



# Tropospheric winds over West Sumatra—a comparison between ERA-5 reanalysis and equatorial atmosphere radar

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## Abstract

This study presents an assessment of ERA-5 reanalysis representation of horizontal and vertical winds based on comparative analysis with data from Equatorial Atmosphere Radar (EAR). Analyzed are long-term average conditions during an extended boreal winter (November–March) as well as sub-diurnal variability, and variability of thereof associated with assorted large-scale phenomena such as El Nino Southern Oscillation (ENSO), Madden–Julian Oscillation (MJO), and Convectively Coupled Kelvin Waves (CCKW). The study reveals a close alignment between average horizontal wind data observed by radar and represented in reanalysis and significant divergence between both data sources in vertical wind. Both EAR and ERA-5 indicate that the influence of large-scale modes on the wind in the troposphere over Sumatra is most pronounced in the lower and upper troposphere. Furthermore, this influence is significantly greater for modes with shorter time scales (MJO, CCKW) than for those with longer time scales (ENSO, QBO). Despite the stratospheric nature of QBO, data from EAR reveal QBOs impact on the upper tropospheric winds as well.

**Keywords** Tropospheric winds · Equatorial atmosphere radar · ERA-5 · Sumatra

## 1 Introduction

The understanding of a variability of wind patterns hold paramount importance in atmospheric sciences. These patterns not only govern local weather conditions but also play a significant role in shaping global climate systems. One of the regions where the dynamics of atmospheric circulation are particularly intriguing is the Maritime Continent (MC),

which experiences a complex interplay of various meteorological phenomena. Diabatic processes over the MC region, mainly a latent heat release during the formation of convective clouds, are known to affect global circulation and climate (Ramage 1968; Simpson et al. 1993).

Sumatra's geographical location, situated within the equatorial belt and being a part of the MC, makes it a unique case study. Atmospheric variability over the region is dominated by a consistent diurnal cycle recognized, among others, in the evolution of clouds and precipitation patterns (Janowiak et al. 1994; Qian 2008; Marzuki et al. 2021), but also clearly imprinted in short-term variability of tropospheric winds (Mori et al. 2004; Szkolka et al. 2023). Its proximity to the Indian Ocean exposes it to a rich tapestry of atmospheric phenomena, including the passage of equatorial waves and the seasonal influence of monsoonal flows. These complex interactions between local processes, augmented by a complex topography, and large-scale atmospheric processes contribute to a dynamic atmospheric environment characterized by both mesoscale and synoptic-scale features. Understanding the wind patterns and their variations in West Sumatra is of great significance due to their implications for regional climate, agriculture, and disaster management. The impacts of El Niño–Southern Oscillation (ENSO), Madden–Julian Oscillation

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(MJO) and Convectively Coupled Kelvin Waves (CCKWs) on the local wind regime add an intriguing layer of complexity to this investigation, as these oscillations have far-reaching consequences on weather and climate patterns across the globe (Donald et al. 2006; Lin and Qian 2019).

Reanalyses represent a crucial data source frequently employed in atmospheric sciences (Kalnay et al. 1996; Wheeler et al. 2000; Hersbach et al. 2020; Uma et al. 2021). They offer a valuable means of investigating variability in atmospheric patterns across a range of temporal and spatial scales, including diurnal cycles, which hold significant importance over the Maritime Continent region (Timmermann et al. 2018). The wind field, characterized as a continuous field, lends itself to relatively straightforward modeling, yet its analysis remains hampered by the scarcity of observational data points, especially in the context of sub-diurnal variability. The long-term measurements can help understand the essence of dynamic and thermodynamic interactions that influence coupled cycles of temperature, humidity, clouds, and precipitation (Baldysz et al. 2024).

This study presents a comprehensive comparison of wind data derived from two distinct sources: the ERA-5 reanalysis dataset over West Sumatra and the Equatorial Atmosphere Radar (EAR) which is a very-high frequency Doppler radar located in Kototabang, Indonesia. The radars of this kind have demonstrated their ability to offer valuable insights into tropospheric dynamics over this region (Gage et al. 1992; Uma and Rao 2009; Szkolka et al. 2023). The aim of this study is to scrutinize the characteristics of wind patterns in this region over an extended period, with a focus on both long-term means and an average sub-diurnal variability. Furthermore, the investigation extends to examining the influence of key atmospheric oscillations, including the ENSO (Timmermann et al. 2018; Fitriany et al. 2021; Peatman et al. 2021), the QBO (Lindzen and Holton 1968; Kane 1996), the MJO (Madden and Julian 1972; Zhang 2005, 2013; Jiang et al. 2020), and the CCKW (Roundy and Frank 2004; Kiladis et al. 2009; Sakaeda et al. 2020b), on the variability of mean wind patterns and diurnal cycles.

In the following sections of this paper, we will delve into the methodology used for data acquisition and analysis, present the results of our comparisons, and discuss the implications of our findings for our understanding of atmospheric dynamics in this region. By shedding light on the intricate interactions between local and global atmospheric processes, this study aims to contribute to broaden understanding with respect to strengths and weaknesses of the ERA-5 reanalysis in representation of multi-scale processes in the MC region.

## 2 Datasets and methodology

The study focuses on the comparison of tropospheric winds over west Sumatra derived from remote sensing observations at EAR facility and modeled winds from ERA-5 reanalysis. Additionally, horizontal wind observations from atmospheric soundings launched in Padang, an administrative center of West Sumatra, 75 km away from EAR location, (Fig. 1), were used. This latter dataset utilizes once-daily profiles (00UTC soundings) and therefore was used to derive mean profiles of horizontal and meridional winds. ERA-5 validation is performed for both daily mean and diurnal variability, including typical long-term mean conditions as well as variability associated with assorted large-scale weather phenomena. All analyses are performed during the extended boreal winter season, that is months of November, December, January, February and March (NDJFM, hereafter extended boreal winter), which mitigates seasonal variations while maximizing number of weather phenomena in composite analyses. Processing of data from EAR and soundings as well as derivation of diurnal variability metrics are the same as in Szkolka et al. (2023) and the full description can be found there. Here, we provide a brief summary of all datasets and methods used.

## 3 Equatorial atmosphere radar

This investigation employed data obtained from the EAR facility, which is 47 MHz Doppler radar providing tropospheric wind data (all three components) with 10-min temporal and about 150 m vertical resolutions. One advantage of EAR is its superior ability to isolate air motion from the movement of other scatterers, such as precipitation and clouds, compared to other remote-sensing sensors. Detailed description of EAR facility is provided in Fukao et al. (2003). This study utilizes data from 2001 to 2019, period. The native 10-min data were averaged to hourly data for consistency with reanalysis dataset. The lowest available in original data point is 1200 m above radar (approximately 2 km above sea level) and observations analyzed here extended up to 20 km above sea level. The data nearest to the ground (the lowest two altitudes), which were showing results inconsistent with the rest of the profile, were deemed implausible and excluded from the analysis. This was likely due to the influence of local topography near the EAR site. In vertical wind, data points with negative magnitudes (downward motions) stronger than  $-0.5$  m/s were removed as they were deemed potentially contaminated by falling droplets. It is noteworthy that this

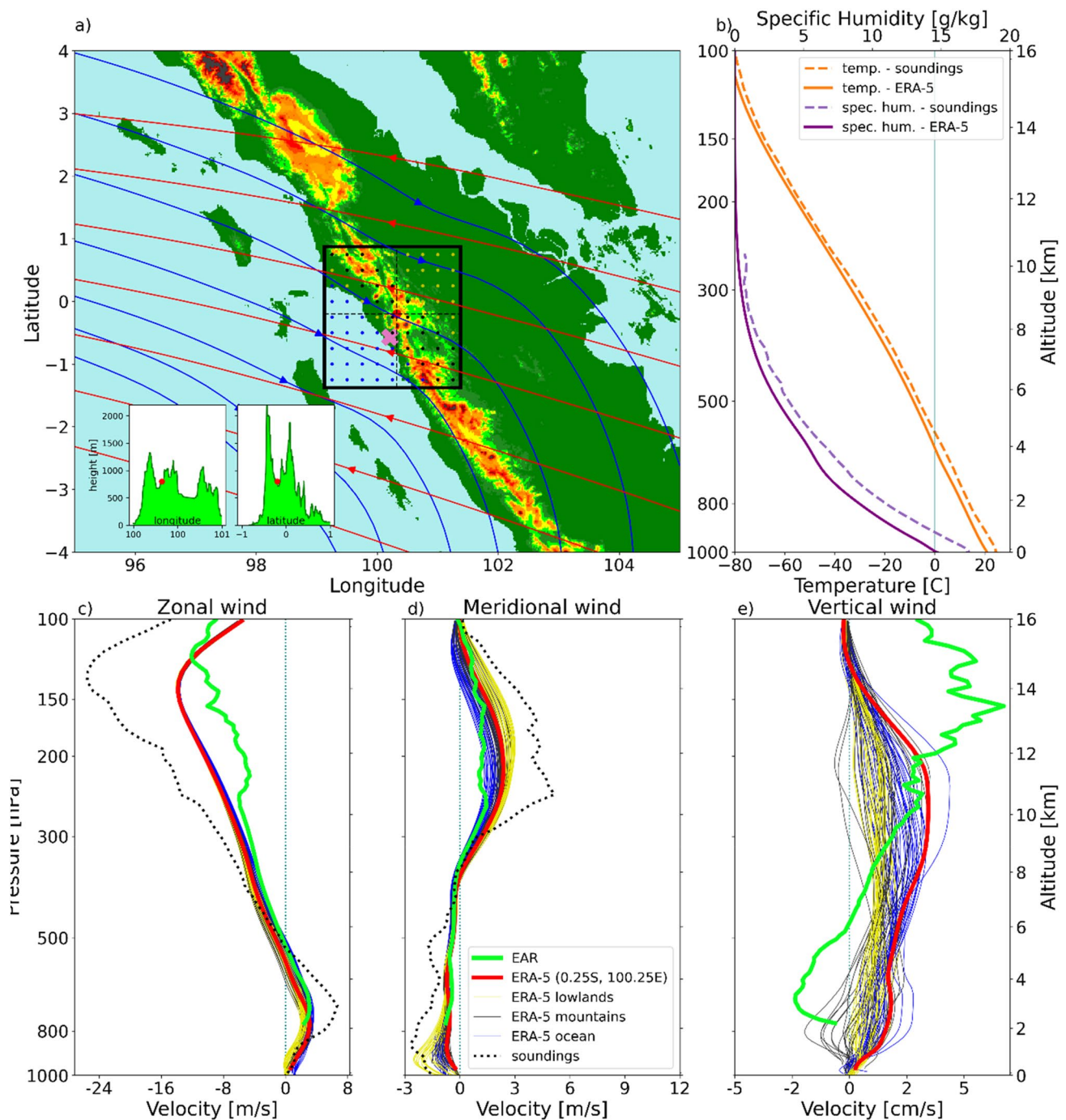


**Fig. 1** **a** Orographic map of Sumatra. The Barisan Mountains are visible as a prominent mountain range running along west coast of the island. Blue lines indicate streamlines of multi-year (2001–2019) November–March mean horizontal winds at 850 hPa; red lines show streamlines at 200 hPa. The black square indicates the area of 1 degree in each direction from EAR location. The EAR location is the center of that square, indicated by an intersection of two dashed lines. Two panels in the lower-left corner of **a**) show cross sections of terrain elevation through Sumatra along the latitude and longitude (along black dashed lines inside the black square). Dots inside black square indicate centers of ERA-5 grid points. Black dots indicate grid points over mountains, yellow dots—grid points over lowlands, and blue dots—grid points over ocean. Pink cross indicates loca-

tion of upper sounding station in Padang. **b** Multi-year (2001–2019) November–March mean temperature (orange lines) and specific humidity (purple lines) profiles from atmospheric soundings data in Padang (BKM station, dashed lines) and ERA-5 (solid lines). **c** Multi-year (2001–2019) mean vertical zonal wind profiles from EAR (green line), soundings (dotted line) and ERA-5 grid points inside the black square (red line—grid point nearest to EAR location, yellow lines—points over lowlands, black lines—points over mountains, blue lines—points over ocean). **d** Same as **c**, but for meridional wind component. **e** Same as **c**, but for vertical wind component (there is no sounding data). This Figure is an modification of the Fig. 1 in Szkolka et al. (2023)

data screening, conducted on the native 10-min resolution data, led to the removal of only a negligible fraction of the overall dataset (less than 3%) and had virtually no impact on composites analyzed in this study. The precision and uncertainty associated with vertical wind data from EAR observations had been previously addressed and validated, confirming the dataset's fidelity in representing the mean atmospheric structure (Uma et al. 2021). All analyses are conducted using pressure coordinates for consistency with reanalysis and soundings data. Conversion from altitude to pressure was done through the application of the hydrostatic equation, using a multi-year-mean observed temperature profile obtained from atmospheric soundings conducted in Padang. These conversions were tested based on the multi-year mean temperature profile by comparing them with conversion derived from soundings on specific days. The results indicate that using the multi-year mean is a reasonable choice. The difference between the two conversions does not exceed 100 m (below 200 hPa) or falls within the 100–200 m range (above 200 hPa). Such differences are acceptable in this research.

Throughout this study, we will refer to lower troposphere, middle troposphere and upper troposphere defined as the layers below 600 hPa, between 600 and 200 hPa, and above 200 hPa, respectively.

## 4 Soundings data

The upper sounding station located in Padang (WMO ID: WIMG, operated by Meteorology, Climatology and Geophysical Agency BMKG), located at 0.88S and 100.35E (near the EAR site), served as the data source for atmospheric soundings from 2001 to 2019 period. The data from these atmospheric soundings, in their refined format as accessible via the Global Telecommunication System, were obtained from the University of Wyoming's—once-daily (00UTC) profiles of temperature, specific humidity (derived from dew point temperature and temperature profiles) and horizontal winds. While this dataset does not provide insights into intra-day variations, the horizontal wind measurements were employed to establish comparisons with the long-term averaged, daily mean values derived from EAR and reanalysis datasets.

## 5 ERA-5 reanalysis data

The fifth generation of reanalysis from the European Centre for Mid-Range Weather Forecasting (ERA5) dataset (Hersbach et al. 2020) was validate against EAR wind data and soundings thermodynamic profiles. To ensure data congruence, we utilized ERA-5 information on all wind

components, temperature and specific humidity spanning from 2001 to 2019, which aligns with the temporal availability of EAR data. In pursuit of higher vertical resolution than standard pressure-level data, we opted for ERA-5 model-level data within a limited spatial domain. This dataset covered the atmospheric range from the surface up to 20 hPa, specifically focusing on model levels 35 to 137. Our area of interest, centered around the EAR location as depicted in Fig. 1, was defined as a 2-degree by 2-degrees square region. All data from this box are used to assess spatial variability in tropospheric winds over this area. However, data from the grid point nearest to the EAR location (centered at 0.25S, 100.25E) are emphasized and used in direct comparison between EAR observations and ERA-5 representation of tropospheric winds.

In order to harmonize the vertical wind data from ERA-5 (derived in pressure coordinates and therefore provided in Pa/s) with EAR data measured in Cartesian coordinates and provided in units of meters per second (m/s), we employed the hydrostatic equation. This conversion was performed using the multi-year-mean temperature profile representative of the extended boreal winter, derived from atmospheric soundings conducted in Padang.

## 6 Large-scale variability indices

This study explores the variability of wind patterns associated with different sub-seasonal and climatic phenomena, with the latter defined by global or local indices that represent the conditions of these patterns. Phenomena of interest include ENSO, QBO, MJO and CCKW events. ENSO occurrences were detected utilizing monthly anomalies in the Niño 4 Sea Surface Temperature (SST) index acquired from the National Oceanic and Atmospheric Administration (NOAA) Global Climate Observing System. Months exhibiting anomalies surpassing 0.5 were categorized as El Niño months (987 days), whereas those with anomalies below −0.5 were labeled as La Niña months (539 days). QBO episodes were discerned through examination of the 50 hPa QBO index data. This index is derived from the zonally averaged equatorial zonal wind anomalies relative to the period spanning 1991 to 2020, obtained from NCEP/NCAR reanalysis (Kalnay et al. 1996). The QBO index data were sourced from NOAA's Climate Prediction Center. Months with positive anomalies in the index were identified as westerly QBO phases, while those with negative anomalies were designated as easterly QBO phases. A total of 1224 days fell under the westerly phase category, and 1104 days were classified as easterly phase.

Because of its proximity to the Indian Ocean, West Sumatra is prone to experience an influence of eastward-propagating atmospheric patterns such as the MJO and

CCKWs. These sub-seasonal modes affect tropospheric wind patterns over the MC region, and interact with local diurnal cycle (Baranowski et al. 2016a). This study also examined how changes are represented by ERA-5 data. The presence of MJO activity was assessed using the Realtime Multivariate MJO (RMM) index (Wheeler and Hendon 2004), where amplitudes below 1 indicated the absence of MJO activity, while amplitudes exceeding 1 signified active intraseasonal convection in one of its eight phases. Special attention was given to phases associated with increased convective activity over and near Sumatra (Peatman et al. 2014), namely RMM phases 1–4, as well as phase 5, during which intraseasonal convection is notably suppressed in the region. Over the duration of the study, there were 136 days classified as phase 1, 200 days as phase 2, 275 days as phase 3, 253 days as phase 4, and 264 days as phase 5. The RMM amplitude remained below 1 for 951 days.

CCKW activity at the EAR longitude (100°E) was assessed using CCKW trajectories derived from satellite precipitation estimates (Baranowski et al. 2016a, b), which involved averaging the Tropical Rainfall Measurement Mission 3B42 precipitation estimates (Huffman et al. 2007) over the equatorial band spanning from 2.5°S to 2.5°N and filtering it in order to retain only CCKW-related spectrum (Wheeler and Kiladis 1999). A CCKW trajectory was considered valid if it existed between longitudes 90E and 110E and if its precipitation anomaly at 100E exceeded 5 mm/day. This threshold corresponds to approximately 2 standard deviations of zonally-averaged CCKW precipitation variations, ensuring the inclusion of only significant events. Through this method, we identified and analyzed a total of 150 CCKW events during NDJFM between 2001 and 2019. For each CCKW trajectory, a reference date (day 0) was defined as the day when it passed the 100E longitude mark.

## 7 Methods

This study employs both direct multi-year averages and composite analysis based on periods of activity of specific large scale modes. The latter, has been performed on data after removal of seasonal cycle. The multi-year seasonal cycle was determined by taking the mean value plus the first three annual harmonics across the entire dataset, encompassing all seasons.

In order to analyze the mean diurnal cycle, a composite diurnal evolution was computed based on many days, specific to a given composite (e.g. long-term mean, El-Nino days, etc.). Subsequently, this composite diurnal evolution was further analyzed and decomposed in accordance with Eq. (1):

$$F(t) = A_m + A_d \cos\left(2\pi \frac{t - \varphi_d}{24}\right) + A_s \cos\left(2\pi \frac{t - \varphi_s}{12}\right) + R(t) \quad (1)$$

where  $t$  indicates Local Standard Time (LST) in hours;  $A_m$  is a mean value of a given wind component  $F$ ;  $R(t)$  indicates the remaining terms;  $A_d, A_s, \varphi_d, \varphi_s$ —corresponds to amplitudes and phases of the diurnal and semidiurnal cycle, respectively. Phase indicate the time when a given component reaches its maximum (e.g. phase of diurnal cycle  $\varphi_d = 15$  LST means that a diurnal mode reaches its maximum at that time). This decomposition has been applied to all wind components based on EAR and ERA-5 data.

In order to assess how large-scale phenomena affect tropospheric winds, we calculated anomalies averaged over specific days, such as El Niño days, to illustrate variations in tropospheric wind patterns compared to their typical structure during these events. Given the varying number of days used for this composite analysis, we employed a 1000-member bootstrap resampling method to estimate uncertainties in mean value calculations for ENSO, QBO, MJO and CCKWs. These uncertainties are represented by standard error of the bootstrap mean and marked by shaded areas in the respective figures.

At the end of the study, a comprehensive comparison between ERA-5 and EAR data, encompassing variability associated with all analyzed modes, is performed in order to better illustrate the differences between the two datasets. First profiles of range of variability based on ERA-5 and EAR data associated with each mode have been calculated as a difference between a maximum and a minimum value at each altitude. Then, it was averaged within five distinct tropospheric layers centered at: 750 hPa, 450 hPa, 300 hPa, 200 hPa, and 160 hPa. This has been done for each variable and a large-scale mode independently. As a result, ranges of variability for a given mode based on each dataset (ERA-5 or EAR) have been derived. Each such difference is associated with estimated errors. Then from the range of variability derived from ERA-5 we subtract the range of variability derived from EAR. Values close to 0 indicate that variability in both data sources compares well. Positive values indicate that ERA-5 overestimates variability in comparison with observations, while negative values point to underestimation of variability by the reanalysis.

## 8 Results

### 8.1 The mean vertical profiles of wind components

A typical extended boreal winter wind and thermodynamic profiles in West Sumatra are presented in Fig. 1. The average temperature profile derived from soundings (red solid line in Fig. 1b) exhibits a linear decrease in temperature

from approximately 23 °C at 1000 hPa to −70 °C at 15 hPa (the average lapse rate ~6.6 °C/km). The 0 °C isotherm is found at around 550 hPa. A similar profile from reanalysis data has very similar shape to the soundings data (orange line in Fig. 1b), but shows a cold bias with the largest differences (on the order of 3 °C) occurring in the lower troposphere (below 600 hPa). The average specific humidity profile from soundings shows quick decrease of the tropospheric moisture content with altitude. While shape of a specific humidity profile from ERA-5 is similar to the observed one, a dry bias is apparent. The difference at 1000 hPa is 3 g/kg, at 500 hPa it is 1.5 g/kg and asymptotically goes to zero in upper and drier troposphere. Using temperature profile from soundings and relative humidity profile from ERA-5, we recalculated specific humidity profile without cold bias. We estimate that a vast majority of the observed ERA-5 dry bias is a result of a observed difference in temperature between the two data sources.

All wind components show shear across the troposphere. The zonal wind profile measured by EAR (green line in Fig. 1c) is dominated by westerly flow in the lower troposphere and easterly flow in the upper troposphere (above 200 hPa). EAR data show that westerly flow increases with height between 800 hPa and around 700 hPa, where it reaches a maximum of around 3 m/s. Above that level, zonal wind decreases nearly linearly with altitude up to around 250 hPa, where it reaches −6 m/s. EAR measurements of zonal wind at higher altitudes show little variability. Reanalysis zonal wind profile from the nearest grid point (red line in Fig. 1c) show similar shape up to 250 hPa. All the ERA-5 profiles in the vicinity of the EAR site show similar structure throughout the troposphere. Although the shape of reanalysis profiles is similar to EAR observations, spread across neighbor locations (grid points shown in Fig. 1) is apparent. It can be quantified by the altitude at which a zonal wind profile shifts from westerlies to easterlies. This level is around 500 hPa for EAR data, while reanalysis shows a spread between 650 and 500 hPa. It is noteworthy that profiles for ocean points (blue lines in Fig. 1c) shift towards larger magnitudes, while points over land (yellow and black lines in Fig. 1c) show lower magnitudes than the EAR data up to 250 hPa. At the upper levels, above 250 hPa, reanalysis and EAR data diverge. Mean profile of zonal wind from soundings data indicate westerlies in the lower troposphere and easterlies in the middle and upper troposphere, similarly to EAR and ERA-5. However, a notable distinction lies in the magnitude of the wind data from soundings, which is significantly greater than that of the EAR dataset. It is worth highlighting that the altitude at which the average zonal wind attains a velocity of 0 m/s in sounding data closely aligns with that observed in the EAR dataset, occurring at approximately 500 hPa.

The meridional wind profile observed by EAR (green line in Fig. 1d) shows the strongest northerlies closest to the lowest data-available height. Above, the meridional wind speed decreases and reaches 0 m/s at 350 hPa. In the upper troposphere, there is an increase of southerlies (shear) up to about 2 m/s around 250 hPa, while above that level stabilization is apparent. The meridional wind profile retrieved from the grid point nearest to EAR location in reanalysis data (red line in Fig. 1d) shows remarkable agreement with EAR observations. At the upper level (above 250 hPa) some discrepancies are visible, but even there the vertical profile of meridional wind agrees with EAR data in terms of direction of wind. In the vicinity of the EAR site, ERA-5 data show scatter below 800 hPa. For points located in the lowlands (yellow lines in Fig. 1d), strong northerly winds in the lowest layer of the atmosphere are observed. Their values significantly exceed velocities estimated over the ocean or mountains (blue and black lines in Fig. 1d). Similar to zonal wind profiles, the mean meridional wind profiles from sounding data exhibit similarities to those obtained from EAR. However, a striking difference lies in the magnitude of the meridional wind data obtained from soundings, which consistently exceeds that of the EAR by over threefold throughout the majority of the troposphere. The altitude at which the mean meridional wind in sounding data change direction closely approximates the corresponding altitude in EAR data, occurring at approximately 400 hPa.

Therefore, the EAR and the reanalysis data show a similar structure of the mean horizontal wind profiles, especially in the middle troposphere (600–200 hPa). The horizontal wind changes direction from northwest to southeast between 500 and 350 hPa. It should be noted, that this change occurs above freezing level (orange line in Fig. 1b), where the tops of the cumulus congestus clouds are most frequently observed (Wall et al. 2013).

A completely different result arises from a comparison between EAR and ERA-5 vertical wind profiles. The EAR data (green line in Fig. 1e) show downward motions below 400 hPa, with maximum subsidence around 700 hPa, and upward motions above 400 hPa. The vertical shear of the vertical wind component decreases above 500 hPa. This change occurs nearby the altitude where horizontal wind shifts direction and tops of cumulus congestus are the most common. Reanalysis data show significant scatter between different grid points in the vicinity of EAR. The profile corresponding to the point nearest to the EAR location (red line) shows upward motions throughout most of the troposphere with one of the largest ascent values among analyzed reanalysis data. Overall, points over ocean (blue lines) show larger ascent values than points over lowlands on the eastern side of the Barisan Mountains (yellow lines). However, they all show the same structure of ascending motions throughout the entire troposphere.

Some ERA-5 grid points over mountains (black lines) show structure vaguely resembling EAR observations with descending motions in the lower troposphere and ascending motions in the middle troposphere. However, both magnitude and shape (altitude of maximum and minimum vertical velocity) are still biased in comparison with observations, and there is no consistency between grid points over mountains.

The mean vertical wind structure in EAR data aligns with the diabatic heating profile associated with a mixture of stratiform and convective clouds in a typical cloud population, while the ERA-5 data profiles consistently resemble diabatic heating profile of deep convective clouds without stratiform contribution in the troposphere. Hence, ERA-5 representation of typical cloud population during extended boreal winter over central-west Sumatra appears biased towards deep convection.

This assessment of the reanalysis representation of vertical wind profile over Sumatra agrees with previous studies, which reported discrepancies between radar derived vertical wind profiles and reanalyzes products (Uma et al. 2021). EAR observations show similar structure of vertical wind to measurements in Christmas Island (Equatorial Pacific: 20N, 1570W) (Gage et al. 1992), who also showed the dominance of subsidence in the lower troposphere and upward motions in the upper troposphere. However, radar observations in Christmas Island showed ascending motions dominating in the 800–650 hPa layer. On the west coast of Sumatra, this altitude range is characterized by the strongest subsidence throughout the profile. This distinction can be explained through interactions with clouds and precipitation, which show an apparent diurnal cycle over Sumatra (Qian 2008; Baranowski et al. 2016a) with the maximum occurring in the afternoon over the EAR site and during the night over the ocean adjacent to Sumatra (Baranowski et al. 2019). Strong downdrafts accompanying convective activity (Houze 2004) and precipitation-driven cold pools (Drager and van den Heever 2017) can explain descending air motions in the lower troposphere observable by the EAR. Similar effects in the tropics have been previously reported (Johnson 1982; Gage et al. 1991). It should be noted that such distinct vertical structure is absent from the ERA-5 vertical wind data.

To conclude, ERA-5 horizontal wind profiles agree well with EAR observations. Their vertical structure compares well with the soundings as well, but magnitudes of sounding retrieved horizontal winds are larger than either EAR or ERA-5 data. ERA-5 vertical wind data show significant differences relative to EAR observations. From this point forward, the analysis will be based on comparison between EAR and the nearest ERA-5 grid point (centered at 0.25S, 100.25E).

## 8.2 Diurnal variations of winds

In this section, we analyze the average diurnal cycle in Local Standard Time (UTC + 7h) based on observations from EAR and data from ERA-5 reanalysis. To achieve this, the daily mean variation of anomalies for all wind components from both data sources was decomposed using Eq. (1), yielding diurnal and semi-diurnal mode amplitudes and phases at each altitude. This decomposition matches well the original diurnal variation (over 95% pattern correlation for horizontal winds, around 90% for vertical wind). The results of the analysis are presented in Fig. 2.

The amplitudes of the diurnal cycle of zonal wind, in both EAR and ERA-5 data, increase with height from around 0.1 m/s to 0.6 m/s between 800 and 250 hPa. Above that layer, EAR amplitude shows an upward trend with altitude, while in ERA-5, this amplitude decreases. The diurnal cycle phases align well between the two data sources below 250 hPa (between 18 and 24 LST below 400 hPa and between 0 and 12 LST above 400 hPa). Above 250 hPa, larger discrepancy in diurnal cycle phases between EAR and ERA-5 is evident—the radar indicates maximum westerly wind around 12 LST, whereas ERA-5 data is shifted towards 00 LST.

For the meridional wind, below 250 hPa, the amplitudes of the diurnal cycle in both data sources range between 0 and 0.2 m/s. Above 250 hPa, an increase in the amplitude values is observed in both datasets; however, in ERA-5, this increase is more rapid, reaching values above 0.5 m/s at around 150 hPa. The phase of the diurnal wind cycle agrees well between both data sources in the lower and middle troposphere. At approximately 200 hPa and above, variations in the zonal wind become apparent. The EAR phase of the diurnal cycle remains between 5 and 10 LST, while for ERA-5, it shifts from 4–5 LST around 200 hPa to earlier hours in the upper layers. At 100 hPa, the phase occurs at 10 LST. In contrast, for the meridional wind, differences in the phases of the diurnal cycle are only noticeable in the layer around 200 hPa.

Since the diurnal evolution of weather over Sumatra is strictly related to the Barisan Mountains (Mori et al. 2004), the wind in the direction perpendicular to the mountain range is also considered in this analysis. The diurnal cycle of this wind agrees very well between both data sources. Below 250 hPa, minimal differences between EAR and ERA-5 in diurnal cycle amplitude are observed (around 0.2 m/s). Above 250 hPa, diurnal cycle amplitudes decrease for ERA-5, while for EAR, they increase with height. It mimics behavior observed for zonal wind, as this component contributes more to the variability in the direction perpendicular to the mountain range. The perpendicular wind also exhibits the highest phase agreement of the diurnal cycle. The phase values are similar to those of the zonal wind, with

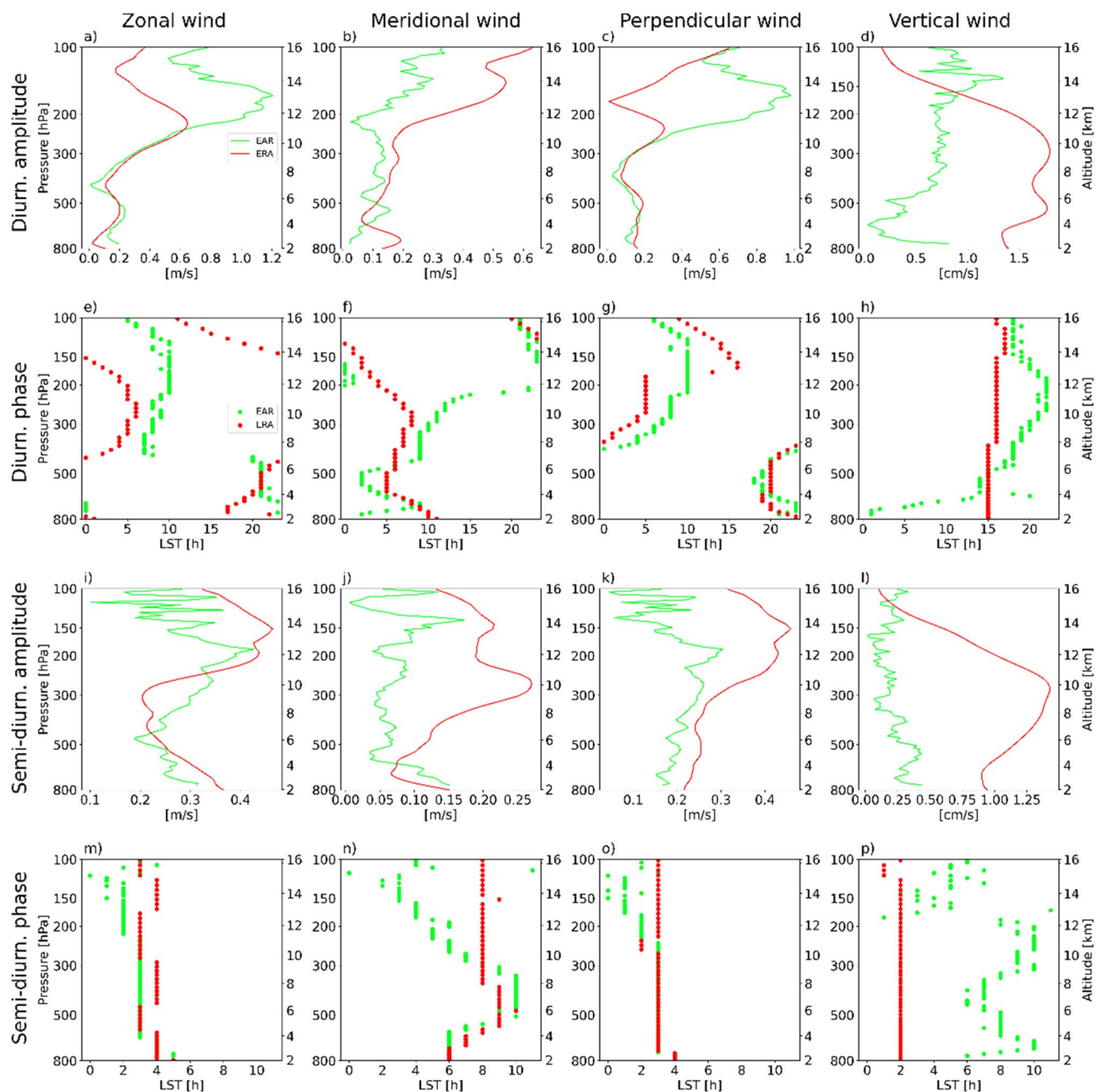


**Fig. 2** Diurnal and semi-diurnal wind cycles over the EAR location. Panels **a–d**: amplitudes of the diurnal cycle, panels **e–h** phases of the diurnal cycle (hour of maximum values), panels **i–l** amplitudes of the diurnal cycle, panels **m–p**: phases of the semi-diurnal cycle. Green

lines and dots correspond to results for EAR, while red lines and dots correspond to results for ERA-5. Perpendicular wind is defined as a wind along an axis perpendicular to the west coast of Sumatra and Barisan Mountains in the vicinity to the EAR location

differences between EAR and ERA-5 being significantly smaller. Hence, variability in the direction perpendicular to the mountain range, which drives local variability in circulation and related evolution of cloud field and precipitation patterns (Mori et al. 2004), agrees well between EAR and ERA-5 data.

Results for the diurnal wind cycle of vertical wind in ERA-5 show an amplitude of about 1.5 cm/s below

250 hPa, followed by a decrease with altitude. In contrast, in EAR, this amplitude is smallest in the lower troposphere (below 0.5 cm/s), increasing afterward to remain relatively constant around 0.8 cm/s from 400 hPa upwards. The diurnal cycle phase in ERA-5 remains unchanged with altitude, oscillating around 15–16 LST. In EAR, this phase notably varies with altitude: between 800 and 400 hPa, a

shift from 1 to 19LST is observed, and subsequently, this phase persists in the evening hours at higher altitudes.

Examining the semi-diurnal cycle of horizontal wind components, the phase once again demonstrates a remarkable alignment between EAR and ERA-5 at all altitudes for zonal wind and below 200 hPa for meridional wind. Conversely, the semi-diurnal zonal wind amplitude shows similar dependence on altitude in both data sources. However, for meridional wind, the reanalysis reveals significantly higher amplitudes in the mid and upper troposphere.

Comparison for vertical wind variability shows fundamental discrepancies between EAR and ERA-5. Both diurnal and semi-diurnal amplitudes are notably greater in ERA-5, and dependence of their phases on altitude differs as well. While EAR demonstrates a clear dependence of diurnal and semidiurnal cycle phase on altitude, the phase in ERA-5 remains nearly constant across all heights. Diurnal variability in vertical wind in both ERA-5 and EAR shows a single maximum throughout the day, as phases of diurnal and semidiurnal cycles align during the maximum. It is noteworthy that lack of phase-shift with altitude is consistent

among all ERA-5 grid points in the vicinity of EAR (all dots inside the black square in Fig. 1a). This indicates that in ERA-5 convection tends to quickly pop up at a given time (e.g. 15LST for the grid point nearest to the EAR location, Fig. 3h) rather than evolve throughout the day as in EAR observations. On the other hand, the phase of diurnal cycle of vertical wind ( $\varphi_d$ ) derived from EAR observations agrees well with diurnal stage development of a cloud field in West Sumatra from shallow cumulus ( $\varphi_d$  below 3 km is less than 12LST) through cumulus congestus ( $\varphi_d$  at 4 km is 13LST), deep convection ( $\varphi_d$  at 8 km is 19LST) and connective anvils ( $\varphi_d$  at 10 km is 21LST) (Szkolka et al. 2023). Hence, these differences underscore the complexity of representing vertical wind behavior and its coupling with parameterized cloud development in a modelled environment. They call for further investigations into the underlying physical mechanisms responsible for the observed bias, especially in parametrization of convection.

In summary, Fig. 2 provides a comprehensive overview of the diurnal and semi-diurnal wind cycles for various components and altitudes. The consistent alignment of phases

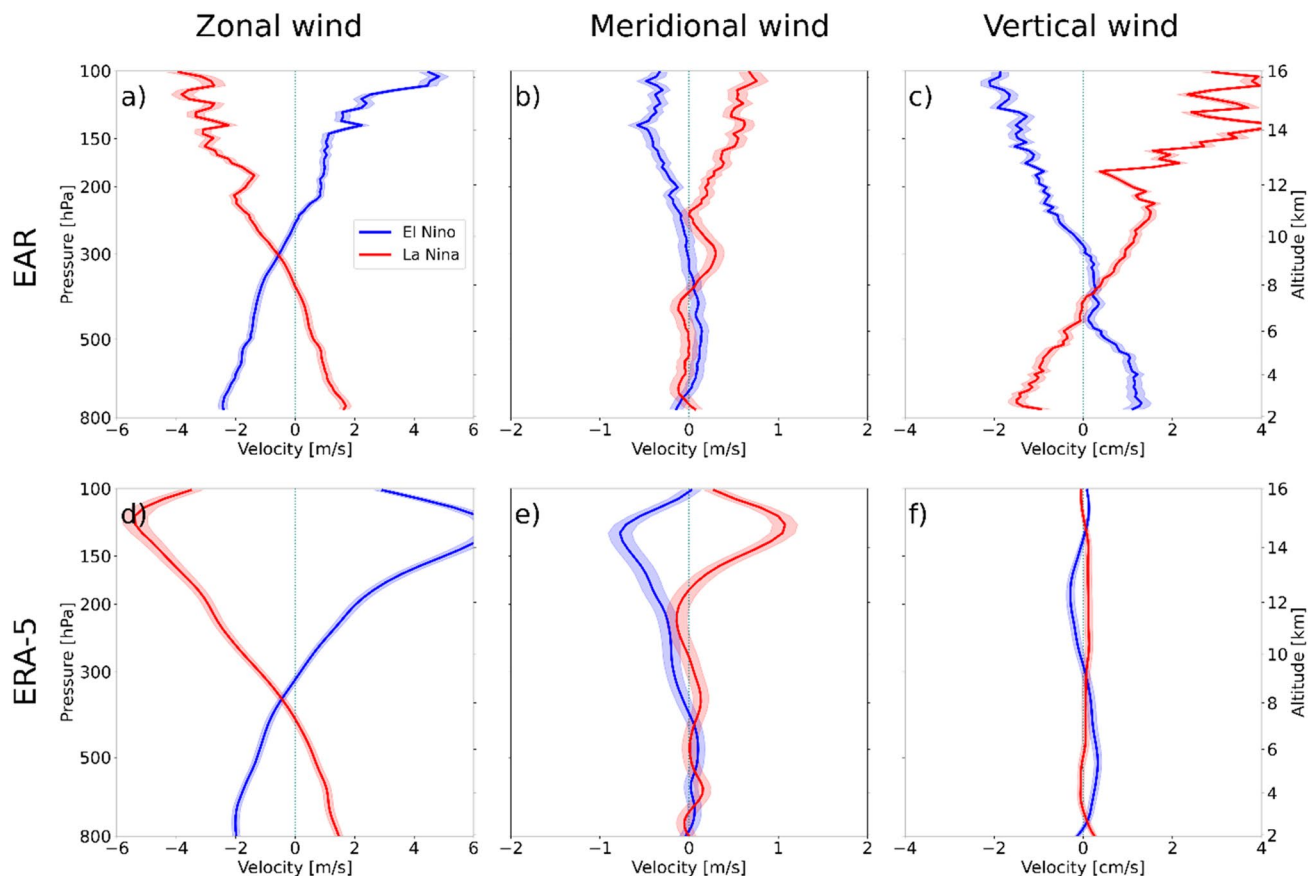


**Fig. 3** Averaged anomalies of zonal wind (a, d) meridional wind (b, e) and vertical wind (c, f) for El Niño (blue lines) and La Niña (red lines). The upper row presents data from EAR, while the lower row

presents data from ERA-5. Shadings corresponds to the standard errors of the mean calculations. Panels a–c in this Figure are a modification of the Fig. 5 in Szkolka et al. (2023)

for horizontal wind components emphasizes the robustness of these patterns, while the altitude-dependent differences and disparities in vertical wind characteristics highlight the significant role of observations in that region in understanding the atmospheric dynamics. These findings shed light on the challenges and potential biases in utilizing diurnal wind cycles for various applications and emphasize the need for cautious interpretation of results derived from different datasets. The following sections will be devoted to investigation of how the typical diurnal and semi-diurnal cycles change in response to large-scale atmospheric forcing.

### 8.3 ENSO-related variability

In subsequent sections, we will examine the influence of large-scale phenomena such as ENSO, QBO, MJO, and CCKW on the average profile and diurnal cycle of all wind components, utilizing data from EAR and ERA-5. Anomalies will be determined relative to the climatological norms spanning from 2001 to 2019, with a specific emphasis on the initial three harmonic components. Profiles of mean

anomalies are represented in Figs. 3, 5, and 7, while Figs. 4, 6, and 8 depict amplitude anomalies of the diurnal cycle derived from EAR and ERA-5, computed for particular days coinciding with ENSO, QBO, and MJO phases, as well as days preceding and following the passage of CCKWs. The amplitude anomalies of the diurnal cycle are calculated as the disparity between the daily-averaged anomaly evolution for a specific phase/day and the amplitude depicted in Fig. 2. Shading indicates the margin of error in the calculation of the respective mean values.

The average anomaly profiles of all wind components for ENSO based on data from EAR and reanalysis are shown in Fig. 3. In the zonal wind, both radar and reanalysis show westerlies anomalies in the lower troposphere and easterlies anomalies above 300 hPa during La Niña events (Fig. 3a). El Niño is characterized by easterlies anomalies in the lower troposphere and westerlies in the upper troposphere. This is consistent with anomalously strong convection over the western Pacific Ocean and Maritime Continent during La Niña, and therefore stronger low-level westerlies and upper-level easterlies over Sumatra (Gushchina et al. 2020).

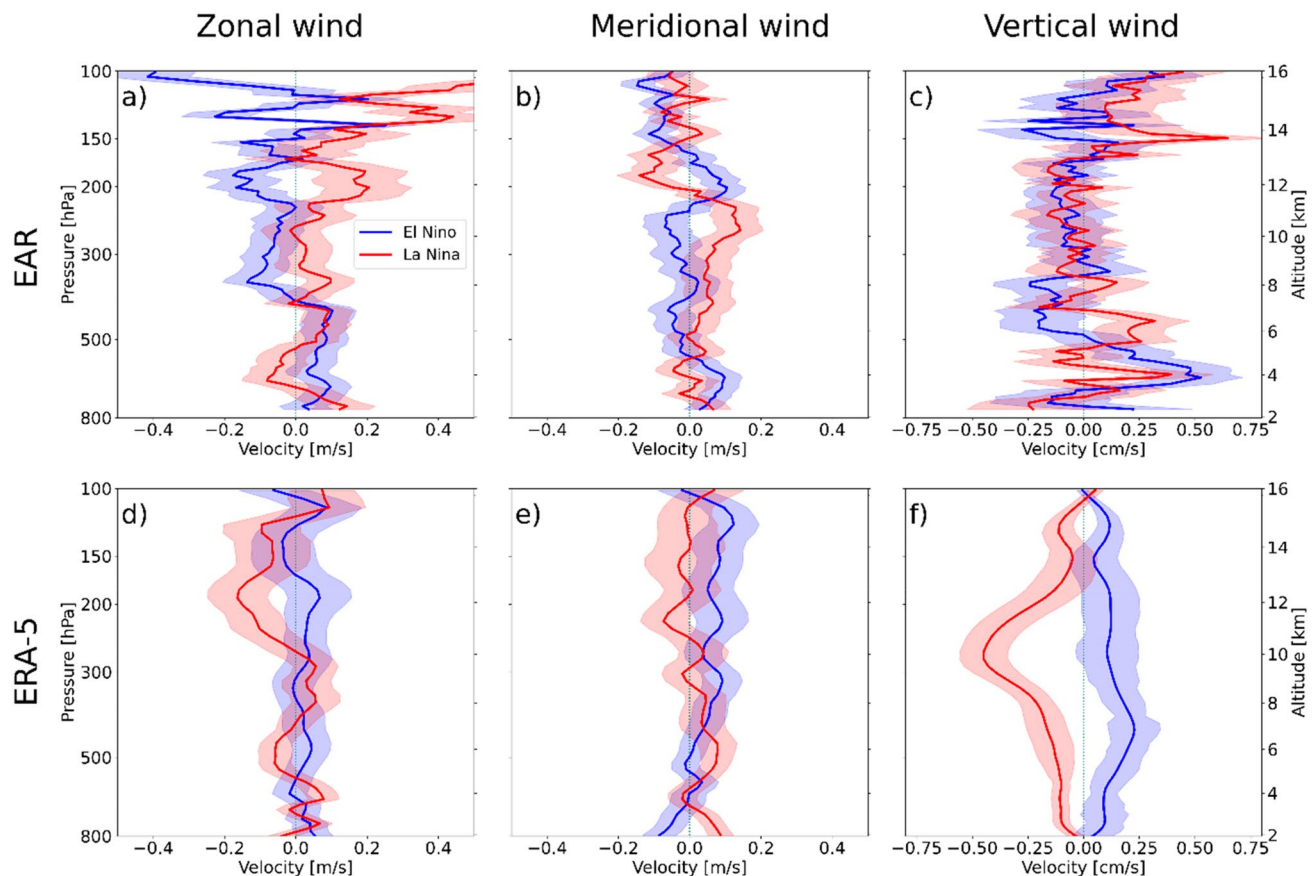


**Fig. 4** Anomalies of the amplitude of the diurnal cycle for El Niño (blue lines) and La Niña (red lines) in zonal wind **a, d**, meridional wind **b, e**, and vertical wind **c, f** for El Niño (blue lines) and La Niña

(red lines). The upper row depicts information from EAR, whereas the lower row displays data from ERA-5. Shadings corresponds to the errors in mean calculations

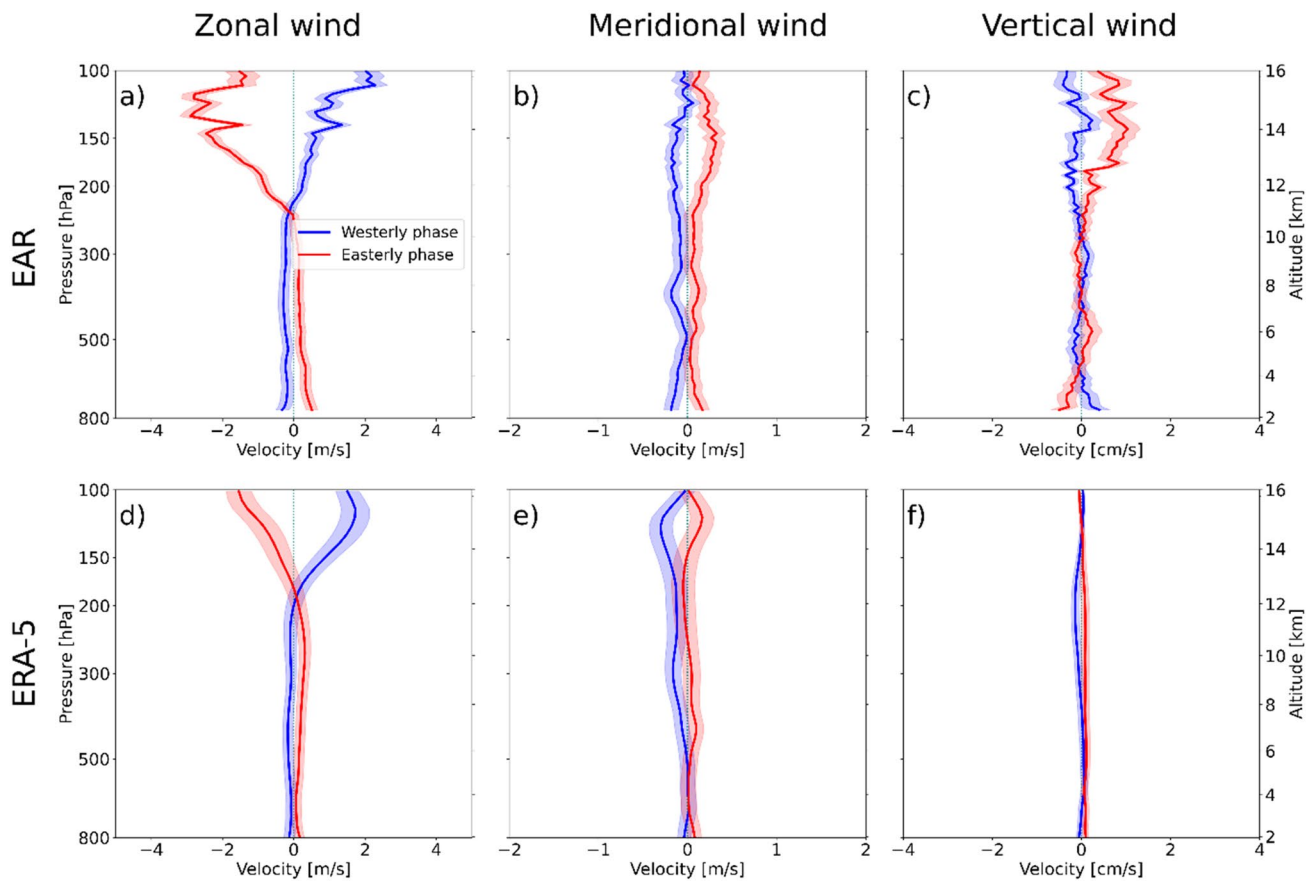


**Fig. 5** Same as Fig. 3, but for QBO phases

Both data sources show minimal variability in the average meridional wind during ENSO below 250 hPa. In the upper troposphere, El Niño (La Niña) is characterized by northerlies (southerlies) anomalies, increasing with altitude to around 0.5 m/s, which is visible in EAR and ERA-5. These changes in the meridional wind are consistent with the outflow in the upper troposphere, related to convection occurring south of the EAR site. Such conditions are prevailing during the extended boreal winter season.

In vertical wind component (Fig. 3c), there is a discrepancy between EAR and ERA-5 results. Radar data exhibits noticeable upward anomalies in the lower troposphere and downward anomalies in the upper troposphere during El Niño events, while it shows downward anomalies in the lower troposphere and upward anomalies in the upper troposphere during La Niña events. Anomalies observed by EAR are consistent with precipitation anomalies over this region during ENSO activity (Reid et al. 2012). Increased convective cloud population and decreased amount of stratiform clouds during El Niño can lead to increased upward movements in the lower troposphere and downward anomalies in the upper troposphere. The opposite occurs during La Niña events. Reanalysis

indicates westerly anomalies below 300 hPa and easterly anomalies between 300 and 120 hPa during El Niño, with the opposite pattern occurring during La Niña. The magnitude of these variations are much smaller than in EAR at all altitudes.

In Fig. 4, anomalies in the amplitude of the diurnal cycle of all wind components based on radar data and reanalysis are shown. For zonal wind, both data sources show variability within the range of  $\pm 0.2$  m/s. During El Niño, both data sources indicate an increased amplitude of the diurnal cycle below 400 hPa. Above that level EAR shows a decreased amplitude with minimum values in the upper troposphere. During La Niña in the upper troposphere EAR observations indicate increased diurnal cycle amplitude of zonal wind. In contrast, ERA-5 shows increased diurnal cycle amplitude of zonal wind in the upper troposphere during El Niño and increased during La Niña.

For meridional wind, radar data shows increased amplitude in the lower and upper troposphere during El Niño, increased amplitude in the middle troposphere and decreased amplitude in the upper troposphere during La Niña. In contrast, reanalysis data during both ENSO phases indicates increased amplitude in the lower troposphere and increased

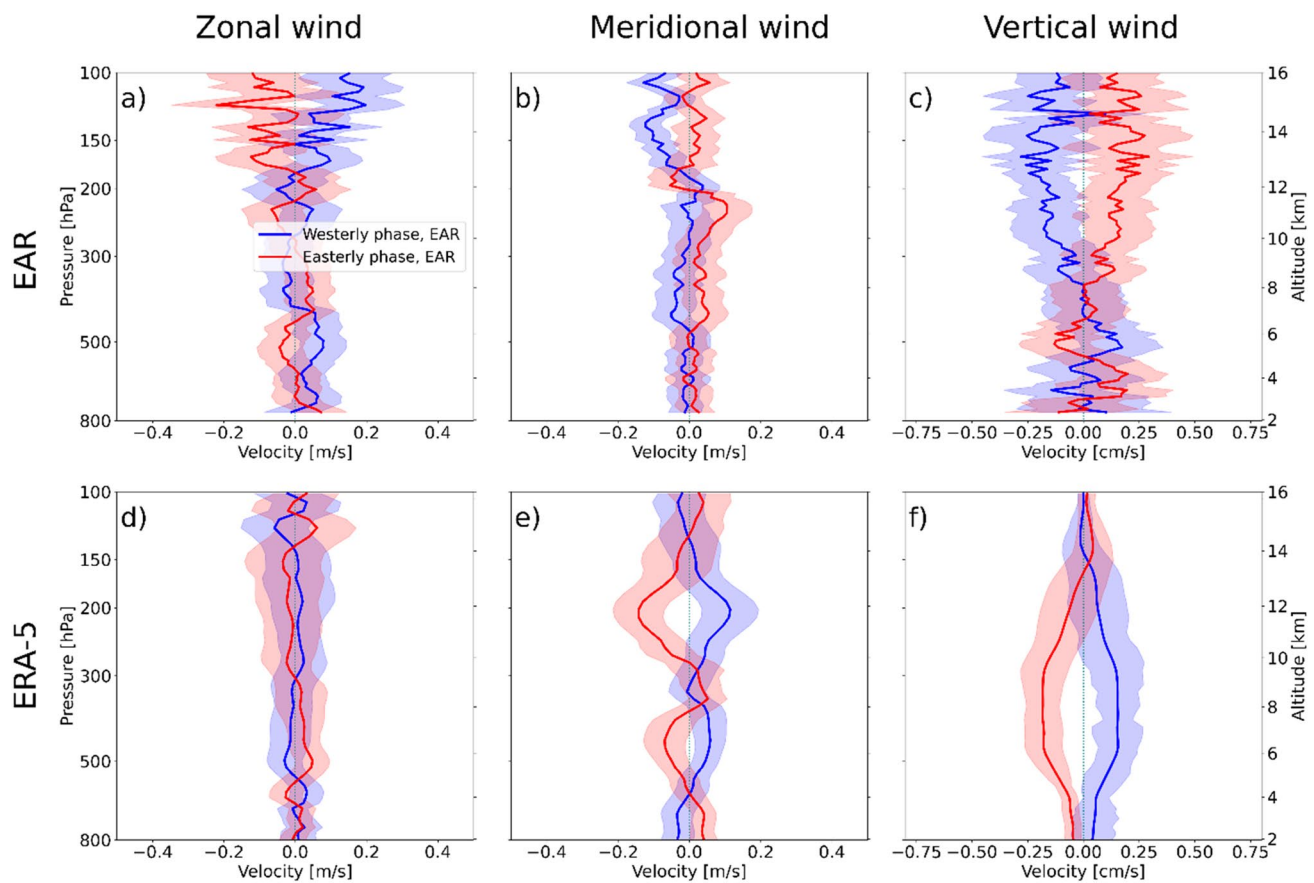


**Fig. 6** Same as Fig. 4, but for QBO phases

(decreased) amplitude in the upper troposphere during El Nino (La Nina).

In vertical wind, radar data show an increase of approximately 0.4 cm/s around 4 km and about 0.2 cm/s above 13 km during both ENSO phases. Both ENSO phases also exhibit slightly decreased amplitudes in the layer between 7 and 13 km. The difference between the two phases occurs around 6.5 km: during La Nina, the amplitude is increased, while during El Nino, it is decreased by approximately 0.2 cm/s. Reanalysis yields significantly different results from radar data. Decreased amplitudes of diurnal amplitudes during La Nina occur throughout the troposphere with minimum of about  $-0.5$  cm/s around 10 km. During El Nino all troposphere exhibit increased amplitude of diurnal cycle with maximum of 0.25 cm/s around 7 km. This is consistent with the variations in convective cloud population due to ENSO activity—more deep convection (with maximum heating around 5 km above ground (Schumacher et al. 2004)) during EL Nino and less deep convection during La Nina (Szkolka et al. 2023).

To sum up, mean horizontal wind anomalies due to ENSO activity show similar structures in ERA-5 data and EAR observations, but both data sources differ in representation

of tendencies in diurnal cycle amplitude of zonal and meridional wind. Vertical wind anomalies profiles of ERA-5 data show almost no variation due to ENSO, especially when compared to EAR. Furthermore, the results for vertical wind diurnal cycle amplitude significantly differ between EAR and ERA-5.

#### 8.4 QBO-related variability

Figure 5 illustrates the variability of the mean anomalies of all wind components influenced by the Quasi-Biennial Oscillation (QBO) as observed by EAR and ERA-5 datasets. Both data sources reveal a minimal impact of QBO phases on winds below 250 hPa. In the zonal wind component, EAR exhibits westerlies anomalies above 250 hPa during the Westerly phase, which increase with altitude, reaching approximately 0.5 m/s at 150 hPa. Conversely, during the Easterly phase, we observe anomalous easterlies above 250 hPa in EAR, increasing in magnitude to around  $-2.5$  m/s at 150 hPa. Interestingly, this effect is much less pronounced in ERA-5. Specifically, significant changes are only evident in ERA-5 above 180 hPa, with variability confined to the range of  $\pm 1$  m/s. It should be noted that ERA-5

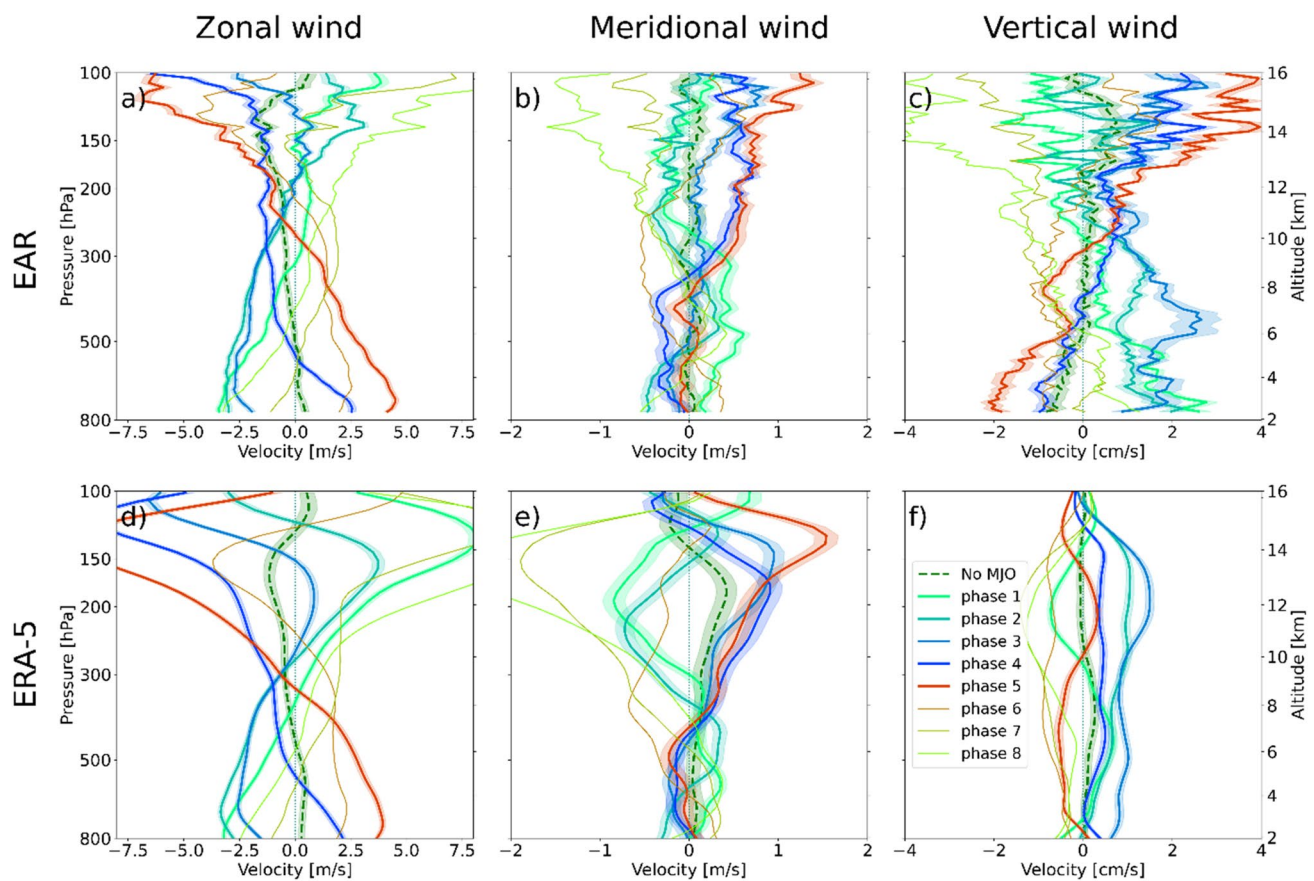


**Fig. 7** Same as Fig. 3, but for MJO phases. Panels **a–c** in this Figure are a modification of the Fig. 7 in Szkolka et al. (2023)

produces a clear QBO signal descending from the stratosphere to a vicinity of a cold point tropopause (Pahlavan et al. 2021a, b). EAR observations show that over western Sumatra QBO signal can be identified at 11 km, roughly 5 km below cold point tropopause at that location.

In the meridional wind component, during the Easterly phase, EAR displays southerlies anomalies above 250 hPa of about 0.3 m/s, whereas during the Westerly phase, we observe northerlies anomalies in this atmospheric layer, around 0.1 m/s. Reanalysis data show similar results to EAR data.

Similar to the zonal and meridional winds, EAR also demonstrates the impact of QBO on vertical wind in the upper troposphere. Above 250 hPa, upward anomalies become more prominent with altitude, reaching approximately 0.8 cm/s at 150 hPa during the Easterly phase. Conversely, during the Westerly phase, we observe minor downward anomalies in this tropospheric layer. The explanation for this behavior may lie in positive temperature anomalies in the lower stratosphere during the Westerly phase and negative anomalies during the Easterly phase (Baldwin et al. 2001). A cooler lower stratosphere leads to greater thermodynamic instability in the upper troposphere,

potentially resulting in increased upward motions. Previous studies have linked the vertical structure of sub-seasonal convective modes and their susceptibility to QBO (Sakaeda et al. 2020a). The observed influence of QBO on upper-tropospheric vertical winds in EAR data suggests that this relationship might be even stronger than what is visible in other datasets.

Figure 6 illustrates the anomalies in the diurnal cycle amplitude of all wind components in both phases of the QBO. In the EAR data, no significant deviations from the typical diurnal cycle amplitude are observed for zonal and meridional winds. However, substantial differences between the QBO phases become apparent in the vertical wind component above 300 hPa. During the easterly phase of QBO, the amplitude is increased by approximately 0.25 cm/s, while during the westerly phase, it is reduced by 0.25 cm/s.

Reanalysis data do not show significant changes in the diurnal cycle amplitude of zonal winds. In the case of meridional winds, significant differences are observed around 500 hPa and 200 hPa, only. In both of these layers, the westerly phase amplifies the diurnal cycle amplitude (by approximately 0.1 m/s at 500 hPa and about 0.15 m/s at 200 hPa), while the easterly phase reduces it (also by approximately

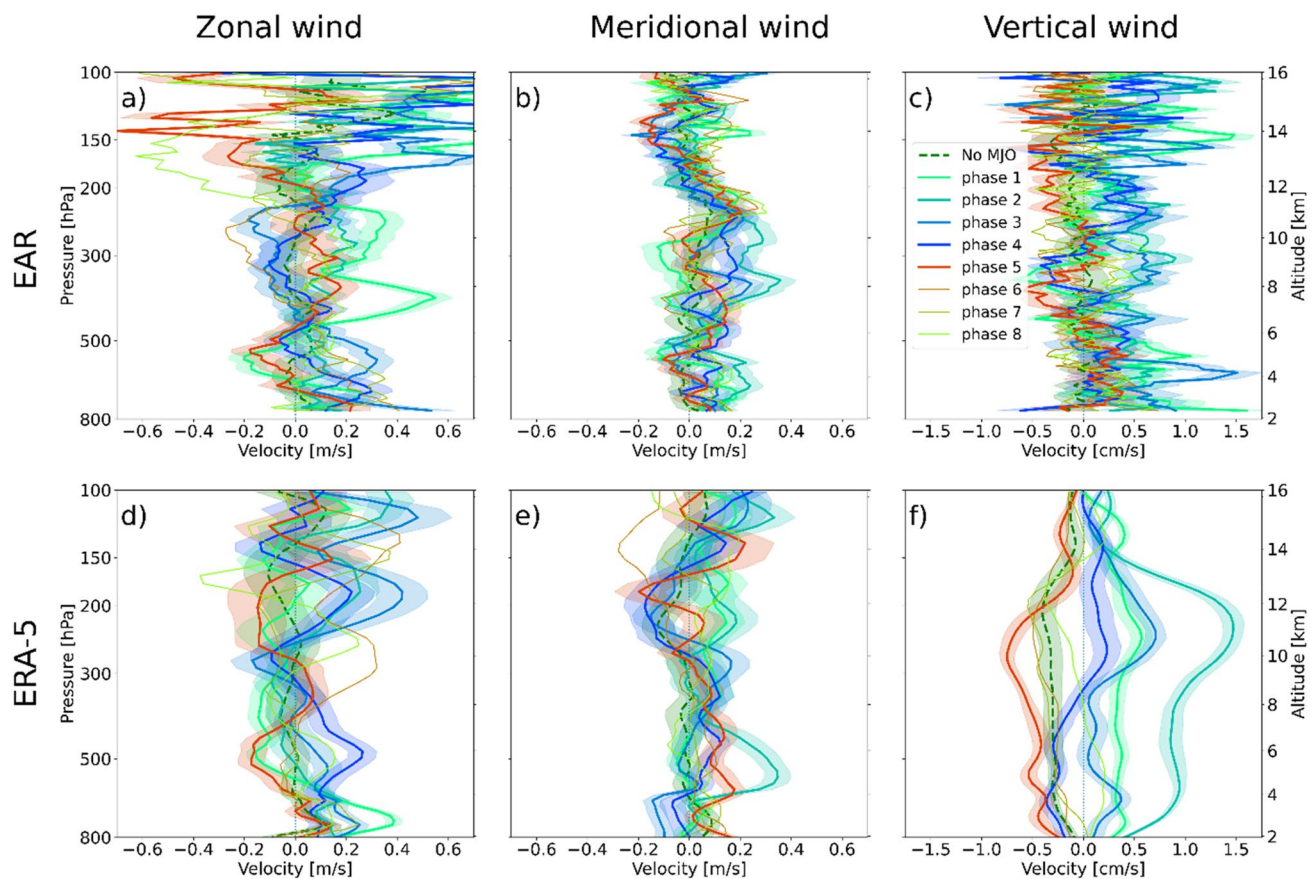


**Fig. 8** Same as Fig. 4, but for MJO phases

0.1 m/s at 500 hPa and about 0.15 m/s at 200 hPa). In the vertical wind component, the reanalysis shows an increased diurnal cycle amplitude during the westerly phase throughout the troposphere (with a maximum increase of about 0.25 cm/s between 500 and 300 hPa) and a decreased amplitude during the easterly phase (with the most significant reduction of about 0.25 cm/s in the 500–300 hPa layer).

Therefore, EAR data suggest that QBO penetrates the troposphere, affecting winds above 250 hPa, compared to ERA-5 data which show any variability higher up (up to 180 hPa). On the other hand, concerning the diurnal cycle, the reanalysis shows significant amplitude changes for meridional winds, which are absent from EAR data. Similarly, in the case of the diurnal cycle of vertical wind, the reanalysis indicates QBO's influence throughout the troposphere, while radar detects a significant impact only above 300 hPa.

### 8.5 MJO-related variability

Figures 8 and 9 present the results of an analysis for MJO related variability in tropospheric winds. Figure 7 presents the average anomalies of all wind components based on

radar data and reanalysis during an evolution of a composite MJO event. In zonal wind, both data sources show variability in the mean wind consistent with the known MJO structure (Kikuchi and Takayabu 2003; Zhang 2005; Morita et al. 2006), characterized by easterly anomalies in the lower troposphere and westerly anomalies in the upper troposphere ahead of convergence zone and opposite effect behind it. Below 300 hPa, the radar and reanalysis results are very similar. Above this level, radar and reanalysis exhibit the same variability in mean zonal wind between phases, however the magnitude of these changes is smaller for radar ( $\pm 3$  m/s) compared to reanalysis (over  $\pm 5$  m/s). Both data sources reveal a westward-tilted structure of a Madden–Julian Oscillation (MJO) as the shift in wind direction in the lower troposphere (e.g. from easterly to westerly anomalies) precedes changes in the middle and upper troposphere.

For meridional wind below 500 hPa, southerly anomalies are observed in EAR and ERA-5 during phase 1, while northerly anomalies occur in phases 3, 4, and 5. Around 400 hPa, EAR data show southerly anomalies in phase 1 and northerly anomalies in phase 6. In this layer, ERA-5 data indicate northerly anomalies in phases 6 and 7. In EAR data, southerly anomalies are observed in phases 4

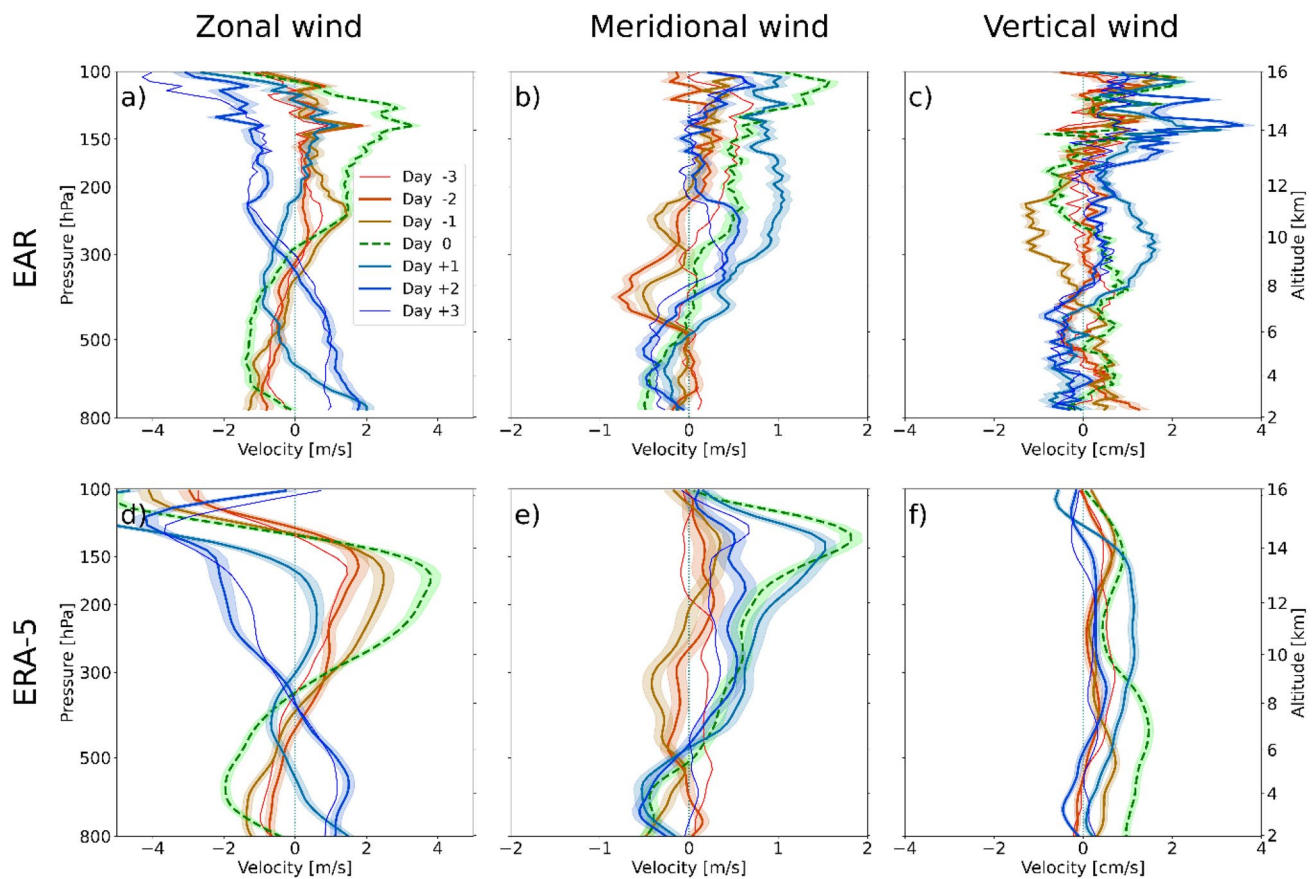


**Fig. 9** Same as Fig. 3, but for CCKW activity. Each line corresponds to specific day prior to and after CCKW event—Day 0 refers to the day of CCKW passage over EAR site. Panels a–c in this Figure are a modification of the Fig. 9 in Szkolka et al. (2023)

and 5 above 300 hPa, while northerly anomalies occur in phases 3, 6, 7, and 8. In contrast, ERA-5 in this layer shows southerly anomalies in phases 3, 4, 5, and northerly anomalies in the remaining phases. These variations in the meridional wind align with the lower tropospheric inflow and upper tropospheric outflow associated with convection occurring south of the EAR site, a pattern typical of the extended boreal winter season. Similar to zonal wind, the variability of mean meridional wind in the upper troposphere is smaller in radar ( $\pm 1$  m/s) than in reanalysis ( $\pm 2$  m/s).

In terms of vertical wind, EAR data show upward anomalies below 300 hPa in phases 1, 2, and 3, and downward anomalies in phases 5 and 6. Above 300 hPa, upward anomalies are observed in phases 4 and 5, while downward anomalies occur in phases 1, 6, and 7. On the other hand, reanalysis indicates upward anomalies in phases 1, 2, 3, and 4, and downward anomalies in phases 5, 6, and 7 below 250 hPa. In the upper troposphere, upward anomalies are visible in phases 2, 3, 4, and 5, with downward anomalies in phases 1, 6, and 7. Reanalysis shows less vertical wind variability with altitude compared to EAR data.

In the context of horizontal wind patterns, the ERA-5 data reveals a top-heavy structure of the MJO (Inoue et al. 2020), manifested by a larger wind variations in the upper troposphere than in the lower troposphere, whereas in EAR this structure appears to be bottom-heavy, as the magnitude of MJO-related variability tend to decrease with altitude. It should be noted that Inoue et al. (2020) used terms “top-heaviness” and “bottom-heaviness” while referring to vertical wind variability, while here we apply this concept to all three wind components. This indicates significant disparities in how ERA-5 represents MJO structure over West Sumatra in comparison with observations. It is also noteworthy that in mean vertical wind anomalies variations due to MJO observed by EAR are of the same order in lower and upper troposphere, while ERA-5—similarly to horizontal winds—shows largest variations in the upper troposphere.

The amplitudes of the diurnal cycle in all wind components exhibit variability influenced by the MJO activity, evident in both data sources. This variability significantly changes with altitude (Fig. 8).

In EAR data, for zonal wind observations below 700 hPa, we observe an increase in diurnal cycle amplitude in all

phases of MJO compared to the long-term average. In the layer between 700 and 500 hPa, phases 1 and 5 show reduced amplitudes, while the remaining phases exhibit increased amplitudes. Between 500 and 200 hPa, decreased diurnal cycle amplitudes are seen in phases 3, 4, and 6, while the other phases show increased amplitudes. Above 200 hPa, reduced amplitudes occur in phases 4, 6, and 7, with increased amplitudes in the remaining phases.

In ERA-5 data, the diurnal cycle amplitude for zonal wind is increased during all MJO phases below 650 hPa. Between 650 and 400 hPa, a distinct increase in amplitude is evident in phases 3 and 4, while phase 5 shows a decrease. In the layer from 400 to 250 hPa, increased amplitudes are observed in phases 1, 2, 4, and 7, while reduced amplitudes are present in the other phases. Above 250 hPa, a clear increase in amplitude is observed in phases 1, 3, and 4, with a decrease in phases 4 and 8.

The analysis of EAR data reveals significant variations in the amplitudes of the meridional wind diurnal cycle attributable to MJO activity. Within the lower troposphere, convective MJO phases lead to an increase in this amplitude. In the mid-troposphere (500–250 hPa), we observe an amplified diurnal wind cycle during phases 1, 2, 3, and 4. However, in the upper troposphere (above 200 hPa), there are no discernible changes in the amplitude of the diurnal cycle of meridional wind.

Contrastingly, the ERA-5 data indicate that wet MJO phases (2–4) are characterized by a reduced amplitude of the diurnal cycle of meridional wind below 600 hPa. Between 600 and 400 hPa, a notable increase in this amplitude is evident during phase 2. In the range of 400 hPa to 250 hPa, phases 1 and 3 of the MJO exhibit an enhanced diurnal cycle amplitude, with maxima occurring at approximately 350 hPa for phase 1 and around 300 hPa for phase 3. Above 250 hPa, only phase 2 shows an increase in the diurnal cycle amplitude, while phases 1 and 3 display clear reductions in this amplitude. These findings shed light on the complex interactions between the MJO and the meridional wind diurnal cycle across different levels of the troposphere.

In vertical wind observed by EAR, we observe significant variability in the amplitude of the diurnal cycle with height influenced by the MJO. While identifying clear structures in these amplitude profiles is challenging, we can discern that the wet phases of MJO exhibit the greatest enhancement in diurnal cycle amplitude at all altitudes.

In ERA-5 data, the amplitude of the diurnal cycle of vertical wind clearly varies between MJO phases. Phase 2 shows a pronounced increase in this amplitude at all altitudes, while in Phase 3, it is enhanced below 600 hPa and above 300 hPa. Phase 4 displays reduced amplitude below 300 hPa and increased amplitude above this altitude. The remaining phases exhibit reduced diurnal cycle amplitudes in vertical wind at all altitudes, with the smallest amplitudes

observed in Phase 5. This means that in reanalysis during MJO activity larger mean vertical winds are related to larger diurnal cycle amplitudes. This may be related to the diurnal evolution of vertical wind in ERA-5 (Fig. 2) where deep convection arises at 15 LST. Hence, increased convection during phases 1–3 increase the amplitude of diurnal cycle of vertical wind in reanalysis.

In conclusion, MJO-related variability in horizontal winds in ERA-5 data is overall consistent with EAR data, but the impact of MJO phases on diurnal variations is underestimated. It is noteworthy that in ERA-5 data the differences in zonal wind anomalies due to MJO are larger in the upper than in the lower troposphere. EAR observations show opposite results: lower tropospheric zonal winds are affected more than the upper tropospheric winds. The ERA-5 results for vertical wind differ from EAR observations, as expected, due to overall bias in representation of vertical wind component (Figs. 1 and 2). However, even for the ERA-5 vertical wind component trends similar to EAR data are visible in averaged anomalies. It is noteworthy that unlike EAR observations, ERA-5 daily variations of vertical wind have coherent structure for all MJO phases.

## 8.6 CCKW-related variability

In this section, the results of the analysis of impacts of CCKW on mean winds and diurnal cycle amplitude for both EAR and ERA-5 are shown. Figure 9 illustrates the mean anomalies of all wind components based on radar data and reanalysis during CCKW activity. In zonal wind, both data sources exhibit variability in the mean wind consistent with the westward-tilted, barotropic structure of a CCKW (Kiladis et al. 2009), namely a shift from low level anomalous easterlies and upper level westerlies before an event, to lower level westerlies and upper level easterlies after it. Below 300 hPa, the radar and reanalysis results closely resemble each other. Above this level, radar and reanalysis display the same variability in mean zonal wind on consecutive days, but the magnitude of these variations are larger in ERA-5. Similar to the MJO, the magnitude of these changes is significantly smaller for radar ( $\pm 2$  m/s) compared to reanalysis (over  $\pm 4$  m/s).

For meridional wind below 500 hPa, northerly anomalies are observed during the passage of CCKW and in the subsequent days in EAR data. Around 400 hPa, there are northerly anomalies on Days  $-2$  and  $-1$  and southerly anomalies on Day  $+1$ . On the day of the wave passage and during the following 2 days, southerly anomalies are observed above 400 hPa. In reanalysis data, northerly anomalies are visible below 500 hPa from Day  $-1$  to 2. Above 500 hPa, northerly anomalies are present before the wave passage, and southerly anomalies occur during and after it. The maximum values of southerly anomalies in the upper troposphere after the

wave passage are on the order of 1 m/s in both data sources. The evolution of meridional wind anomalies, observed in both ERA and reanalysis data, along with the previously described zonal wind variability during successive days of Kelvin wave activity over Western Sumatra, suggests a shift in the propagation direction of the convection center—its deviation towards the south.

The vertical wind variability below 400 hPa shows upward anomalies before and during the wave passage and downward anomalies after the wave passage based on EAR data. In the layer between 400 and 200 hPa, significant upward anomalies are observed one day after a wave passage, followed by downward anomalies one day before the wave passage. ERA-5 vertical wind data exhibit similar variability in vertical wind anomalies as EAR data. In reanalysis, maximum upward anomalies in the lower and middle troposphere are observed on the day of the wave passage. In the upper troposphere, ERA-5, as radar, shows maximum upward anomalies one day after the wave passage; however, reanalysis does not indicate downward anomalies before the passage of CCKW. This implies that the reanalysis reasonably captures the trends in vertical wind changes over successive days of Kelvin wave activity. However, it should be

noted that magnitude of vertical wind variability associated with CCKW passage is lower in ERA-5 representation than in EAR observations.

Two days before the passage of the Kelvin wave, the amplitude of the diurnal cycle of zonal wind observed by EAR is increased around 400 hPa and decreased above 250 hPa (Fig. 10a). The following day, this amplitude is heightened throughout the layer below 300 hPa and reduced above this level. On the day of the wave passage, the most significant increase in the diurnal wind cycle amplitude occurs in the lowest tropospheric layers (more than 1.5 m/s greater than during typical conditions). In the vicinity of the freezing level, the increase in this amplitude is slight. A subsequent distinct increase is observed between 500 and 200 hPa, with a maximum of about 0.7 m/s at 300 hPa. A day after the wave passage, the anomaly in the amplitude of the diurnal cycle of zonal wind decreases almost linearly from around 0.7 m/s at 700 hPa to  $-0.2$  m/s at 300 hPa. Above this layer, no significant deviations from typical conditions are observed. Two days after the wave passage, increased amplitude persists in the lower troposphere and between 550 and 300 hPa. Interestingly, a notable increase in this amplitude also appears in the upper tropospheric

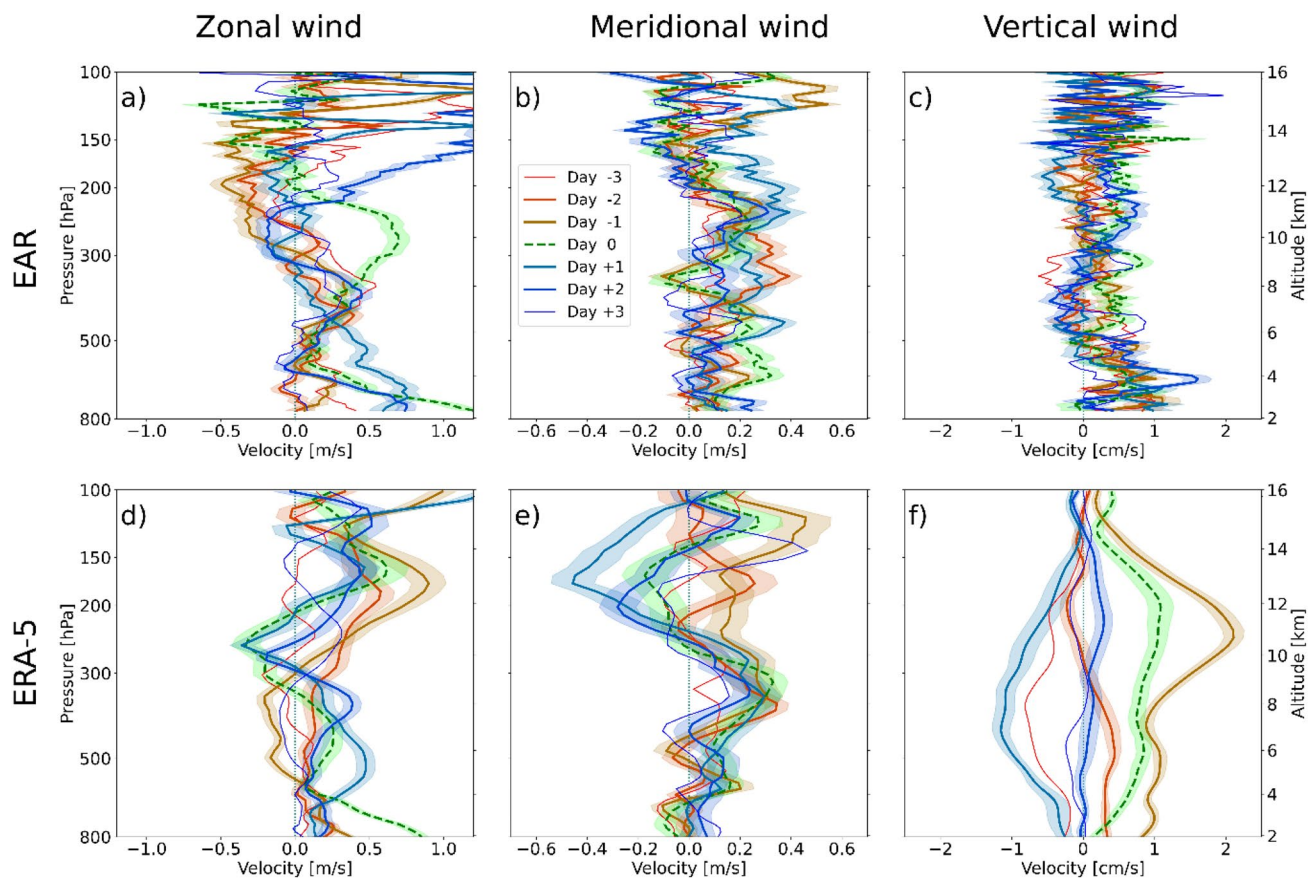


**Fig. 10** Same as Fig. 4, but for CCKW activity. Each line corresponds to specific day prior to and after CCKW event

layers (above 250 hPa, with a maximum around 1.3 m/s at 150 hPa). The results of the reanalysis for days preceding the passage of the wave differ from those obtained using the ERA dataset. On Days  $-2$  and  $-1$ , the reanalysis shows a significant increase in the amplitude of the diurnal cycle of zonal wind above 300 hPa, whereas in ERA, this amplitude was reduced. Conversely, on the day of the wave passage, the reanalysis accurately captures the strengthening of the diurnal cycle amplitude in the lower tropospheric layers, but discrepancies with EAR reappear in the higher layers. The reanalysis reveals an enhancement of the diurnal cycle amplitude around 400 and 170 hPa, in contrast to the pronounced enhancement in EAR between 500 and 200 hPa. On Day  $+1$ , the reanalysis displays an amplitude enhancement between 700 and 300 hPa, as well as above 200 hPa. On Day  $+2$ , we observe an enhancement below 300 hPa with a clear maximum around 350 hPa, and above 250 hPa. This structure aligns well with the EA–R results, but, similar to Day  $+1$ , the reanalysis does not show the strengthening effect in the lowest tropospheric layers.

In the meridional wind, EAR shows an increase in the amplitude of the diurnal cycle in almost the entire troposphere during all Days from  $-2$  to  $+2$  during the CCKW activity. Although distinct structures are challenging to discern, we can observe that below 700 hPa, the most significant amplification of amplitude occurs on Day  $+2$ , in the 700–500 hPa layer on Day 0, around 500 hPa on Day  $+1$ , between 400 and 250 hPa on Day  $-2$ , and above 250 hPa on Day  $+1$ . The results from the reanalysis differ from those obtained from the EAR. The most significant discrepancies are observed in the upper troposphere. The reanalysis indicates a substantial reduction in the amplitude of the diurnal cycle of meridional wind from Day 0 to  $+3$ , with a minimum on Day  $+1$  and an amplification of the amplitude before the passage of the wave. Furthermore, in the ERA-5 data, we observe an enhancement of the amplitude around 350 hPa throughout all days of Kelvin wave activity. None of these effects are evident in the EAR data.

Variations in the amplitude of the diurnal cycle of vertical wind, as observed by the EAR, exhibit significant changes with altitude, making it challenging to pinpoint specific structures. Nonetheless, a noticeable enhancement in this amplitude is discernible around 650 hPa during the entire Kelvin wave activity, with a peak occurring on the second day. Furthermore, on the day of a CCKW passage, a distinct increase in amplitude is observed above 550 hPa. In contrast, reanalysis data reveal clear alterations in the amplitude of the diurnal cycle of vertical wind. On Days  $-1$  and 0, this amplitude is notably elevated, while on Day  $+1$ , it is substantially reduced throughout the troposphere. On Days  $-2$  and  $+2$ , these values are much closer to typical conditions. Similarly as for other modes, these variations in ERA-5 data may be related to the typical evolution of vertical wind

in reanalysis and increased amplitudes of its diurnal cycle being parallel to the increased convection.

To sum up, horizontal wind anomalies in ERA-5 composites for CCKW activity show comparable variability to EAR data and the baroclinic structure of CCKW is apparent in both datasets. However, differences are visible in diurnal cycle amplitudes. Vertical wind data results differ between ERA-5 and EAR for both the mean and diurnal cycle amplitude, however similar trends (day-to-day changes during CCKW activity) in anomalies profiles are visible, especially below 250 hPa.

## 9 Discussion

In this study, we undertake a comparative analysis of horizontal and vertical wind data as observed by radar and represented in ERA-5 reanalysis datasets. The average horizontal wind data observed by radar closely aligns with the reanalysis representation (Fig. 1c, d). Noteworthy differences between the two datasets emerge primarily in the upper troposphere, where the reanalysis consistently exhibits greater magnitudes compared to radar measurements. Additionally, upper soundings data reveal similar structures to EAR observations and ERA-5 representation for both horizontal wind components throughout the troposphere, albeit with consistently higher magnitudes at all altitudes compared to radar. However, concerning the average vertical wind data, radar observations significantly diverge from the representation in the reanalysis, indicating substantial discrepancies between the two datasets (Fig. 1e). It should be noted that validation of ERA-5 performance is primarily based on data from the grid point nearest to the EAR location. An analysis of spatial variability in ERA-5 dataset indicates that vertical profiles of vertical wind in the coastal region north-west of EAR location show closer resemblance to EAR observations, which indicates potential issue with ERA-5 representation of vertical motions in complex topography.

The sub-diurnal variability of tropospheric winds was assessed by decomposing them into diurnal and semi-diurnal components, as these collectively account for the majority of observed variability in horizontal (correlation between full field and decomposition into diurnal and semi-diurnal modes exceeding 95%) and vertical (correlation exceeding 85%) winds. An analysis of the average diurnal cycle of tropospheric winds shows that reanalysis and radar data converge on both the phase and amplitude for horizontal wind components, with minor discrepancies primarily noted in the diurnal cycle amplitude in the upper troposphere. Conversely, in the case of vertical wind, significant differences emerge between the two data sources. The observed change in the diurnal cycle phase with height in radar data can be related to a typical daily cloud evolution (Mori et al. 2004),

from shallow cumulus before noon, through thicker congestus around noon to deep convective clouds in the afternoon. Reanalysis data fail to represent that interaction and indicate no dependence of the phase of diurnal cycle on the time as if the convection (positive diurnal anomalies) occurs simultaneously around 3pm local time (notably a correct timing for deep convective clouds) at all levels of the atmosphere. Analysis of a spatial variability in the phase of diurnal cycle of vertical wind from grid points around EAR (not shown) reveals that the phase changes from local afternoon in inland and mountainous sub-regions to night-time in coastal and oceanic sub-regions, but always shows the same vertical structure.

Bias in ERA-5 representation of vertical wind and its diurnal variability can be related to reanalysis inability to properly represent evolution of atmospheric convection over complex topography in the coastal area. The bias in the daily mean profile appears primarily related to the topography, as some of neighbor, coastal grid points show more structures that compare better with EAR observations. The bias in diurnal evolution of vertical wind is likely related to the parameterization of subscale convective processes. ERA-5 seems to favor an unrealistically rapid growth of atmospheric convection into deep convection state in response to environmental conditions in contrast to a gradual progression coupled with development and evolution of a cloud field (Mori et al. 2004). This behavior is consistent with ERA-5 performance validation in Western Pacific during PISTON field campaign (Serra et al. 2023). Therefore, caution should be used when analyzing ERA-5 sub-daily variability in atmospheric convection, vertical winds or cloud field evolution in the Maritime Continent region.

Further, the study investigates variability in tropospheric winds associated with assorted, large-scale atmospheric conditions. A comprehensive assessment of ERA-5 representation of tropospheric winds variability during ENSO, QBO, MJO and CCKW events is presented in Fig. 11 (detailed description of the methodology behind this analysis is provided at the end of Methodology, Sect. 2).

This analysis reveals that ERA-5 underestimated the daily mean zonal wind variability (Fig. 11a) at low levels by approximately 1–2 m/s for all modes, while differences in the middle troposphere (450 hPa layer) are considerably smaller. In the upper troposphere, reanalysis data overestimate variability in the mean zonal wind in CCKW, ENSO and MJO (with increasing bias) and slightly underestimate for QBO. ERA-5 underestimates the diurnal amplitude of the zonal wind variability by 0.6–0.9 m/s for CCKW and MJO in the lowest and highest atmospheric layers. For other layers and modes the two data sources compare well, with difference in observed variability of less than  $\pm 0.3$  m/s. The result for MJO variability is related to the observed bottom-heavy structure of MJO in radar observations over West Sumatra

and top-heavy structure identified in ERA-5 (Inoue et al. 2020). The difference in the top-to-bottom distribution of MJO variance between ERA-5 and EAR may be important for investigating the impact of QBO on MJO. Earlier research has indicated that the vertical arrangement of a specific convective mode plays a crucial role in delineating its responsiveness to QBO (Sakaeda et al. 2020a). It should be noted here that reanalysis shows daily mean zonal wind variability between QBO phases only above 170 hPa while EAR observations show measurable, consistent changes above 250 hPa, that is about 2 km lower. Therefore, EAR observations show clear influence of dynamical upper troposphere and lower stratosphere coupling above 250 hPa associated with convective modes.

The range of variability in ERA-5 daily mean meridional wind compares well with EAR observations with a bias of less than 0.4 m/s in the lower and middle troposphere (Fig. 11c). A significantly larger bias is observed in the upper troposphere (300 hPa and above), where ERA-5 significantly overestimates variability for MJO and, to a lesser extent, for CCKW and ENSO. The bias in ERA-5 representation of variability in the diurnal amplitude of meridional wind shows vertical dependence. The reanalysis tends to overestimate variability at all levels except for 300 hPa. The bias is the largest for MJO and CCKW events. Notably, for CCKW events, the range of variability of the diurnal amplitude of meridional wind tends to agree across most levels but shows significant bias in the upper troposphere (160 hPa).

ERA-5 shows significant bias in representation of variability in vertical winds (Fig. 11e). The reanalysis tends to underestimate variability in the daily mean vertical wind, while the range of variability of diurnal amplitude is underestimated in the lowest and highest levels of the troposphere and overestimated in the middle troposphere. However, bias in representation of the vertical winds variability should not be surprising given the apparent bias in representation of the long-term average daily mean (Fig. 1) and sub-diurnal amplitudes and phases (Fig. 2). It is noteworthy that the overestimation of the amplitude of the diurnal cycle in the middle troposphere in ERA-5 is likely related to consistent appearance of deep convective plumes across the entire troposphere at 15LST in the model, rather than gradual evolution of convective updrafts throughout a day. As a result, ERA-5 presents a rather simplistic view of vertical movements over the EAR location, dominated by relatively short-lived pulses of convection. Consequently, any changes in convection intensity will significantly affect the amplitude of the diurnal cycle but will have limited effect on the daily mean.

The bias in ERA-5 representation of diurnal variability in all wind components (Fig. 11, right column) shows dependence on a time scale of an event. It is smallest for long modes such as ENSO and QBO, significantly larger for MJO and the largest for CCKW. This is likely because composites for

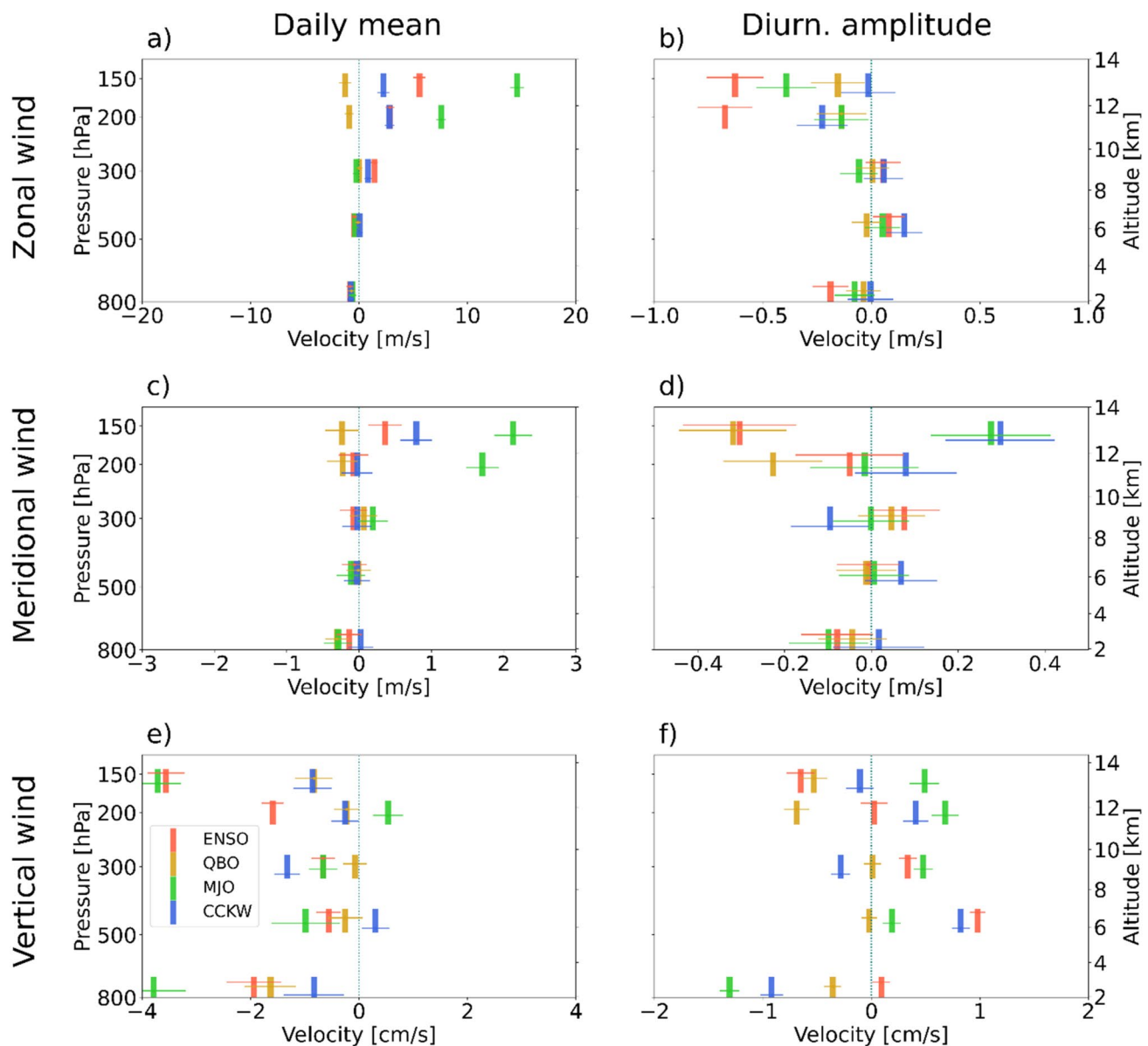


**Fig. 11** A summary depicting the validation of ERA-5 tropospheric wind variability associated with ENSO (red), QBO (yellow), MJO (green), and CCKW (blue). Shown are biases (differences between range of variability in ERA-5 and EAR data) in the range of variability at five distinct, 0.5 km—thick layers centered at 750 hPa, 450 hPa, 300 hPa, 200h Pa, and 160 hPa. Presented are results for daily mean values (left column) and diurnal amplitudes (right column) derived

long modes include averaging of relatively long records of consecutive days (e.g. a single ENSO phase lasts several months), while for higher frequency modes these sequences are shorter (4–5 days for MJO) or virtually absent (for CCKW a single event composite uses isolated days). As a result, composites for higher frequency modes can be more sensitive to representation of day-to-day variability in the ERA-5. Hence, it is possible that reanalysis fails to represent synoptic changes in the sub-diurnal variability of dynamical

from three wind components (rows). Positive values indicate over-estimation of variability by ERA-5, while negative values indicate underestimation. A variability range is defined as the absolute difference between the maximum and minimum values of a given variable throughout the lifecycle of each mode. Horizontal lines represent errors in the calculation of these values

fields. On the other hand, it represent well changes in the daily mean fields, especially for horizontal winds.

In summary, the ERA-5 reanalysis demonstrates its effectiveness in representing the average horizontal wind and its variability due to large-scale modes over Western Sumatra. However, it falls short in capturing vertical wind patterns, with ERA-5 results significantly deviating from observational data. Discrepancies between reanalysis and observations also manifest in the context of analyzing diurnal cycle

variations influenced by ENSO, QBO, MJO, or CCKW. These findings underscore the significance of high resolution wind observations as well as other parameters in the Sumatra region and the broader Maritime Continent, essential for a more comprehensive understanding of coupling between dynamics, convection and cloud field evolution.

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**Author contributions** W.R.S., D.B.B. and P.J.F. contributed to the conceptualization and design of this study. M. and H.H. contributed to the processing and analysis of the EAR data. T.S. provided rain gauge data. W.R.S. and D.B.B. designed the methodology of this study and analyzed the data. W.R.S. performed formal analysis, investigation, software development, and visualization. All authors discussed the results. W.R.S. and D.B.B. wrote the draft manuscript. All authors contributed to the final manuscript. D.B.B. and P.J.F. supported this work through funding acquisition. All authors have read and agreed to the published version of the manuscript.

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**Data availability** Equatorial Atmosphere Radar data available on: <http://www.rish.kyoto-u.ac.jp/ear/data/data/ver02.0212/>. The ERA5 dataset is available at <https://www.ecmwf.int/en/forecasts/datasets/browse-reanalysis-datasets>. Sounding data were downloaded from the University of Wyoming (<http://weather.uwyo.edu/upperair/sounding.html>).

## Declarations

**Conflict of interests** The authors declare that they have no conflict of interest.

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