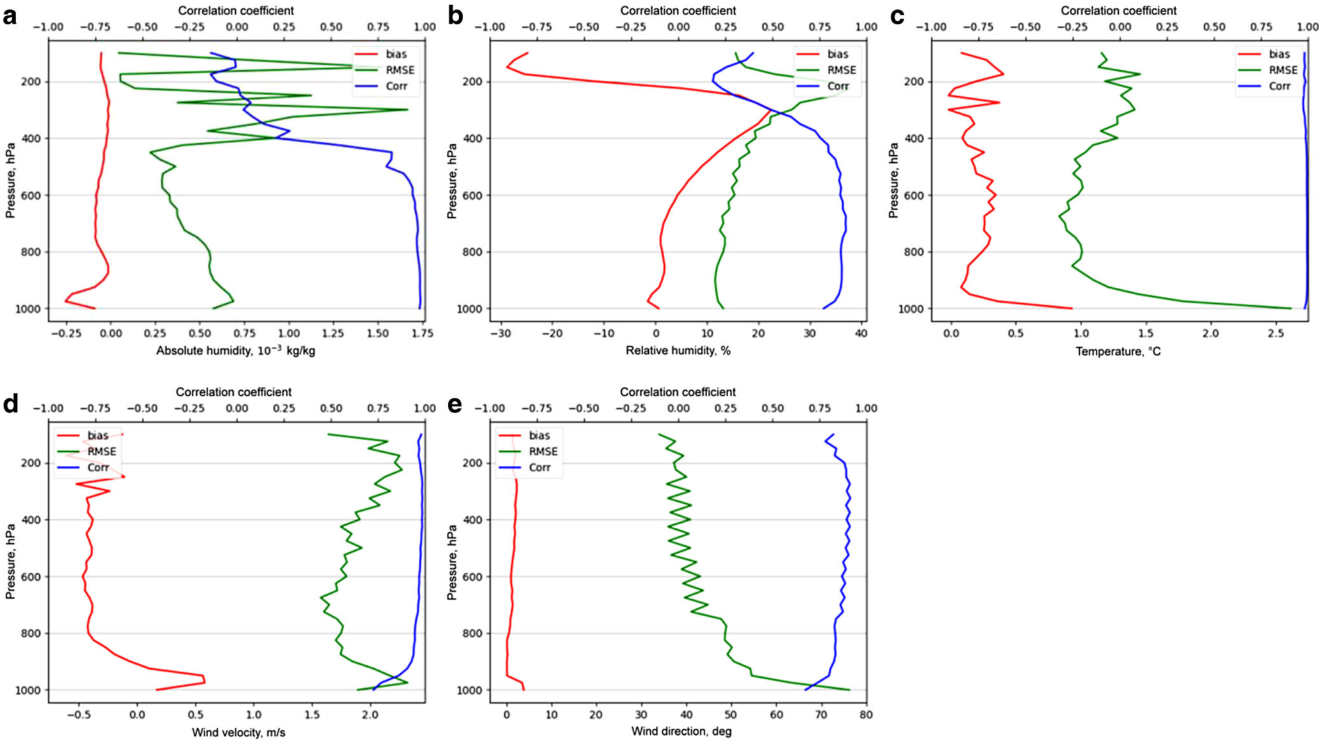

Fig. 6 RMSE, bias, correlation coefficient vertical profiles for ERA5 and RAOB meteorological data for the years 2009–2023 obtained at different stations: **a** absolute humidity, **b** relative humidity, **c** temperature, **d** wind velocity, **e** wind direction

dramatically decreases. The correlation coefficient drops to negative values. The restored relative humidity reaches $3.7 \cdot 10^{-3}$ kg/kg. With regard to the fact that the HLC formation occurs at a height of 5 to 12 km and a 400 hPa pressure matches the height of ~6 km, it can be concluded that the ERA5 is not suitable for restoring the values of relative humidity at the HLC formation altitude.

Let us try to restore relative humidity values according to the ERA5 data (Fig. 2). Within 1000–400 hPa, the correlation coefficient varies from 0.75 to 0.9, which also indicates good reliability of the ERA5 data. Relative humidity restores at RMSE = 10–20%, the bias ranging between 0 and 20%. At a lower pressure, a significant data mismatch shows the correlation coefficient < 0.75 and rather high 30 to 40% RMSE. Therefore, the ERA5 data on the relative humidity are not applicable to HLC studies.

As can be seen from Fig. 3, the ERA5 restores temperature values with the high accuracy over the entire pressure (altitude) range. The tendency of profiles obtained from the five weather stations, are the same, i.e., within 1000 to 850 hPa, the temperature can be restored with the accuracy of 1.75 °C. At 850 to 500 hPa, it is restored with the accuracy of 0.8 to 1.0 °C, and at 500 to 0 hPa, the temperature restoration accuracy is 1.4 or 1.5 °C. It can be thus concluded that the ERA5 temperature data can be used to interpret radiosonde measurements.

Let us consider the reliability of restoring wind velocity values according to the ERA5 data for the lidar data analysis. As can be seen from Fig. 4, RAOB and ERA5 data matching is satisfactory in the pressure range of 1000 to 800 hPa. The correlation coefficient varies from 0.75 to 0.9, and the restored value deviation is 1.9 to 2.5 m/s. At 200 hPa, the correlation coefficient does not change and is approximately 0.95. A further increase in the altitude leads to a slight deterioration in the results (the correlation coefficient varies between 0.9 and 0.95). Over the entire pressure range, the recovery accuracy varies from 1.75 to 2.75 m/s. At a pressure of 800 to 600 hPa, the recovery accuracy remains unchanged. Nevertheless, the wind velocity at the HLC formation altitude is recoverable from the ERA5 data with sufficient accuracy.

Figure 5 shows that the ERA5 restores the wind direction with insufficient accuracy over the entire pressure (altitude) range. The recovery accuracy at 600–400 hPa is characterized by the RMSE of ~40 degrees, which is an unacceptably high value. In the pressure range from 1000 to 600 hPa, there is a sharp RMSE increase up to 75 degrees. The situation is better at the HLC formation altitudes, while not enough, because the wind direction is restored with accuracy of 30–40 degrees.

In Fig. 6, one can see dependences for the whole considered data, and the same conclusions can be drawn: absolute and relative humidity values at the HLC formation altitudes are restored by the ERA5 with insufficient accuracy. The wind direction value is often unreliable and cannot be used without additional clarifications. Vertical profiles for the temperature and wind direction at the HLC formation altitudes correlate with the ERA5 data.

Conclusions

This paper clearly showed that despite the data array expansion from 5 to 15 years, the obtained results correlated with those obtained in [20]. The suggested diagrams showed a correct restoration of temperature and wind velocity values at the HLC formation altitudes by the ERA5 data. Restoration of the wind direction, apparently, required an in-depth analysis with the involvement of additional information sources. Restoration of absolute and relative humidity by the ERA5 data was incorrect. Thus, only temperature values were available from the considered meteorological information for studying the HLC microstructure. The additional analysis is required for identifying and investigating contrails. Future works should consider these mechanisms.

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Author Contribution O.K., I.B., I.S., and K.P. developed the idea for this article. I.B., M.P., E.N., and K.P. developed software for data processing, visualization, and validation. All authors analyzed the measurement and computation data, discussed results, and wrote and edited the paper. All authors have read and agreed to the published version of the manuscript.

Conflict of interest The authors declare no conflict of interest.

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