



A new observational perspective on global winds: consistent evidence for changes in large-scale atmospheric dynamics

Annika Reiter¹, Irena Nimac¹, Julia Danzer¹

¹Wegener Center for Climate and Global Change, University of Graz, Graz, 8010, Austria

5 *Correspondence to:* Annika Reiter (annika.reiter@uni-graz.at)

Abstract. This study provides a holistic observational perspective on global upper-air winds over recent decades. We focus on a new wind record from radio occultation (RO) satellite observations to explore current circulation changes, embedded in a literature review and discussion on specific atmospheric features and their trends. Complementary to the RO wind fields, we consider multiple reanalyses (ERA5, MERRA-2, JRA-3Q) and radiosonde (IGRA v2.2) data for our investigation. Global
10 wind trends in the free troposphere and stratosphere are cross-evaluated to identify spatial and temporal consistencies and discrepancies among the datasets. Our results reveal overall coherence between RO and reanalyses for zonal and meridional wind trends in both horizontal and vertical cross-sections. This includes a consistent general representation of jet stream changes as well as a pronounced negative geopotential height trend above north-eastern Canada and Greenland accompanied by corresponding changes in the wind fields. Especially the individual reanalysis products show a high degree of consistency
15 at synoptic scales. To substantiate our findings, vertical wind trend profiles from observational RO data and reanalyses are compared to radiosonde data, further strengthening our confidence in the new RO wind dataset. The combined results showcase the potential for robust trend assessment of wind patterns using long-term stable RO observations, particularly in the stratosphere. Our study underscores the importance of complementing commonly used reanalysis products with purely observational wind data to reliably enhance climate monitoring and analysis.

20 1 Introduction

The anthropogenic increase of the atmospheric greenhouse gas concentration has not only led to a significant rise in the global mean temperature, but also impacted the dynamics of the atmosphere (IPCC, 2023). Synoptic-scale features of the general circulation in the troposphere and stratosphere have been found to change. Model-based data, for example, show a poleward shift in jet streams (Ossó et al., 2025; Woollings et al., 2023), an expansion of the Hadley cell (Grise et al., 2019; Staten et al.,
25 2018), and a weakening of the quasi biannual oscillation (QBO) (Butchart et al., 2020; Kawatani and Hamilton, 2013). To study the general circulation and its characteristic structures, high-quality upper-air data is necessary. Climate studies essentially rely on three key data sources: observations, reanalyses, and climate models. These datasets must meet substantial requirements, which include high three-dimensional spatial resolution, global coverage and temporal consistency (Baker et al., 2014; Eyre et al., 2020, 2022).



30 As a result, most studies investigate model-based datasets (i.e., climate models and reanalyses), which for instance, offer fine-gridded spatial and temporal resolution. Nevertheless, model-based data is influenced by numerous factors, such as parametrization schemes, initial and boundary conditions, and with respect to reanalysis, also the type, amount, and quality of the assimilated data (Fujiwara et al., 2017; Hersbach et al., 2020; Kosaka et al., 2024). This in turn can introduce complex uncertainties that are less understood and often overlooked in trend analyses (Baldassare et al., 2023; Belmonte Rivas and Stoffelen, 2019; Hoffman et al., 2017). Furthermore, inconsistencies in long-term wind trends and regional differences in the wind components have been found in reanalyses, including discrepancies in the trend magnitude and the trend direction (Davis and Davis, 2018; Simmons, 2022; Yu et al., 2026).

Observational data, by contrast, can provide necessary validation and bias estimation, although studies using such data remain limited when investigating the dynamics of the atmosphere. This is partly due to the requirements imposed on the dataset as described above. Combining these key properties in one single wind observation product is an ongoing challenge, further complicated by the necessity of a sufficiently long record for climate monitoring and analysis. To name a few specific examples, radiosondes provide high-accuracy and high-vertical resolution up to the lower stratosphere, yet they are mainly available over the land surface and the Northern Hemisphere (NH) (Durre et al., 2006, 2018). Atmospheric wind profiles from the Aeolus satellite mission, using a Doppler wind lidar, offer global data with a broad horizontal and vertical resolution, nevertheless this data is only available for the troposphere and spanning a limited time period, as the mission was launched in 2018 (Martin et al., 2021). As a last example, cloud motion vectors from the Multi-angle Imaging SpectroRadiometer Changes have been gathering global data over the past two decades, this observation method is however highly sensitive to weather conditions and favouring the troposphere (Di Girolamo et al., 2025).

Recently, awareness of the critical need for more observations in the free troposphere and stratosphere (FTS) has grown, particularly in the stratosphere, a lack of wind observations was identified (Baker et al., 2014; Kozubek et al., 2021; Ossó et al., 2025; Yu et al., 2026). Moreover, a global observation-based study of the general circulation in the atmosphere and its changes over recent decades is still missing. Simmons (2022) and Butchart (2022) provide a comprehensive investigation utilizing reanalysis data within the troposphere and stratosphere, respectively. These studies offer an important overview of the dataset performance on a global-scale and valuable insights into how specific features of the atmospheric circulation, and their changes, are connected and how they compare in magnitude and extent. A solely observational analysis could additionally exploit long-term consistency, which allows for a robust trend assessment and validation of model-based data results.

In that sense, a new wind product from Global Navigation Satellite System (GNSS) radio occultation (RO) data has been developed which can provide this global observational perspective. RO multi-satellite data present an independent source of benchmark-quality atmospheric profiles, with key advantages such as being long-term stable, with global-coverage and high-quality in the FTS through near-all weather operational capability (Foelsche et al., 2011; Scherllin-Pirscher et al., 2017; Steiner et al., 2020a; Zeng et al., 2019). Building on recent major progress, monthly climatic wind fields have been derived from RO geopotential height climatologies, moving beyond fundamental geostrophic and gradient wind approximations (Danzer et al., 2024; Nimac et al., 2025). In this newly applied formulations, advection and curvature terms are included, capturing now also



large-scale planetary wave activity and jet–wave interactions (Nimac et al., 2026; Unegg et al., 2026). This leads to a promising potential of new applications showcased for example by Reiter et al. (2025) for tropical width metrics.

Consequently, the objective of this study is twofold, (i) based on RO data, we want to examine observed trends of the general circulation in the FTS over the most recent decades, and (ii) determine how these trends and patterns compare to other datasets such as reanalyses and radiosondes. We consider a holistic view to gain insights into overall changes of the general circulation, supported by a discussion of current literature on characteristic structures of the atmosphere. By assuming a different – observational – perspective, we investigate the quality, as well as strength and weakness, of multiple observational and reanalyses datasets building a basis for future studies on specific atmospheric features using also the RO wind dataset.

2 Data and methods

2.1 GNSS RO data

Radio occultation is an active limb sounding technique measuring the state of the atmosphere from space, whereby observational data is gathered in the form of profiles (see e.g., Kursinski et al., 1997). This study builds on the profiles from six satellite missions: CHAMP (Wickert et al., 2001), GRACE (Beyerle et al., 2005), FORMOSAT-3/COSMIC (Anthes et al., 2008), C/NOFS (de La Beaujardière, 2004), SAC-C (Hajj et al., 2004), MetOp (Luntama et al., 2008), which collectively average 60 000 globally distributed profiles per month. The excess phase data from these missions is provided at UCAR/CDAAC (University Corporation for Atmospheric Research/COSMIC Data Analysis and Archive Center) and further processed with the Occultation Processing System OPSv5.6 by the Wegener Center for Climate and Global Change (WEGC) at the University of Graz (Angerer et al., 2017; Steiner et al., 2020a). Following quality assessment, such as removing outliers at the excess phase stage and applying an ionospheric correction (Danzner et al., 2013; Vorob’ev and Krasil’nikova, 1994), the OPSv5.6 retrieval provides a daily geopotential height record on pressure levels from 2001 to 2020 (Schwärz et al., 2013). This daily data is then aggregated using temporal and spatial weighting to monthly fields on a 2.5×2.5 latitude $\times$ longitude grid.

In a next step, climatological wind fields from these geopotential fields are derived, following the approach by Nimac et al. (2026) and Unegg et al. (2026). In more detail, the wind field estimation approach separates the FTS into three regions and applies the best estimation method for each. Consequently, the global wind product is comprised of geostrophic wind including advection in the extratropical troposphere, gradient wind including advective terms in the extratropical stratosphere and the equatorial balance approach including curvature terms in the equatorial region.

The WEGC RO OPSv5.6 wind fields, hereafter RO winds, are computed at 127 pressure levels, in the FTS ranging from 800 hPa to 10 hPa. This altitudinal range is determined by two decisive factors: Firstly, the quality of the RO retrievals and secondly, the utility and validation of the wind field method. Regarding the first, RO data is solely observation-based from the mid stratosphere to the mid to upper troposphere. However, towards even lower levels, where the air is moist, the RO method requires additional information from ECMWF short-term forecasts, serving as a background (Steiner et al., 2020a). Hence,



RO data does not hold independent observations in the lowest levels of the atmosphere, which would conflict with the objective of this study. With regard to the second factor, the wind field approximations have been specifically explored and tested for this altitude range, where frictional force can be neglected (Nimac et al., 2025; Unegg et al., 2026). As for the temporal domain of this study, while satellite RO data is available from 2001 onward, we investigate the WEGC RO OPSv5.6 record which spans the time range from 2001 to 2020. For this specific study we choose the period September 2006 to December 2020, as profile-statistics are higher due to the availability of multiple satellite missions (Angerer et al., 2017; Steiner et al., 2020a).

2.2 Reanalysis data

Reanalysis datasets provide temporally and spatially continuous, fine gridded information on the state of the climate system by combining observational data with state-of-the-art numerical weather prediction models. Multiple reanalysis products exist, differing, for example, in their assimilated data and underlying model configurations. Here we compare three of the most-recent reanalyses, which are: ERA5 (Hersbach et al., 2020) by the European Center for Medium-Range Weather Forecasts (ECMWF), JRA-3Q (Kosaka et al., 2024) by the Japanese Meteorological Agency (JMA) and MERRA-2 Analysis (Gelaro et al., 2017) by the National Aeronautics and Space Administration (NASA). For the present analysis we retrieve monthly fields on pressure levels provided on their respective regular latitude-longitude grid (see Table 1). We note that these reanalyses assimilate RO information (i.e., bending angle or refractivity profiles).

2.3 Radiosonde data

Radiosondes provide in situ measurements of atmospheric variables, via sensors mounted on weather balloons which transmit information as the balloon rises through the troposphere up to the lower stratosphere (Durre et al., 2006). Radiosonde data is available as profile information for atmospheric variables such as temperature, pressure, humidity and wind. In this study quality-controlled radiosonde information is used as a second observational data source. More specifically, the monthly mean Integrated Global Radiosonde Archive (IGRA) Version 2.2 record (Durre et al., 2018) from the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NCEI) is utilized. A continuous record of monthly data, consistent with the temporal coverage of the RO dataset, is available for 337 stations, for which data is provided either at 00:00 UTC, 12:00 UTC or both. As only one radiosonde dataset is used in this work, the term radiosondes will hereafter refer to the IGRA v2.2 dataset.

2.4 Methods

The main focus of this paper is on monthly zonal and meridional wind information from observations (i.e., RO and radiosondes) and reanalyses (i.e., ERA5, JRA-3Q, MERRA-2) as introduced above. Each respective dataset possesses unique data characteristics and details, some of which are summarized in Table 1. For the purpose of this study, specific dataset properties, such as the horizontal resolution, vertical range and the available time period must be aligned. As the RO winds represents the key element of this investigation, the other datasets are fitted to these data characteristics, which are: (i) temporal

coverage from September 2006 to December 2020, (ii) a vertical range from 800 hPa to 10 hPa, and (iii) a horizontal 2.5×2.5 latitude $\times$ longitude grid. Respectively, the reanalysis data are regridded using Climate Data Operators (CDO) bilinear interpolation function “remapbil” (Schulzweida, 2023). For cross comparisons with wind information from radiosonde data, which is only available for individual stations, we use collocated grid points for RO and reanalyses.

From this input data we calculate monthly anomaly values at each grid point. This is done by subtracting the climatological monthly means over the investigation period from each individual month. Linear trends for each grid point and for zonal mean fields, are then calculated using ordinary least square regression. For the latter, the zonal averaging is done prior to the trend calculation. As temporal autocorrelation in the data can lead to an inflated estimate of the trend significance, we follow the established approach by Santer et al. (2008) to account for the lag-1 temporal autocorrelation in the wind data. Consequently, statistical significance was assessed with a two-sided *t*-test using the effective sample size, assuming significance for *p*-values < 0.05 (95% confidence level).

Additionally, to assess similarities as well as differences between the trend results from the chosen datasets, we applied simple statistical methods including ordinary least-square regression lines fitted to each dataset pairing and the corresponding Pearson correlation coefficients.

Table 1: List of datasets used in this study and their original horizontal grid, number of pressure levels as well as their vertical range, and temporal coverage. For IGRA v2.2 only stations fully covering our investigation period were selected. The full temporal range of individual stations can however vary, with some records reaching back as far as 1905.

Data product	Institution	Horizontal grid (lat $\times$ lon)	No. of pressure levels	Vertical range (hPa)	Available time range
RO_OPSv5.6	WEGC	$2.5^\circ \times 2.5^\circ$	127	800–10	2006–2020
ERA5	ECMWF	$0.25^\circ \times 0.25^\circ$	37	1000–1	1940–2026
MERRA-2 ASM	NASA	$0.5^\circ \times 0.625^\circ$	42	1000–10	1980–2026
JRA-3Q	JMA	$0.375^\circ \times 0.375^\circ$	45	1000–0.01	1947–2026
IGRA v2.2	NCEI	–	22	1000–1	2006–2020

3 Results

3.1 Observation-based winds over recent decades

In this study, we begin by looking at mean global wind fields in the FTS based on a novel wind record from RO observations. Figure 1 illustrates the average zonal and meridional wind flow of the general circulation over the RO measurement period on three pressure levels representative of the lower stratosphere (50 hPa), the tropopause region (200 hPa), and the free troposphere (500 hPa). On a global perspective, the zonal wind generally has greater magnitudes than the meridional wind, such as presented in this figure. While the average zonal wind component has wind speeds up to 40 m s^{-1} , the meridional wind component is mostly in range of less than 5 m s^{-1} . Focusing on the zonal wind, easterlies are located around the equatorial

region throughout the investigated layers. In the lower stratosphere (Fig. 1a) easterlies dominate between 30° N and 30° S. Outside this area, the westerly flow prevails, with a stronger flow in the Southern Hemisphere (SH). Westerlies govern the troposphere over most of the extra tropics. The strongest winds are evident near the tropopause, where the STJ is located (Fig. 1c). At lower levels the flow is again slightly weaker (Fig. 1e). Generally, the zonal wind flow is more uniform in the SH compared to the NH. As for the meridional wind, large-scale patterns are weaker and less apparent (Fig. 1b, d, f). In particular, at 200 hPa the meridional wind shows very regional bipolar patterns (Fig. 1d). The most distinctive patterns of the mean meridional wind component can be identified in the high latitudes of the stratosphere (Fig. 1b).

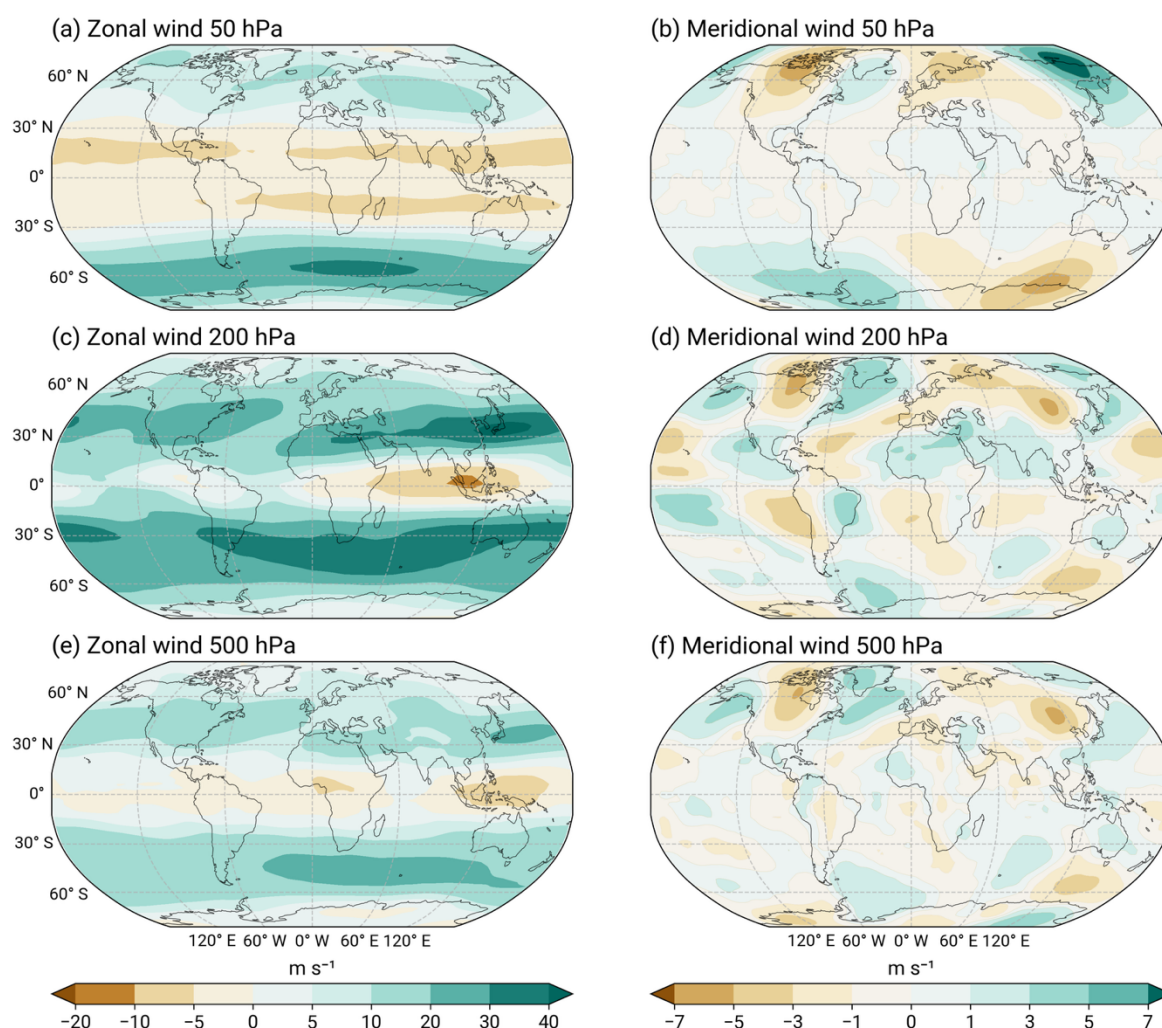


Figure 1: Mean zonal (left) and meridional (right) RO wind from September 2006 to November 2020 on three pressure levels, 50 hPa (a-b), 200 hPa (c-d), 500 hPa (e-f).



In concept, the mechanisms of the troposphere and stratosphere are inherently different. The troposphere is characterized by differential heating of the Earth's surface, its decreasing temperature with height, and the presence of water vapor, which contribute to the troposphere containing most of the mass of Earth's atmosphere and the occurrence of weather. In contrast, the stratosphere presents a strong stable stratification with temperature increasing with height. Furthermore, the stratosphere contains only minimal water vapor, so latent heating effects are negligible, but the presence of the ozone layer introduces its own distinct dynamics (e.g., Holton and Hakim, 2012). Consequently, the drivers of wind variability differ for these two layers. Finally, we note that the phenomena that signify the general circulation and prominent modes of natural variability are distinct for each atmospheric layer (Butchart, 2022).

3.2 Observed changes of the wind components

Building on the foundation of the average zonal and meridional wind flow, we now examine how these patterns have changed over recent decades (Fig. 2). Contrasting the large-scale patterns of the mean flow presented in Fig. 1, the observed trends are more heterogeneous, depicting many regional changes over the globe. The trends for both wind components are mostly in range between $\pm 3.0 \text{ m s}^{-1}$ per decade, with stronger trend patterns at the tropopause and in the troposphere, and slightly weaker and more uniform trends in the lower stratosphere. The similarities in trend strength between the wind components has also been identified by Simmons (2022) in ERA5 over the period 1979 to 2022.

We will start our discussions with the zonal wind component, then move to the meridional flow and with each, shift the focus from the lower stratosphere to the troposphere. At the 50 hPa level (Fig. 2a), a negative trend signal is found, that indicates a strengthening of the temporal-mean easterly flow in the tropics. For context, the equatorial region of the stratosphere is characterized by the QBO, which is a very distinct mode of natural variability. The QBO describes how the zonal wind transitions between an easterly flow and a westerly flow within a period of about 28 months (Baldwin et al., 2001). A long-term weakening of the QBO amplitude in the lower stratosphere has been found with distinct disruptions of the QBO in the year 2016 and 2019/2020 (Anstey et al., 2022; Healy et al., 2020; Kawatani and Hamilton, 2013). Returning to the present study, we inspect a relatively short time series and do not expect to capture a long-term trend signal. However, we see a potential area of application of the RO wind record in future studies. Other than this trend pattern, a positive trend in the subtropics presenting a weakening of the easterlies is evident in Fig. 2a. Particularly in the SH Pacific equatorward of 30° , a significant trend is shown. Also, a significant strengthening trend of the westerly winds over North America stands out. This represents the strongest zonal wind trend pattern in the lower stratosphere.

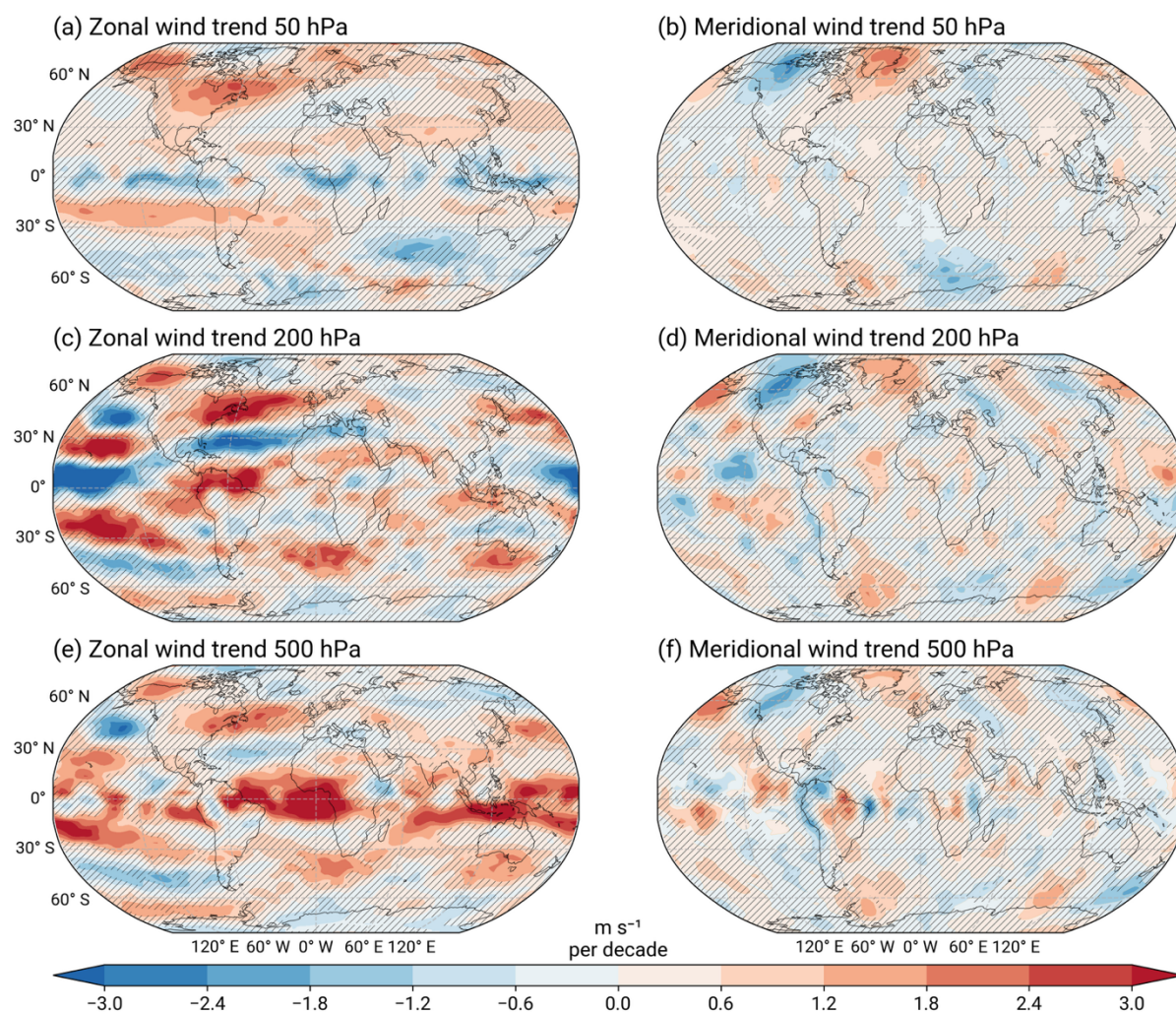


Figure 2: Observed trends of the zonal (left) and meridional (right) RO wind over recent decades. Trends are shown for three pressure levels, 50 hPa (a-b), 200 hPa (c-d), 500 hPa (e-f). Unhatched areas indicate statistical significance at the 95% confidence interval, while hatching denotes regions with no robust statistical trend.

At the 200 hPa level (Fig. 2c), in the NH a noticeable band-pattern stretches from the central Pacific all the way over Europe. These bands of positive and negative trends occur alternating along the latitude lines and could be a shift of the jet latitude or change of the jet strength. A possible displacement or change in the strength of the jet is also observed in the SH over Australia and the Pacific Ocean. However, for the jets, a comparison to existing literature has proven difficult as studies show strong dependencies on the time period and season, as well as the region, vertical level, and dataset investigated. For example, Woollings et al. (2023) have found that the NH winter (December-January-February; DJF) westerly jet on both hemispheres has shifted poleward over the period 1979 to 2019 in ERA5 reanalysis data. They further substantiated their findings by climate model experiments, attributing the changes to the increasing GHG concentrations in the atmosphere. Another study by Hallam



et al. (2022) based on the second version Twentieth Century Reanalysis (20CR) stretching over the period 1871 to 2011, found no displacement or increase of the jet speed over the North Pacific, while a poleward shift and significant increase in jet speed were found for the North Atlantic jet. The later findings are in agreement with Hermoso et al. (2024), who identified an intensification of the North Atlantic jet for the period 1979 to 2022 studying ERA5 data for DJF. A prior study for the SH by Waugh et al. (2020), has identified considerable regional variations over the individual ocean basins. Over the period 1980 to 2018, they discovered a significant strengthening and insignificant equatorward shift over the Southern Pacific Ocean and a slight strengthening and significant poleward trend for the Southern Atlantic and Indian Ocean basins. Their findings are based on 850 hPa level data, hence focusing on lower tropospheric changes. Besides the jet regions, changes at the 200 hPa level have also been noted for the tropics. In this respect, Simmons (2022) found a statistically significant strengthening of the tropical easterlies for the period 1979 to 2022, when analysing ERA5 data. This pattern is not evident for the period investigated here, which is depicting strengthening as well as weakening trends over easterly flow areas.

In the troposphere at 500 hPa (Fig. 2e), a strong weakening trend of the tropical easterlies is visible in the RO data, which deviates from results of the reanalyses over the same period (plots not shown). These results need to be viewed cautiously. Towards lower levels the moisture content of air becomes increasingly relevant, affecting the RO retrieval process. The strong positive trend in the tropics could therefor potentially be an artefact or bias from moisture changes in the tropical troposphere (Danzon et al., 2014; Scherllin-Pirscher et al., 2011). Other than that, the positive trend pattern over the northern Atlantic and the band-pattern in the SH identified at 200 hPa (Fig. 2c) persist, see also discussion above.

In contrast to the zonal flow, changes of the meridional wind component are more difficult to interpret. While the mean wind fields (Fig. 1b, d, f) already are more nuanced with less distinct patterns, the corresponding trends (Fig. 2b, d, f) are even more regional, particularly at lower levels. Still, a prominent trend pattern is visible over Canada and Greenland. Over this region, strong trends are evident for both the zonal and meridional wind throughout all levels shown in this investigation. Fig. 2 indicates a strengthening of the equatorward flow above western Canada and the poleward flow over Greenland. Consistent with the changes in the zonal flow, this points to an increase in the large-scale cyclonic regime. Other than that, the meridional flow shows alternating trend patterns at higher latitudes. At the tropopause and in the troposphere (Fig. 2d, f) some of these extend all the way towards the tropics, for example in the NH between 60° E and 120° E. These trend patterns do not coincide with the underlying structure of average meridional or zonal flow (Fig. 1d, f).

3.3 Underlying changes in geopotential height

To gain a broader understanding of the observed wind trends, we extend our analyses and examine the trend of geopotential height fields. Geopotential height quantifies the vertical extent of pressure surfaces above mean sea level, as these undulate in response to horizontal density variations in the atmosphere under the influence of Earth's gravity field. Whereby, differences in geopotential height on a constant pressure surface create a horizontal pressure gradient force, which is responsible for large-scale atmospheric motion (Holton and Hakim, 2012). As detailed in the data and methods section, geopotential height data from RO represents an established long-term stable, high-quality record (Scherllin-Pirscher et al., 2017; Steiner et al., 2020a)



and builds the foundation for the RO wind fields. Hence, we assume trends, but also biases within the RO wind dataset, could potentially be visible at this stage of the processing.

Figure 3 shows that geopotential height has been predominantly increasing over the last decades, with some of the strongest trends occurring near the tropopause, where global values largely exceed 20 m per decade (Fig. 3b) and zonal mean values show a rising trend of more than 40 m per decade in the tropical region (Fig. 3d). A positive trend in geopotential height, such as depicted here, can in most cases be indicative of either a warming of the atmospheric column below or a decrease (increase) in cyclonic (anticyclonic) regimes within the air column (He et al., 2024). Thus, trends in geopotential height can be framed as an indicator of the combined response of the climate system to thermodynamic and dynamic changes (Christidis and Stott, 2015). Already initial fingerprinting studies using RO geopotential height data for the observation period 2001 to 2010 detected an emerging climate change signal, which reflects the overall warming of the troposphere (Lackner et al., 2011).

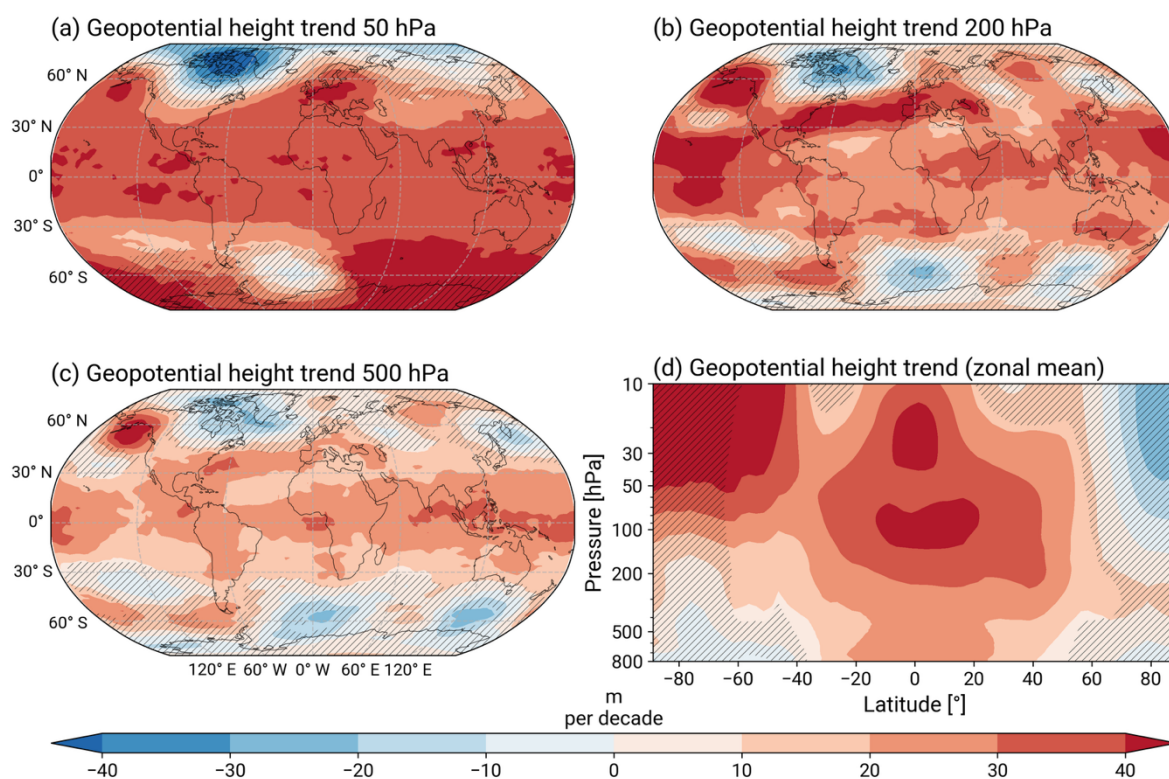


Figure 3: RO geopotential height trends from September 2006 to November 2020 displayed on three pressure levels, 50 hPa (a), 200 hPa (b), 500 hPa (c) and as vertical cross-section of the zonal mean (d). Unhatched areas indicate statistical significance at the 95% confidence interval, while hatching denotes regions with no robust statistical trend.

The elevating trends seen throughout Fig. 3 are in accordance with the rise of global mean temperature. However, atmospheric heating has been observed to take place within the lower layers of the atmosphere. Whilst the troposphere has been found to



255 warm, the stratosphere exhibits a cooling signal due to human-induced climate change (e.g., Ladstädter et al., 2023; Steiner et al., 2020b). As a result, care needs to be taken when interpreting Fig. 3a which depicts the lower stratosphere. The shown trend in this figure realistically stems from the expanding troposphere below. Indeed, Fig. 3d shows that in the NH, the magnitude of the positive geopotential height trend signal is becoming smaller towards the mid stratosphere. In the SH, over the midlatitudes the rise in geopotential height stays relatively consistent up to 10 hPa.

260 Over the poles, geopotential height has been decreasing at higher altitudes. Particularly over north-eastern Canada and Greenland a strong negative trend was identified for this period of observations, which stretches throughout the stratosphere and troposphere. This negative trend can be interpreted as a lowering of the pressure surfaces and possibly indicate a weakening of the prominent high-pressure regime above Greenland during this observational period. Kumar et al. (2025) found a similar trend pattern of geopotential height over the period 2000 to 2021 at the 500 hPa level, while prior to that, trend patterns are significantly different. It has to be noted, that the dynamics over Greenland and its ice masses are highly complex and
 265 influenced by e.g. internal variability of the climate system, such as the North Atlantic Oscillation (Woollings et al., 2010). In this regard, the time period investigated here, is presumably not long enough to determine long-term trends. Consequently, studies based on longer records may show different results for specific regions.

3.4 Comparison to reanalyses

We now turn to the second part of this investigation, in which we compare the RO wind record with reanalyses to interpret the
 270 robustness of our findings and assess the quality of the datasets. Figure 4 and Fig. 5 show a cross-comparison of trend results for the zonal and meridional wind components at each grid point between all pairs of datasets to indicate their consistency or lack thereof. The first three columns display the comparison of RO and reanalyses, the later three are comparisons between the different reanalysis datasets. Overall, the trend results from these individual datasets show relatively strong agreement, especially in the lower stratosphere the results are highly consistent.

275 Taking a specific look at the zonal wind component (Fig. 4), the trend results from individual datasets align very closely towards the poles and towards higher altitudes. In general, there are greater variations between RO and reanalyses than there are between the individual reanalysis records and the results from all comparisons scatter more widely at the tropopause. The greatest variability of the datasets can be found between the RO record and reanalyses over the equatorial latitudes in the troposphere. In contrast to this, the closest agreement can be seen from ERA5 and JRA-3Q for all latitude sections and levels.

280 Comparison of these two reanalysis datasets with MERRA-2 show some deviations of the trend results specifically over the equatorial region in the troposphere and towards the tropopause.

This plot also corroborates the results found in Fig. 2. While the strongest trends are observed around the equator and low latitudes towards the tropopause, the weakest trends are located above the poles and in the lower stratosphere. Trends in the SH tend to be smaller than in the NH. Moreover, the absolute magnitude of the trends is found to be within a highly consistent
 285 range for all datasets under consideration. It is notable that no dataset includes trend values that deviate to a greater extent, as these would be evident along the identity line.

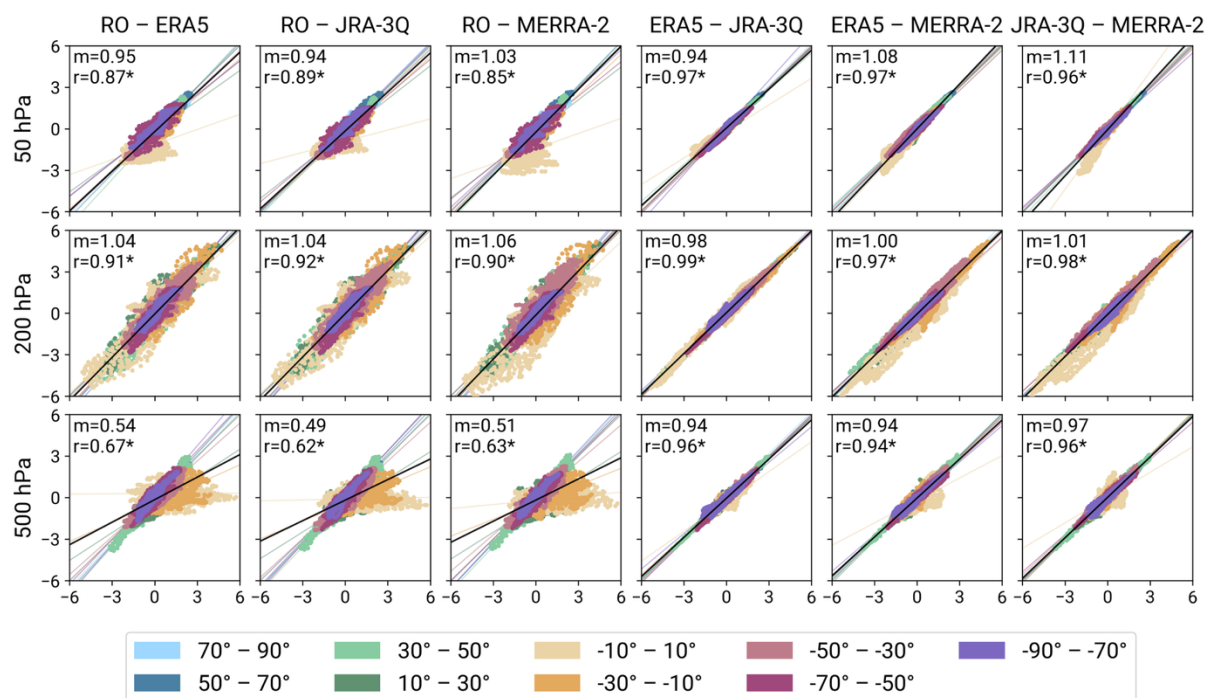


Figure 4: Correlation of the zonal wind trend of dataset pairs from RO and multiple reanalyses for each grid point. The colours split the scatterplot into different latitudinal sections. Each dataset correlation is labelled respectively, the first dataset indicated in the labelling is drawn on the x-axis, whereas the second dataset of the label is set along the y-axis. Linear regressions are shown for each latitude section in the according colour, the overall fit for all datapoints is shown in a bold black line. The respective regression coefficient is denoted by m, r indicates the correlation value, where the statistical significance is indicated by an asterisk for the 95% confidence interval.

Regarding the meridional wind (Fig. 5), the results look similar, although the distinction between the troposphere and lower stratosphere is less pronounced. Here the correlation reveals comparable results on multiple levels. As for the zonal wind, the meridional results from different reanalysis are more closely connected than the ones from RO and reanalyses and the trends spread most at the tropopause. For the meridional wind the differences indicated around the equator between RO and reanalyses are less than for the zonal wind. Also, the deviations between ERA5 and JRA-3Q towards MERRA-2 are less with some exceptions south of the equator at the tropopause level. Concerning the magnitude of the trends, Fig. 5 shows that the trends of the meridional wind are strongest in the NH mid to high latitudes, whereas trends in the SH are again slightly weaker.

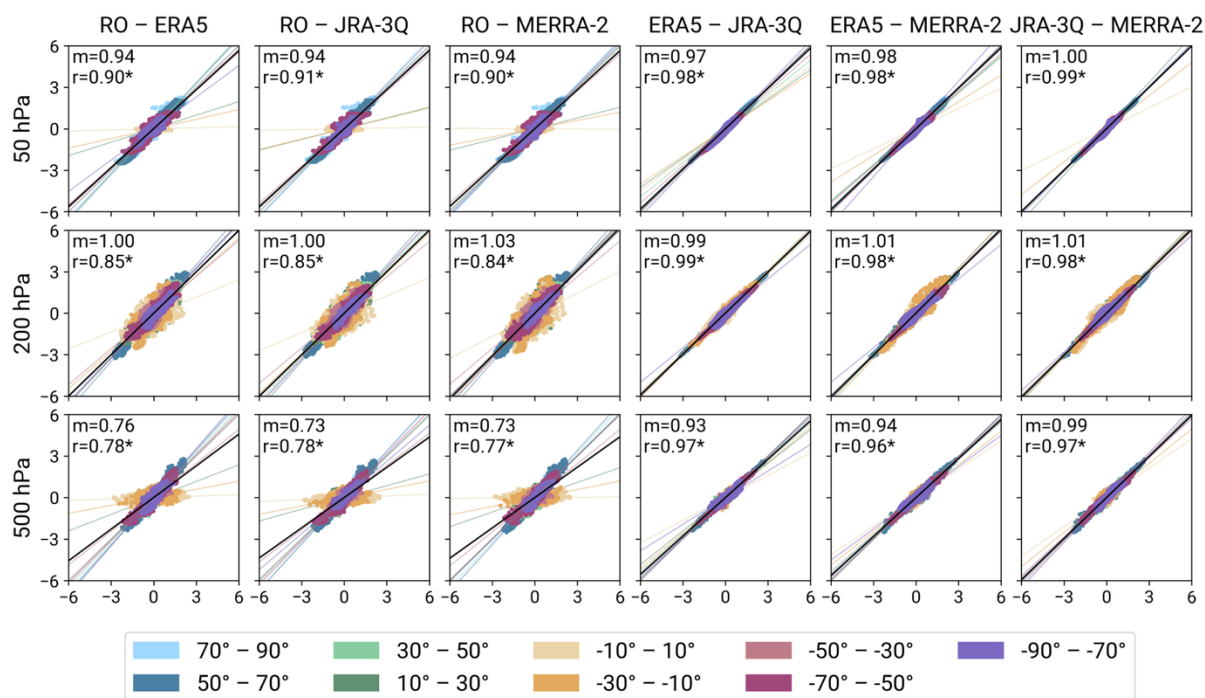


Figure 5: Same as Fig. 4 for the meridional wind component.

305 Following this pairwise-comparison of global wind trends at individual levels, we next consider the vertical structure of zonal-mean wind trends. Figure 6 displays the results from RO data and reanalysis datasets, providing a perspective on the performances of the datasets over the vertical range. Overall, the datasets appear to agree on the major trend patterns and trend directions, except for the tropical troposphere.

In the stratosphere, a distinct positive trend is centred around 20 hPa over the tropical latitudes, presenting a weakening of the mean easterlies, consistent with the findings in Fig. 2a. From there, a negative trend pattern stretches over the mid latitudes that shifts into a positive pattern again towards the higher latitudes. The magnitude of the corresponding trends differs with the hemisphere. The negative trend of the mid latitudes is stronger in the SH, while the positive trend of the high latitudes is stronger in the NH. The general structure and magnitude of the pattern is coherent throughout all datasets.

310 In the troposphere, the datasets indicate consistent trend results over the poles and high latitudes. The structure of the trend patterns at about 40° N and 30° S, with positive trends towards the poles and negative trends towards the equator, is indicative of a poleward shift of the STJ (see also of Fig. 2c). Towards the tropics the findings get somewhat inconsistent. More precisely below 100 hPa and between ±20° latitude, the datasets depict varied trend directions and trend magnitudes. While RO signifies a strong positive trend pattern, ERA5 shows a weaker positive trend. Contrary to this, MERRA-2 presents a negative trend, whereas JRA-3Q has a very weak negative trend pattern in this region. As mentioned above, changes in the moisture content
 320 of the atmosphere could potentially bias RO retrievals and the derived findings in this area. Vergados et al. (2015) found

distinct patterns of high relative humidity in the tropical atmosphere up to 500 hPa and identified discrepancies between RO observations and older reanalyses. Moreover, the tropical troposphere is affected by complex dynamics such as, tropical cyclones, gravity waves, atmospheric planetary waves and the Monsoon dynamics, which can make the accurate representation of wind fields and the corresponding trend detection more difficult (Anstey et al., 2022; Emanuel, 2024; Scherllin-Pirscher et al., 2021; Zhang et al., 2025).

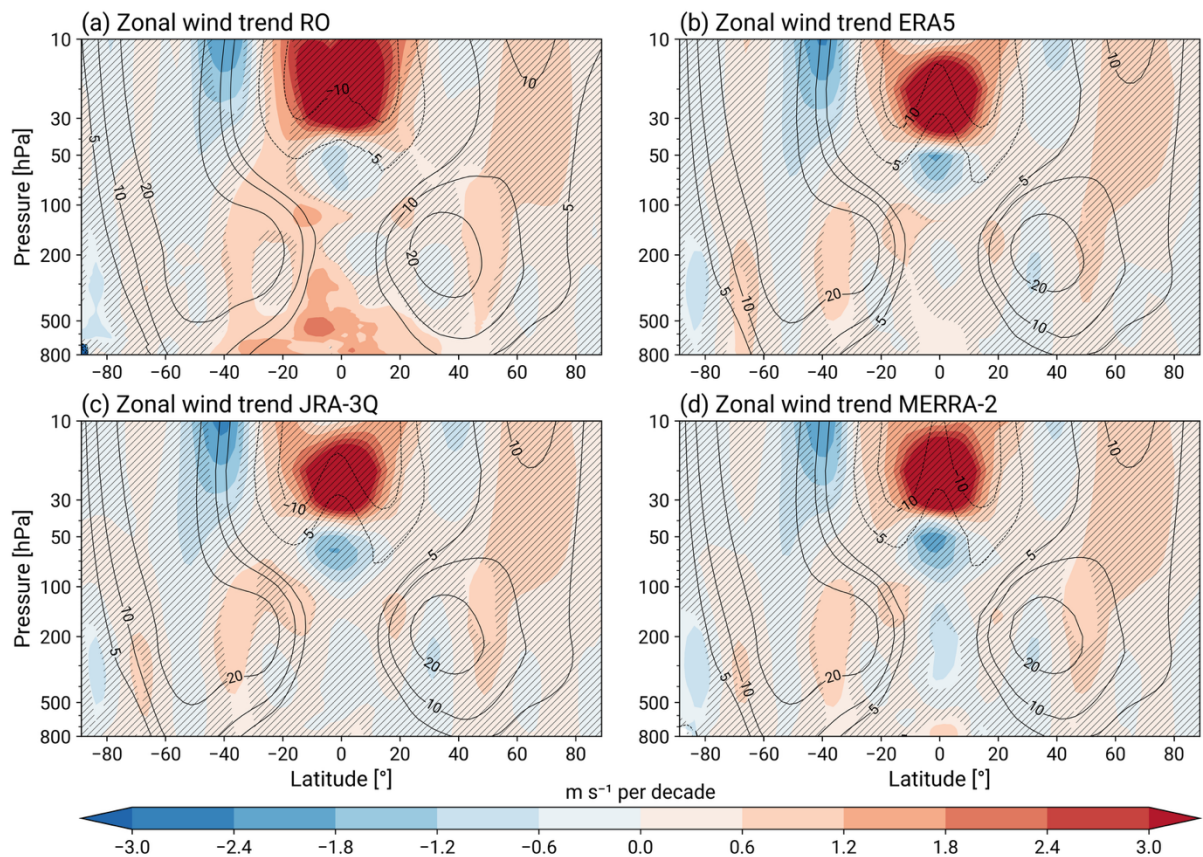


Figure 6: Zonal mean zonal wind trend for RO (a), ERA5 (b), JRA-3Q (c) and MERRA-2 (d) over the period September 2006 to November 2020. The contour lines indicate the underlying zonal mean zonal wind field in m s^{-1} . Solid lines indicate positive windspeeds, the dashed lines indicate negative values. Unhatched areas indicate statistical significance at the 95% confidence interval, while hatching denotes regions with no robust statistical trend.

3.5 Comparison to radiosonde data

To conclude our investigation of large-scale dynamics in the FTS and offer yet more insights into the performance of RO and reanalyses, their wind trends are compared to another independent upper-air observational record, namely radiosondes. Figure 7 includes zonal and meridional wind trends from eight exemplary radiosonde stations located across the globe. The stations

are selected to showcase diverse vertical wind trend profiles, with distinct trend magnitudes and trend directions. All datasets appear to perform well in this intercomparison, although some differences are noticeable. For instance, the single reanalysis trends match very closely throughout all altitude layers and at all stations, while the consistency with the other datasets is not as strict.

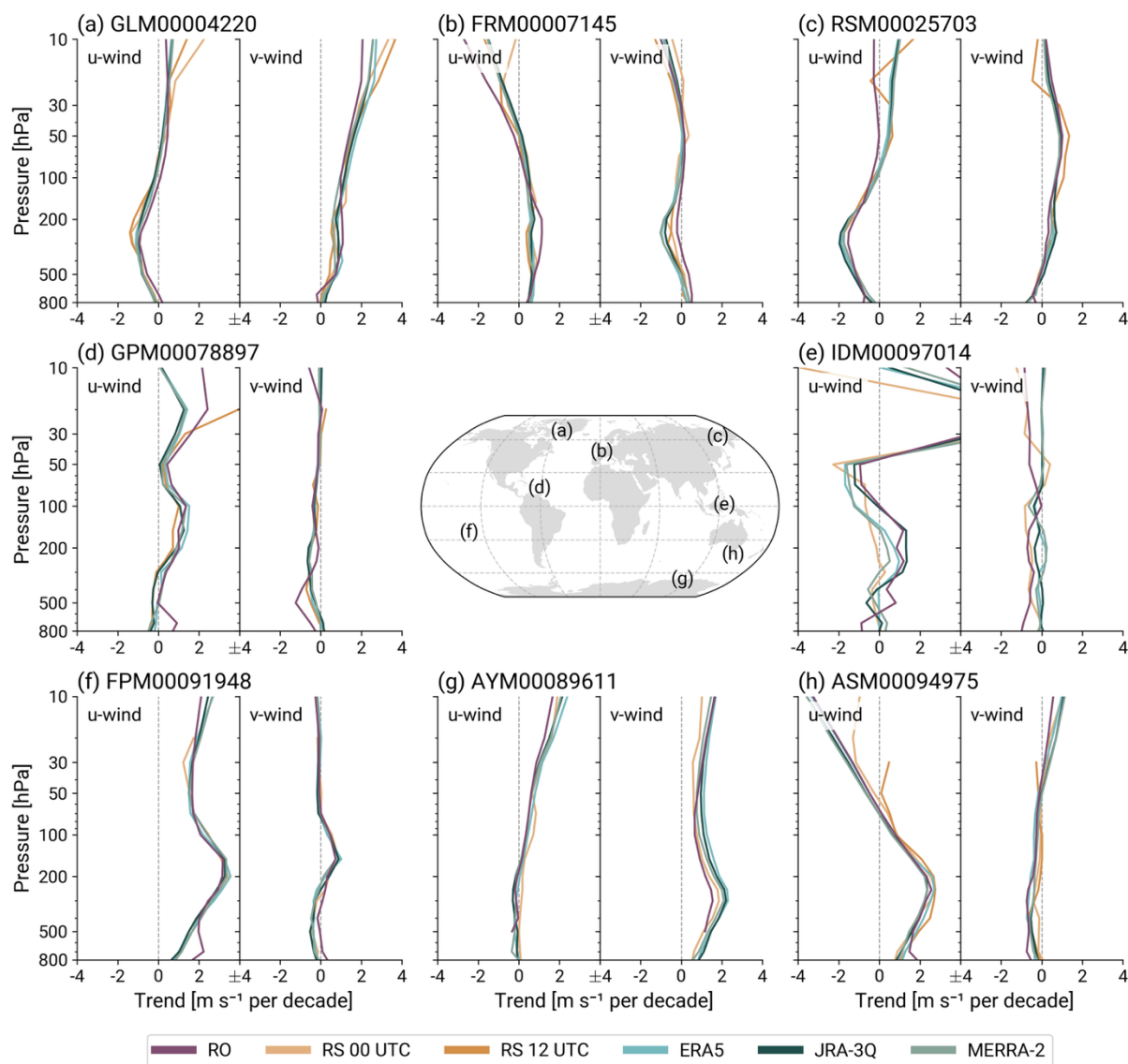


Figure 7: Zonal and meridional wind trends at specific locations (a-h) for RO (purple), radiosondes (apricot) and reanalyses (teal) data from September 2006 to November 2020. Eight radiosonde stations were selected and compared to the nearest grid point of the other datasets. For each subplot, the respective location and station identification code of the radiosonde record are indicated. Radiosondes are abbreviated with RS in the figure.

Specifically, from 30 hPa up in the NH and around the equator, the trend results from RO, radiosondes and reanalyses tend to diverge. Some greater deviations between the trend profiles also occur towards the lowest levels, below 500 hPa, by the RO data. These findings were expected as RO has its core region of highest data quality in the upper troposphere to the mid stratosphere, with increasing bias towards the surface (Scherllin-Pirscher et al., 2011; Steiner et al., 2020b). Contrary to that, some results from radiosondes deviate strongly at high altitudes (for low-pressure levels i.e., in the stratosphere). Radiosondes provide highest accuracy throughout the troposphere to the lower stratosphere, with considerably less soundings available above 30 hPa. Consequently, there are some data gaps for radiosondes at the highest levels of this investigation. Furthermore, we note that although we are using IGRAv2 radiosonde data (Durre et al., 2018), which has a quality assurance system in place, some trend values do not seem plausible. For example in Fig. 7b, d, and h trends of the zonal wind component from radiosondes diverge strongly from the other datasets above 30 hPa.

Finally, we want to draw the attention to Fig. 7e, which was selected to highlight a region of relatively strong disagreement between the individual datasets. Multiple stations within this area around Malaysia and Indonesia were tested, showing similar unsteady results, which might suggest important local effects affecting the wind trends in this region.

4 Conclusions and discussion

In this work we provide a new observational perspective on the atmospheric general circulation over recent decades by using both independent observational records and reanalysis data. A central focus was the use of a new wind dataset from RO multi-satellite observations, representing its first systematic application for global wind field analysis. Based on the different datasets, we show that the dynamics of the atmosphere have been changing. Over the period September 2006 to December 2020 trends in zonal and meridional winds are largely within 3 m s^{-1} per decade. Notable during this period are e.g., the poleward-shifting pattern of the upper-tropospheric jet streams visible in the trend of the zonal wind component and an increasing cyclonic regime over north-eastern Canada and Greenland identified in the zonal wind, meridional wind, and geopotential height trends. The present work specifically evaluated and cross-compared observations (RO and radiosondes) and multiple reanalyses (ERA5, JRA-3Q, MERRA-2). The findings are mostly consistent between the data records over horizontal and vertical cross-sections, with wide agreement in the general representation of the patterns and magnitude of change. Particularly towards the tropopause and stratosphere, there is consistency between the wind records, which increases the confidence in the identified trend patterns and the utilized datasets in the respective regions. Differences in the wind trends occur primarily in the equatorial latitudes between $\pm 20^\circ$. These inconsistencies, between individual reanalyses datasets and also when compared to RO, point to the complex dynamics of the equatorial region and to observational limitations of the RO winds towards the lower troposphere likely to due to the impact of water vapor on the RO retrieval (see e.g., Vergados et al., 2015). The vertical profile analysis of wind trends from IGRA v2.2 radiosonde data shows encouraging results compared to RO and reanalyses. Only the upper and lower altitudinal boundaries can illustrate larger deviations, highlighting the need for cautious use of datasets outside



their specific core regions. In this context, RO winds are especially valuable for stratospheric studies, as they provide high data quality up to the mid-stratosphere (Danzer et al., 2021; Liu et al., 2024).

380 Previous studies have noted that consistency between individual reanalysis datasets and their agreement with climate models increases the trust in the derived trends (Butchart, 2022; Simmons, 2022). Still, we emphasize through our cross-comparison, including purely observational data, that independent observational constraints remain essential to further strengthen confidence in reanalyses and climate model results. The study of Di Girolamo et al. (2025) showed the value of providing a comprehensive global evaluation combined with the analysis of specific atmospheric features. In line with this, our global
385 investigation provides a complementary and more general assessment of the dataset performance, giving insights into the spatial and temporal consistency of the datasets, which is particularly important for trend analysis and consequently, for the assessment of climate change. We note that the found discrepancies among datasets in the tropical troposphere merit further investigation.

Despite the limited temporal extent, which does not yet allow to explicitly address anthropogenic climate change, the RO
390 record and its observational period, provide an additional data source for investigating recent and ongoing atmospheric changes. One prominent example within this period is the recovery of the ozone layer, which has affected long-term trends particularly in the SH. Since the year 2000, a pausing and in some cases even a reversing of the reported poleward shift of the Hadley cell edge and jet stream latitude (long-term trend signals) was identified (Banerjee et al., 2020). Another example for the NH, is a short term trend in the intensity of the stratospheric polar vortex, depicting a weakening trend from 1980 to 2000
395 and a strengthening trend from 2000 onwards (Kumar et al., 2025). Both these examples could potentially be investigated using the RO record in future studies. This underscores the value of utilizing also relatively short but high-quality data sets to capture and analyse most recent trends, offering a different perspective with other learnings and insights from those obtained by long-term records.

To summarize, our analysis demonstrates that studies of global upper-air winds and their trends can substantially benefit from
400 the use of multiple observational datasets. In particular, the consensus among independent records strengthens confidence in the obtained results and thereby provides a robust foundation for advancing our understanding of atmospheric dynamics. We showed that the newly proposed RO winds successfully captured current trends, revealing their potential for climate analysis of large-scale atmospheric circulation characteristics. Finally, we conclude that long-term consistent, high-quality observational records, including RO winds, are essential for the robust quantification of changes and the critical validation of
405 model-based trend results.

Data availability

The WEGC RO OPSv5.6 record used to produce the wind fields is available at <https://doi.org/10.25364/WEGC/OPS5.6:2021.1> (EOPAC Team, 2021). ERA5 was downloaded from the climate data store (<https://climate.copernicus.eu>, last access: 30 July 2026; Hersbach et al., 2023), MERRA-2 was acquired from GES DISC



410 (<https://disc.gsfc.nasa.gov>, last access: 30 July 2026; Global Modeling and Assimilation Office (GMAO), 2015), JRA-3Q was obtained from NSF NCAR Research Data Archive (<https://rda.ucar.edu>, last access: 30 July 2026; Japan Meteorological Agency, 2024). Monthly-mean IGRA v2.2 sounding data are available at NOAA National Centers for Environmental Information (<https://www.ncei.noaa.gov/pub/data/igra/monthly/>, last access: 30 July 2026; Durre et al. 2016).

Author contribution

415 Conceptualization: AR, JD; Data curation: AR; Formal analysis: AR, IN; Funding acquisition: AR, JD; Methodology: AR, IN, JD; Supervision: JD; Validation and visualization: AR, JD; Writing (original draft preparation): AR, JD; Writing (review and editing): AR, IN, JD.

Competing interests

The authors declare that they have no conflict of interest.

420 Acknowledgements

We thank the UCAR/CDAAC RO team for providing the RO excess phase and orbit data, and the WEGC RO team for supplying the OPSv5.6 retrieved profile data. We are grateful to Florian Ladstädter (WEGC) for providing the monthly gridded climatology data and especially thank Gottfried Kirchengast (WEGC) and Andrea K. Steiner (WEGC) for all productive discussions on important details. We also wish to acknowledge Selina Maderthaner for her part in the initial exploratory
425 investigation. Finally, we gratefully acknowledge this work was co-funded by the European Space Agency (ESA) and the Government of Styria under the project FOCUS-JET.

Financial support

This work was co-funded by the European Space Agency (ESA) under Open Space Innovation Platform (OSIP) (contract number 4000152241) and the Government of Styria within the project FOCUS-JET.

430 References

Angerer, B., Ladstädter, F., Scherllin-Pirscher, B., Schwärz, M., Steiner, A. K., Foelsche, U., and Kirchengast, G.: Quality aspects of the Wegener Center multi-satellite GPS radio occultation record OPSv5.6, *Atmospheric Measurement Techniques*, 10, 4845–4863, <https://doi.org/10.5194/amt-10-4845-2017>, 2017.



- 435 Anstey, J. A., Osprey, S. M., Alexander, J., Baldwin, M. P., Butchart, N., Gray, L., Kawatani, Y., Newman, P. A.,
and Richter, J. H.: Impacts, processes and projections of the quasi-biennial oscillation, *Nat Rev Earth Environ*, 3,
588–603, <https://doi.org/10.1038/s43017-022-00323-7>, 2022.
- Anthes, R. A., Bernhardt, P. A., Chen, Y., Cucurull, L., Dymond, K. F., Ector, D., Healy, S. B., Ho, S.-P., Hunt, D.
C., Kuo, Y.-H., Liu, H., Manning, K., McCormick, C., Meehan, T. K., Randel, W. J., Rocken, C., Schreiner, W. S.,
440 Sokolovskiy, S. V., Syndergaard, S., Thompson, D. C., Trenberth, K. E., Wee, T.-K., Yen, N. L., and Zeng, Z.: The
COSMIC/FORMOSAT-3 Mission: Early Results, *Bull. Amer. Meteor. Soc.*, 89, 313–334,
<https://doi.org/10.1175/BAMS-89-3-313>, 2008.
- Baker, W. E., Atlas, R., Cardinali, C., Clement, A., Emmitt, G. D., Gentry, B. M., Hardesty, R. M., Källén, E., Kavaya,
M. J., Langland, R., Ma, Z., Masutani, M., McCarty, W., Pierce, R. B., Pu, Z., Riishojgaard, L. P., Ryan, J., Tucker,
S., Weissmann, M., and Yoe, J. G.: Lidar-Measured Wind Profiles: The Missing Link in the Global Observing
445 System, *Bulletin of the American Meteorological Society*, 95, 543–564, <https://doi.org/10.1175/BAMS-D-12-00164.1>, 2014.
- Baldassare, D., Reichler, T., Plink-Björklund, P., and Slawson, J.: Large uncertainty in observed estimates of
tropical width from the meridional stream function, *Weather and Climate Dynamics*, 4, 531–541,
<https://doi.org/10.5194/wcd-4-531-2023>, 2023.
- 450 Baldwin, M. P., Gray, L. J., Dunkerton, T. J., Hamilton, K., Haynes, P. H., Randel, W. J., Holton, J. R., Alexander,
M. J., Hirota, I., Horinouchi, T., Jones, D. B. A., Kinnnersley, J. S., Marquardt, C., Sato, K., and Takahashi, M.: The
quasi-biennial oscillation, *Reviews of Geophysics*, 39, 179–229, <https://doi.org/10.1029/1999RG000073>, 2001.
- Banerjee, A., Fyfe, J. C., Polvani, L. M., Waugh, D., and Chang, K.-L.: A pause in Southern Hemisphere circulation
trends due to the Montreal Protocol, *Nature*, 579, 544–548, <https://doi.org/10.1038/s41586-020-2120-4>, 2020.
- 455 Belmonte Rivas, M. and Stoffelen, A.: Characterizing ERA-Interim and ERA5 surface wind biases using ASCAT,
Ocean Science, 15, 831–852, <https://doi.org/10.5194/os-15-831-2019>, 2019.
- Beyerle, G., Schmidt, T., Michalak, G., Heise, S., Wickert, J., and Reigber, C.: GPS radio occultation with GRACE:
Atmospheric profiling utilizing the zero difference technique, *Geophysical Research Letters*, 32,
<https://doi.org/10.1029/2005GL023109>, 2005.
- 460 Butchart, N.: The stratosphere: a review of the dynamics and variability, *Weather and Climate Dynamics*, 3, 1237–
1272, <https://doi.org/10.5194/wcd-3-1237-2022>, 2022.
- Butchart, N., Anstey, J. A., Kawatani, Y., Osprey, S. M., Richter, J. H., and Wu, T.: QBO Changes in CMIP6 Climate
Projections, *Geophysical Research Letters*, 47, e2019GL086903, <https://doi.org/10.1029/2019GL086903>, 2020.
- Christidis, N. and Stott, P. A.: Changes in the geopotential height at 500 hPa under the influence of external climatic
465 forcings, *Geophysical Research Letters*, 42, 10,798–10,806, <https://doi.org/10.1002/2015GL066669>, 2015.
- Danzer, J., Scherllin-Pirscher, B., and Foelsche, U.: Systematic residual ionospheric errors in radio occultation data
and a potential way to minimize them, *Atmospheric Measurement Techniques*, 6, 2169–2179,
<https://doi.org/10.5194/amt-6-2169-2013>, 2013.



- 470 Danzer, J., Foelsche, U., Scherllin-Pirscher, B., and Schwärz, M.: Influence of changes in humidity on dry temperature in GPS RO climatologies, *Atmospheric Measurement Techniques*, 7, 2883–2896, <https://doi.org/10.5194/amt-7-2883-2014>, 2014.
- Danzer, J., Haas, S. J., Schwaerz, M., and Kirchengast, G.: Performance of the Ionospheric Kappa-Correction of Radio Occultation Profiles Under Diverse Ionization and Solar Activity Conditions, *Earth and Space Science*, 8, e2020EA001581, <https://doi.org/10.1029/2020EA001581>, 2021.
- 475 Danzer, J., Pieler, M., and Kirchengast, G.: Closing the gap in the tropics: the added value of radio-occultation data for wind field monitoring across the Equator, *Atmospheric Measurement Techniques*, 17, 4979–4995, <https://doi.org/10.5194/amt-17-4979-2024>, 2024.
- Davis, N. A. and Davis, S. M.: Reconciling Hadley Cell Expansion Trend Estimates in Reanalyses, *Geophysical Research Letters*, 45, 11,439–11,446, <https://doi.org/10.1029/2018GL079593>, 2018.
- 480 Di Girolamo, L., Zhao, G., Zhang, G., Wang, Z., Loveridge, J., and Mitra, A.: Decadal changes in atmospheric circulation detected in cloud motion vectors, *Nature*, 643, 983–987, <https://doi.org/10.1038/s41586-025-09242-1>, 2025.
- Durre, I., Vose, R. S., and Wuertz, D. B.: Overview of the Integrated Global Radiosonde Archive, *Journal of Climate*, 19, 53–68, <https://doi.org/10.1175/JCLI3594.1>, 2006.
- 485 Durre, I., Yin, X., Vose, R. S., Applequist, S., Arnfield, J., Korzeniewski, B., and Hundermark, B.: Integrated Global Radiosonde Archive (IGRA), Version 2, <https://doi.org/10.7289/V5X63K0Q>, 2016.
- Durre, I., Yin, X., Vose, R. S., Applequist, S., and Arnfield, J.: Enhancing the Data Coverage in the Integrated Global Radiosonde Archive, *Journal of Atmospheric and Oceanic Technology*, 35, 1753–1770, <https://doi.org/10.1175/JTECH-D-17-0223.1>, 2018.
- 490 Emanuel, K.: Limitations of reanalyses for detecting tropical cyclone trends, *Nat. Clim. Chang.*, 14, 143–145, <https://doi.org/10.1038/s41558-023-01879-y>, 2024.
- EOPAC Team: Wegener Center GNSS Radio Occultation Record (2001–2020), <https://doi.org/10.25364/WEGC/OPS5.6:2021.1>, 2021.
- 495 Eyre, J. R., English, S. J., and Forsythe, M.: Assimilation of satellite data in numerical weather prediction. Part I: The early years, *Quarterly Journal of the Royal Meteorological Society*, 146, 49–68, <https://doi.org/10.1002/qj.3654>, 2020.
- Eyre, J. R., Bell, W., Cotton, J., English, S. J., Forsythe, M., Healy, S. B., and Pavelin, E. G.: Assimilation of satellite data in numerical weather prediction. Part II: Recent years, *Quarterly Journal of the Royal Meteorological Society*, 148, 521–556, <https://doi.org/10.1002/qj.4228>, 2022.
- 500 Foelsche, U., Scherllin-Pirscher, B., Ladstädter, F., Steiner, A. K., and Kirchengast, G.: Refractivity and temperature climate records from multiple radio occultation satellites consistent within 0.05%, *Atmospheric Measurement Techniques*, 4, 2007–2018, <https://doi.org/10.5194/amt-4-2007-2011>, 2011.



- 505 Fujiwara, M., Wright, J. S., Manney, G. L., Gray, L. J., Anstey, J., Birner, T., Davis, S., Gerber, E. P., Harvey, V. L., Hegglin, M. I., Homeyer, C. R., Knox, J. A., Krüger, K., Lambert, A., Long, C. S., Martineau, P., Molod, A., Monge-Sanz, B. M., Santee, M. L., Tegtmeier, S., Chabrillat, S., Tan, D. G. H., Jackson, D. R., Polavarapu, S., Compo, G. P., Dragani, R., Ebisuzaki, W., Harada, Y., Kobayashi, C., McCarty, W., Onogi, K., Pawson, S., Simmons, A., Wargan, K., Whitaker, J. S., and Zou, C.-Z.: Introduction to the SPARC Reanalysis Intercomparison Project (S-RIP) and overview of the reanalysis systems, *Atmospheric Chemistry and Physics*, 17, 1417–1452, <https://doi.org/10.5194/acp-17-1417-2017>, 2017.
- 510 Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., Randles, C. A., Darmenov, A., Bosilovich, M. G., Reichle, R., Wargan, K., Coy, L., Cullather, R., Draper, C., Akella, S., Buchard, V., Conaty, A., Silva, A. M. da, Gu, W., Kim, G.-K., Koster, R., Lucchesi, R., Merkova, D., Nielsen, J. E., Partyka, G., Pawson, S., Putman, W., Rienecker, M., Schubert, S. D., Sienkiewicz, M., and Zhao, B.: The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2), *Journal of Climate*, 30, 5419–5454, <https://doi.org/10.1175/JCLI-D-16-0758.1>, 2017.
- 515 Grise, K. M., Davis, S. M., Simpson, I. R., Waugh, D. W., Fu, Q., Allen, R. J., Rosenlof, K. H., Ummenhofer, C. C., Karnauskas, K. B., Maycock, A. C., Quan, X.-W., Birner, T., and Staten, P. W.: Recent Tropical Expansion: Natural Variability or Forced Response?, *Journal of Climate*, 32, 1551–1571, <https://doi.org/10.1175/JCLI-D-18-0444.1>, 2019.
- 520 Hajj, G. A., Ao, C. O., Iijima, B. A., Kuang, D., Kursinski, E. R., Mannucci, A. J., Meehan, T. K., Romans, L. J., de la Torre Juárez, M., and Yunck, T. P.: CHAMP and SAC-C atmospheric occultation results and intercomparisons, *Journal of Geophysical Research: Atmospheres*, 109, <https://doi.org/10.1029/2003JD003909>, 2004.
- 525 Hallam, S., Josey, S. A., McCarthy, G. D., and Hirschi, J. J.-M.: A regional (land–ocean) comparison of the seasonal to decadal variability of the Northern Hemisphere jet stream 1871–2011, *Clim Dyn*, 59, 1897–1918, <https://doi.org/10.1007/s00382-022-06185-5>, 2022.
- He, C., Chen, X., Collins, M., Song, F., Hu, Y., Jiang, X., Liu, Y., Ding, Y., and Zhou, W.: Rising geopotential height under global warming, *Clim Dyn*, 62, 5769–5786, <https://doi.org/10.1007/s00382-024-07175-5>, 2024.
- 530 Healy, S. B., Polichtchouk, I., and Horányi, A.: Monthly and zonally averaged zonal wind information in the equatorial stratosphere provided by GNSS radio occultation, *Quarterly Journal of the Royal Meteorological Society*, 146, 3612–3621, <https://doi.org/10.1002/qj.3870>, 2020.
- Hermoso, A., Rivière, G., Harvey, B., Methven, J., and Schemm, S.: A Dynamical Interpretation of the Intensification of the Winter North Atlantic Jet Stream in Reanalysis, *Journal of Climate*, 37, 5853–5881, <https://doi.org/10.1175/JCLI-D-23-0757.1>, 2024.
- 535 Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., and Thépaut, J.-N.: The ERA5 global reanalysis, *Quarterly Journal of the Royal Meteorological Society*, 146, 1999–2049, <https://doi.org/10.1002/qj.3803>, 2020.
- 540



- Hoffman, R. N., Privé, N., and Bourassa, M.: Comments on “Reanalyses and Observations: What’s the Difference?,” *Bulletin of the American Meteorological Society*, 98, 2455–2459, <https://doi.org/10.1175/BAMS-D-17-0008.1>, 2017.
- Holton, J. R. and Hakim, G. J.: *An Introduction to Dynamic Meteorology*, Academic Press, 553 pp., 2012.
- 545 IPCC: *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by: Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.), Cambridge University Press, <https://doi.org/10.1017/9781009157896>, 2023.
- 550 Kawatani, Y. and Hamilton, K.: Weakened stratospheric quasibiennial oscillation driven by increased tropical mean upwelling, *Nature*, 497, 478–481, <https://doi.org/10.1038/nature12140>, 2013.
- Kosaka, Y., Kobayashi, S., Harada, Y., Kobayashi, C., Naoe, H., Yoshimoto, K., Harada, M., Goto, N., Chiba, J., Miyaoka, K., Sekiguchi, R., Deushi, M., Kamahori, H., Nakaegawa, T., Tanaka, T. Y., Tokuhiro, T., Sato, Y., Matsushita, Y., and Onogi, K.: The JRA-3Q Reanalysis, *Journal of the Meteorological Society of Japan. Ser. II*, 102, 49–109, <https://doi.org/10.2151/jmsj.2024-004>, 2024.
- 555 Kozubek, M., Laštovička, J., and Zajicek, R.: Climatology and Long-Term Trends in the Stratospheric Temperature and Wind Using ERA5, *Remote Sensing*, 13, <https://doi.org/10.3390/rs13234923>, 2021.
- Kumar, S., Oberheide, J., Zhang, J., Pedatella, N. M., and Lu, X.: Linking Long-Term Arctic Surface Variability and Changes in the Stratosphere, Mesosphere, and Lower Thermosphere, *Journal of Geophysical Research: Atmospheres*, 130, e2025JD045294, <https://doi.org/10.1029/2025JD045294>, 2025.
- 560 Kursinski, E. R., Hajj, G. A., Schofield, J. T., Linfield, R. P., and Hardy, K. R.: Observing Earth’s atmosphere with radio occultation measurements using the Global Positioning System, *Journal of Geophysical Research: Atmospheres*, 102, 23429–23465, <https://doi.org/10.1029/97JD01569>, 1997.
- de La Beaujardière, O.: C/NOFS: a mission to forecast scintillations, *Journal of Atmospheric and Solar-Terrestrial Physics*, 66, 1573–1591, <https://doi.org/10.1016/j.jastp.2004.07.030>, 2004.
- 565 Lackner, B. C., Steiner, A. K., Hegerl, G. C., and Kirchengast, G.: Atmospheric Climate Change Detection by Radio Occultation Data Using a Fingerprinting Method, *Journal of Climate*, 24, 5275–5291, <https://doi.org/10.1175/2011JCLI3966.1>, 2011.
- Ladstädter, F., Steiner, A. K., and Gleisner, H.: Resolving the 21st century temperature trends of the upper troposphere–lower stratosphere with satellite observations, *Sci Rep*, 13, 1306, <https://doi.org/10.1038/s41598-023-28222-x>, 2023.
- 570 Liu, C., Danzer, J., Kirchengast, G., Haas, S. J., Proschek, V., Schwaerz, M., Sun, Y., and Wang, X.: Understanding Ionospheric and Geomagnetic Effects on Residual Biases in Radio Occultation Data for Stratospheric Climate Monitoring, *Journal of Geophysical Research: Space Physics*, 129, e2023JA032110, <https://doi.org/10.1029/2023JA032110>, 2024.
- 575



- Luntama, J.-P., Kirchengast, G., Borsche, M., Foelsche, U., Steiner, A., Healy, S., Engeln, A. von, O’Clerigh, E., and Marquardt, C.: Prospects of the EPS GRAS Mission For Operational Atmospheric Applications, *Bulletin of the American Meteorological Society*, 89, 1863–1876, <https://doi.org/10.1175/2008BAMS2399.1>, 2008.
- 580 Martin, A., Weissmann, M., Reitebuch, O., Rennie, M., Geiß, A., and Cress, A.: Validation of Aeolus winds using radiosonde observations and numerical weather prediction model equivalents, *Atmospheric Measurement Techniques*, 14, 2167–2183, <https://doi.org/10.5194/amt-14-2167-2021>, 2021.
- Nimac, I., Danzer, J., and Kirchengast, G.: The added value and potential of long-term radio occultation data for climatological wind field monitoring, *Atmospheric Measurement Techniques*, 18, 265–286, <https://doi.org/10.5194/amt-18-265-2025>, 2025.
- 585 Nimac, I., Unegg, J., and Danzer, J.: Climatic Higher-Order Balanced Winds Beyond Geostrophic and Gradient Wind Fields, *Earth and Space Science*, 13, e2025EA004393, <https://doi.org/10.1029/2025EA004393>, 2026.
- Ossó, A., Bladé, I., Karpechko, A., Li, C., Maraun, D., Romppainen-Martius, O., Shaffrey, L., Voigt, A., Woollings, T., and Zappa, G.: Advancing Our Understanding of Eddy-driven Jet Stream Responses to Climate Change – A Roadmap, *Current Climate Change Reports*, 11, <https://doi.org/10.1007/s40641-024-00199-3>, 2025.
- 590 Reiter, A., Danzer, J., and Steiner, A. K.: The potential of GNSS radio occultation data for the analysis of the tropical width: a comparison with reanalyses, *Weather and Climate Dynamics*, 6, 1683–1698, <https://doi.org/10.5194/wcd-6-1683-2025>, 2025.
- Santer, B. D., Thorne, P. W., Haimberger, L., Taylor, K. E., Wigley, T. M. L., Lanzante, J. R., Solomon, S., Free, M., Gleckler, P. J., Jones, P. D., Karl, T. R., Klein, S. A., Mears, C., Nychka, D., Schmidt, G. A., Sherwood, S. C., and Wentz, F. J.: Consistency of modelled and observed temperature trends in the tropical troposphere, *International Journal of Climatology*, 28, 1703–1722, <https://doi.org/10.1002/joc.1756>, 2008.
- 595 Scherllin-Pirscher, B., Kirchengast, G., Steiner, A. K., Kuo, Y.-H., and Foelsche, U.: Quantifying uncertainty in climatological fields from GPS radio occultation: an empirical-analytical error model, *Atmospheric Measurement Techniques*, 4, 2019–2034, <https://doi.org/10.5194/amt-4-2019-2011>, 2011.
- 600 Scherllin-Pirscher, B., Steiner, A. K., Kirchengast, G., Schwärz, M., and Leroy, S. S.: The power of vertical geolocation of atmospheric profiles from GNSS radio occultation, *Journal of Geophysical Research: Atmospheres*, 122, 1595–1616, <https://doi.org/10.1002/2016JD025902>, 2017.
- Scherllin-Pirscher, B., Steiner, A. K., Anthes, R. A., Alexander, M. J., Alexander, S. P., Biondi, R., Birner, T., Kim, J., Randel, W. J., Son, S.-W., Tsuda, T., and Zeng, Z.: Tropical Temperature Variability in the UTLS: New Insights from GPS Radio Occultation Observations, *Journal of Climate*, 34, 2813–2838, <https://doi.org/10.1175/JCLI-D-20-0385.1>, 2021.
- 605 Schulzweida, U.: CDO User Guide, <https://doi.org/10.5281/zenodo.10020800>, 2023.
- Schwärz, M., Scherllin-Pirscher, B., Kirchengast, G., Schwarz, J., Ladstädter, F., Fritzer, J., and Ramsauer, J.: Multi-Mission Validation by Satellite Radio Occultation (Final Report), Wegener Center, University of Graz, Graz, Austria, https://wegcwww.uni-graz.at/publ/wegcpubl/arsclisys/2013/Schwaerz-etal_MMValRO_Report-2013.pdf (last access: 20 August 2026), 2013.
- 610



- Simmons, A. J.: Trends in the tropospheric general circulation from 1979 to 2022, *Weather and Climate Dynamics*, 3, 777–809, <https://doi.org/10.5194/wcd-3-777-2022>, 2022.
- 615 Staten, P., Lu, J., Grise, K., Davis, S., and Birner, T.: Re-examining tropical expansion, *Nat. Clim. Chang.*, 8, <https://doi.org/10.1038/s41558-018-0246-2>, 2018.
- Steiner, A. K., Ladstädter, F., Ao, C. O., Gleisner, H., Ho, S.-P., Hunt, D., Schmidt, T., Foelsche, U., Kirchengast, G., Kuo, Y.-H., Lauritsen, K. B., Mannucci, A. J., Nielsen, J. K., Schreiner, W., Schwärz, M., Sokolovskiy, S., Syndergaard, S., and Wickert, J.: Consistency and structural uncertainty of multi-mission GPS radio occultation records, *Atmospheric Measurement Techniques*, 13, 2547–2575, <https://doi.org/10.5194/amt-13-2547-2020>, 2020a.
- 620 Steiner, A. K., Ladstädter, F., Randel, W. J., Maycock, A. C., Fu, Q., Claud, C., Gleisner, H., Haimberger, L., Ho, S.-P., Keckhut, P., Leblanc, T., Mears, C., Polvani, L. M., Santer, B. D., Schmidt, T., Sofieva, V., Wing, R., and Zou, C.-Z.: Observed Temperature Changes in the Troposphere and Stratosphere from 1979 to 2018, *Journal of Climate*, 33, 8165–8194, <https://doi.org/10.1175/JCLI-D-19-0998.1>, 2020b.
- 625 Unegg, J., Nimac, I., and Danzer, J.: Beyond Geostrophic and Gradient Wind: Enhancing the Estimation of Climatic Wind Fields From Radio Occultation, *Earth and Space Science*, 13, e2025EA004579, <https://doi.org/10.1029/2025EA004579>, 2026.
- Vergados, P., Mannucci, A. J., Ao, C. O., Jiang, J. H., and Su, H.: On the comparisons of tropical relative humidity in the lower and middle troposphere among COSMIC radio occultations and MERRA and ECMWF data sets, *Atmos. Meas. Tech.*, 8, 1789–1797, <https://doi.org/10.5194/amt-8-1789-2015>, 2015.
- 630 Vorob'ev, V. V. and Krasil'nikova, G. K.: Estimation of the accuracy of the atmospheric refractive index recovery from doppler shift measurements at frequencies used in the NAVSTAR system, *USSR Atmospheric and Oceanic Physics*, 29, 602–609, 1994.
- Waugh, D. W., Banerjee, A., Fyfe, J. C., and Polvani, L. M.: Contrasting recent trends in southern hemisphere westerlies across different ocean basins, *Geophysical Research Letters*, 47, <https://doi.org/10.1029/2020GL088890>, 2020.
- 635 Wickert, J., Reigber, C., Beyerle, G., König, R., Marquardt, C., Schmidt, T., Grunwaldt, L., Galas, R., Meehan, T. K., Melbourne, W. G., and Hocke, K.: Atmosphere sounding by GPS radio occultation: First results from CHAMP, *Geophysical Research Letters*, 28, 3263–3266, <https://doi.org/10.1029/2001GL013117>, 2001.
- 640 Woollings, T., Hannachi, A., Hoskins, B., and Turner, A.: A Regime View of the North Atlantic Oscillation and Its Response to Anthropogenic Forcing, *Journal of Climate*, 23, 1291–1307, <https://doi.org/10.1175/2009JCLI3087.1>, 2010.
- Woollings, T., Drouard, M., O'Reilly, C. H., Sexton, D. M. H., and McSweeney, C.: Trends in the atmospheric jet streams are emerging in observations and could be linked to tropical warming, *Commun Earth Environ*, 4, 125, <https://doi.org/10.1038/s43247-023-00792-8>, 2023.
- 645 Yu, Y., Shen, C., Wen, G., Chen, D., and Li, Z.-B.: Global intensification of mean tropospheric winds from IGRA radiosonde and reanalyses, *Clim Dyn*, 64, 132, <https://doi.org/10.1007/s00382-025-08005-y>, 2026.



650 Zeng, J., Sokolovskiy, S., Schreiner, W., and Hunt, D.: Representation of vertical atmospheric structures by radio occultation observations in the UTLS: comparison to high resolution radiosonde profiles, *Journal of Atmospheric and Oceanic Technology*, 36, <https://doi.org/10.1175/JTECH-D-18-0105.1>, 2019.

Zhang, S., Chen, J., Wright, J. S., Davis, S. M., Gao, J., Konopka, P., Li, N., Lu, M., Tegtmeier, S., Yan, X., Zhang, G. J., and Zhu, N.: Covariability of dynamics and composition in the Asian monsoon tropopause layer from satellite observations and reanalysis products, *Atmospheric Chemistry and Physics*, 25, 10109–10139, <https://doi.org/10.5194/acp-25-10109-2025>, 2025.

655