This study is organized as follows. In Sect. 2 we present details on the data and methods used to identify the important quantities of TIL characteristics. Section 3 presents the results. First a comparison of measurements and reanalysis data is provided, followed by an investigation of the influence of the relative humidity on TIL properties. Finally, we extend the examination to geographical and seasonal variations. Conclusions are found in Sect. 4.

2 Data and methods

In this section we describe the data sets, the relevant variables and the methods for the statistical investigations.

2.1 Data

This study is partly based on radiosonde data from a single measurement site at Idar-Oberstein, Germany (49.69° N, 7.33° E). This site was selected because the German weather service (Deutscher Wetterdienst, DWD) provides 9 years of high-resolution radiosonde data as open access. The exact time frame used spans from 1 January 2011 to 31 December 2019.

The radiosonde measurements are compared with the reanalysis data set ERA5 (Hersbach et al., 2020) provided by the ECMWF. After the comparison and evaluation of the data at the selected site, profiles at different geographical locations are investigated based on the ERA5 data set.

2.1.1 Radiosonde data

Idar-Oberstein is 1 out of 12 stations in Germany where the DWD executes synoptic (daily at 00:00, 06:00, 12:00 and 18:00 UTC) high-resolution radiosonde soundings. The station is located at 49.69° N, 7.33° E, and 376 m altitude above sea level. For the radiosonde measurements the Vaisala RS92-SGP (1 January 2011–12 March 2017 and 15 June 2017–31 December 2019) sonde and the Vaisala RS41-SGP (28 March 2017–14 June 2017) sonde are used. The characteristics of the two types of radiosondes are very similar; however, the RS41-SGP has slightly higher precision than the RS92-SGB (https://www.vaisala.com/sites/default/files/documents/RS-Comparison-White-Paper-B211317EN.pdf, last access: 5 September 2024). Therefore, the data are treated as if the entire data set is measured by the RS92-SGP radiosonde.

During one ascent of the radiosonde, the meteorolog variables are measured with a time resolution of ~~0.5~~ 1 Hz TS1, providing the longitude and latitude with a GPS sensor, the geopotential height (Φ_g, m), the ambient pressure (p, hPa), the temperature (T, K) and the relative humidity over liquid water (RH, %). In a first approximation, the geopotential height (Φ_g) is equal to the vertical height (z). For the considered data set, this approximation is quite good because of Idar-Oberstein's latitude of 49.69° N and our focus on investigations in the UTLS.

This investigation focuses on the upper troposphere and lower stratosphere (UTLS). For obtaining a complete and consistent data set, profiles with a maximum height lower than 20 km and profiles containing missing data are discarded. Over the period from 1 January 2011 to 31 December 2019, the data set contains 10 224 single profiles. A total of 419 profiles are discarded: 311 due to insufficient maximum height, 19 due to missing data, and 89 due to unreliable values of temperature and relative humidity.

The uncertainties of the RS92-SGP regarding the measurements are given by the manufacturer (https://www.bodc.ac.uk/data/documents/nodb/pdf/RS92SGP-Datasheet-B210358EN-F-LOW.pdf, last access: 5 September 2024). The temperature sensor has a reaction time less than 2.5 s and a total uncertainty of 0.5 °C. The humidity sensor has a response time between 0.5 and 20 s with a total uncertainty of RH = 5 %. The pressure sensor has a total uncertainty of 1 hPa for 1080 to 100 hPa and 0.6 hPa for 100 to 3 hPa.

The radiosonde humidity data are time-lag-corrected according to Miloshevich et al. (2004), and the water vapor measurements are corrected using the algorithm and coefficients used by Miloshevich et al. (2009). Although the algorithm was developed for the RS92 sonde, it can be applied to the few data points as obtained from the RS41-SGP sonde.

2.1.2 ERA5

ERA5 is the most recent reanalysis product of the ECMWF (Hersbach et al., 2020). The reanalysis is a mix of a recalculation of past weather with one fixed forecast model version (IFS CY41R2) and assimilated measurements made for each available time. The high-resolution data set has a horizontal resolution 0.25° in longitude and latitude. The vertical dimension of the atmosphere is represented by hybrid sigma (model) levels in ERA5 (Hersbach et al., 2020); the number of levels is 137, of which only levels up to the lower stratosphere are used. In the tropopause region, the vertical resolution is about 300 m.

For the comparison with the radiosonde data, we obtained pseudo-radiosonde profiles, i.e., a vertical column at a fixed grid point. The vertical profile is extracted at the 49.75° N, 7.25° E, grid point, which is the closest grid point of ERA5 to the actual location of Idar-Oberstein (49.69° N, 7.33° E). The date and the time of the extracted columns are matched with the reduced radiosonde data set to obtain the maximum comparability between the data sets. The relevant variables, e.g., the geopotential height (Φ_g), are calculated for comparison.

The radiosonde data as described above (Sect. 2.1.1) are also assimilated into the ERA5 data set.