



Coupled tropospheric and stratospheric dynamics of Kelvin waves over West Sumatra and its implications for precipitation variability in the Maritime Continent

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Abstract

This study investigates the dynamical structure across the troposphere and lower stratosphere associated with convectively coupled Kelvin waves (CCKWs) as they propagate over Sumatra. Utilizing 19 years of continuous measurements from the Equatorial Atmosphere Radar (EAR) in West Sumatra, along with ERA5 reanalysis data and IMERGv6 precipitation estimates, we analyze variability in zonal, meridional, and vertical wind components in relation to the CCKW precipitation footprint across the Maritime Continent region. The results reveal coherent dynamical structures spanning the troposphere and lower stratosphere during CCKW activity. While stratospheric circulation features propagating coherently with tropospheric CCKWs have been documented before, our analysis provides a detailed local characterization of these interactions. While the stratospheric structure is consistent with the theoretical Kelvin wave, it exhibits a zonal group velocity similar to that of a tropospheric CCKW, indicating that it is linked to the tropospheric CCKWs rather than behaving as an independent, freely propagating wave. The magnitude of the stratospheric response, quantified using the newly introduced Stratospheric zonal wind Index (SzI), is linked to the eastward propagation extent of CCKWs. Events with a stronger in-phase stratospheric response tend to propagate farther eastward. Additionally, variations in meridional wind over West Sumatra, monitored via the newly introduced Tropospheric meridional wind Index (TmI), serve as a predictor for the CCKW waveguide, as they are associated with the poleward displacement of maximum precipitation. These findings highlight the potential for forecasting CCKW trajectory and rainfall distribution across the Maritime Continent based on the dynamical structure monitored in the West Sumatra.

Keywords Convectively coupled Kelvin waves · Troposphere-stratosphere interaction · Maritime Continent · Precipitation variability · Equatorial Atmosphere Radar

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1 Introduction

The Maritime Continent (MC), a region of immense geographical complexity, straddles the equator and is characterized by a vast network of islands and surrounding seas. This area includes parts of Indonesia, Malaysia, the Philippines, and Papua New Guinea, making it one of the most climatically dynamic regions on Earth (Ramage 1968; Simpson et al. 1993). The unique interplay between land and sea in this region significantly influences global atmospheric circulation patterns. One of the prominent features in the atmospheric dynamics of the MC is the atmospheric convectively coupled Kelvin wave (CCKW), a type of eastward-propagating tropical wave that plays a crucial role in

modulating weather and climate in the tropics (Baranowski et al. 2016b,a).

CCKWs, a subset of equatorial convectively coupled waves, are characterized by their symmetrical (around the equator) spatial structure of zonal winds and precipitation, as well as ability to travel long distances without losing energy (Wheeler and Kiladis 1999). These waves are instrumental in the distribution of heat and moisture across the tropics, impacting phenomena such as the Madden–Julian Oscillation (MJO), monsoon systems, and convective activities (Roundy and Frank 2004; Sakaeda et al. 2020). Understanding the behavior of these waves, especially in the context of the MC, is critical for improving weather prediction models and climate forecasts (Janiga et al. 2018; Kim et al. 2018).

Sumatra, one of the largest islands within the MC, serves as a focal point for studying CCKWs as it lies on the western flank of the MC, adjacent to Indian Ocean where these waves frequently originate (Baranowski et al. 2016a). Hence, the region of the island provides an ideal natural laboratory for investigating the interaction between atmospheric waves and regional weather variability (Mori et al. 2004; Marzuki et al. 2022). The island experiences a complex interplay of atmospheric dynamics influenced by its topography, land-sea contrast, and seasonal variations, making it a key area for studying the modulation of CCKWs activity, among others.

In tropical atmosphere, circulation and precipitation patterns exhibit complex and multi-scale interactions. While wind field can directly affect the distribution and intensity of convection, which drives the formation of clouds and precipitation (Neelin et al. 1987; Jun-Ichi Yano and Emanuel 1991), large-scale dynamical systems, such as the trade winds and monsoon flows, help transport moisture from oceans to land, fueling heavy rainfall (Trenberth and Guillemot 1998). Additionally, variations in wind shear and upper-level outflow can either enhance or suppress convective activity, further modulating rainfall.

However, precipitation itself also exerts a significant feedback on wind circulation. The latent heat release in convective systems drives vertical motion, influencing large-scale tropical circulations, including the Hadley and Walker circulations (Gill 1980). Convective heating associated with organized rainfall systems modulates upper-level divergence and low-level convergence, which in turn affects wind anomalies in both the troposphere and lower stratosphere (Hartmann et al. 1984). Moreover, mesoscale convective systems (MCS) can modify local and regional wind patterns by generating cold pools and low-level jets, which subsequently impact moisture transport and convergence zones (Schumacher et al. 2003).

This bidirectional interaction between wind and precipitation is particularly important in the Maritime Continent,

where complex land-sea contrasts modulate both atmospheric convection and wind patterns across spatial and temporal scales (Birch et al. 2016; Szkolka et al. 2023). In this study, we investigate how CCKWs influence precipitation and assess the extent to which wind anomalies in the troposphere and lower stratosphere respond to convective activity over Sumatra. The primary objectives of this study are to elucidate the dynamics of Kelvin waves in the troposphere over Sumatra, assess the impact of these waves on regional precipitation patterns, and explore the associated stratospheric phenomena. We utilize reanalysis data from ERA5 (Hersbach et al. 2020), radar observations from the Equatorial Atmosphere Radar (EAR) (Fukao et al. 2003), and precipitation data from the Integrated Multi-satellite Retrievals for GPM (IMERGv6) (Huffman et al. 2019). ERA5 reanalysis data offers high-resolution information on atmospheric variables, providing insights into the behavior of Kelvin waves in the troposphere. The EAR, located in West Sumatra, delivers detailed radar observations that are crucial for understanding the vertical structure and movement of these waves. Additionally, IMERGv6 data offers measurements of precipitation, enabling us to track the evolution of rainfall patterns associated with CCKWs passages. These datasets provide a comprehensive overview of atmospheric conditions, allowing for an in-depth analysis of Kelvin wave activity and its associated meteorological impacts.

In this study, we also explore phenomena occurring in the lower stratosphere that accompany Kelvin wave activity. The interactions between the troposphere and stratosphere are critical for understanding the full impact of Kelvin waves, as these waves can induce significant changes in stratospheric conditions (Flannaghan and Fueglistaler 2012). By examining the lower stratosphere, we aim to identify any concomitant anomalies or patterns that might be linked to Kelvin wave events.

Furthermore, we investigate the relationships between indices for wind fields over Sumatra and the evolution of precipitation throughout the MC during the passage of Kelvin waves. The meridional wind index serves as a key parameter in our analysis. Understanding how this index correlates with rainfall distribution offers valuable insights into the mechanisms driving precipitation variability in the region.

2 Methodology

This study investigates the variability of tropospheric and lower stratospheric winds during the extended boreal winter season, which is defined as the period from November through March (NDJFM) here. The choice of this specific period is motivated by the annual cycle of winds in Sumatra

and the seasonal variability of CCKWs. By extending the typical DJF period by two additional months we aim to maximize the availability of cases for composite analyses. In the following sections, we present a comprehensive description of all relevant datasets and provide an overview of the data analysis methods employed.

2.1 Radar measurements

The Equatorial Atmosphere Radar (EAR) facility is in Kototabang, north of Bukittinggi (0.20°S, 100.32°E) in West Sumatra, Indonesia, at an altitude of approximately 800 m above sea level. It serves as the primary source for zonal, meridional, and vertical wind data. EAR is a large Doppler Very High-Frequency radar (47 MHz) with the capability to measure wind data between 2 km and approximately 20 km above sea level. The radar provides data at 120 levels, with an approximate vertical resolution of 150 m and a temporal resolution of 10 min. This dataset contains information on zonal, meridional, and vertical winds, where positive values represent westerly, southerly, and upward winds, respectively. Further information on the radar's design and EAR facility can be found in Fukao et al. (2003).

This study utilized radar data spanning from 2001 to 2019. During data processing, repeated, sudden and short-lived deviations in wind values at all altitudes were observed for specific times of the day. Specifically, three data points (equivalent to 30 min of data) around 6 LST, 18 LST, and 24 LST were identified as systematically biased and consequently excluded from the analysis. Those biases likely originate from scheduled switching in mode of operations of the EAR between lower atmosphere and ionosphere modes. Additionally, data from the two lowest available altitudes were omitted due to unrealistic results. Vertical wind data points with values less than -0.5 m/s were also removed because of their unphysical magnitudes, potentially caused by falling droplets (Uma and Rao 2009; Uma et al. 2021). After excluding these, the data were binned to hourly means, which are used throughout the rest of the study.

In addition to the default vertical coordinate (altitude in km above sea level), a secondary vertical coordinate (pressure) has been calculated to enable a direct comparison with reanalysis data provided at pressure levels. At each altitude, the pressure value has been derived using the hydrostatic equation and a multi-year-mean temperature profile for the extended boreal winter obtained from atmospheric soundings in Padang (see next subsection).

2.2 Atmospheric soundings data

Atmospheric soundings data from Padang (BMKG station, 0.88°S, 100.35°E, around 100 km from EAR site) for

2001–2019 have been used to obtain the mean vertical profiles of horizontal winds, temperature and humidity as well as the altitude of cold point tropopause. Soundings launched at 00 UTC were utilized. Atmospheric sounding data have been downloaded from the University of Wyoming website. All available profiles for the extended boreal winter were used to calculate the mean vertical structure of horizontal winds, temperature, humidity, which were used to transform between altitude and pressure coordinates, as well as the Brunt-Väisälä frequency.

2.3 ERA5

The fifth ECMWF reanalysis (ERA5) data (Hersbach et al. 2020) were used for the analysis of horizontal structure of CCKWs, mean thermodynamic conditions and for comparison with EAR data. ERA5 data from 2001 to 2019 were utilized for consistency with EAR data availability. The ERA5 model-level data over a limited spatial domain were employed as they offer higher vertical resolution than standard pressure level data. All available data between the surface and 20 hPa height (model levels: 35–137) were used. The area of interest spans between 12.5°S and 12.5°N in latitude, and between 60 and 140°E in longitude. For direct comparison between EAR and ERA5, data from the 0.25×0.25 degrees grid-point nearest to the EAR facility, centered at 0.25°S and 100.25°E, were used.

2.4 Precipitation data

Precipitation data were used to investigate the impact of CCKW activity on rainfall distribution over MC. The Integrated Multi-satellite Retrievals (IMERG) Version 6 Final Run (IMERG-F) product (Huffman et al. 2017), based on Global Precipitation Measurement Mission (GPM) satellite among others, were used. Daily precipitation estimates for the same period as in EAR and ERA5 data (2001–2019) at $0.1^\circ \times 0.1^\circ$ spatial resolutions from IMERGv6 were utilized in this study. IMERGv6 precipitation estimates were used for calculation of climatological background as well as composite structures associated with CCKW activity.

2.5 Convectively Coupled Kelvin wave events

To assess variability in the dynamical structure of the atmosphere during CCKW events, we assessed CCKW activity in the vicinity of the west coast of Sumatra. The identification and tracking of individual CCKW events follows the methodology described by Baranowski et al. (2016a, 2016b), which is based on the space–time spectral filtering technique introduced by Wheeler and Kiladis (1999). To identify CCKWs, we first use precipitation data from the

TRMM 3B42v7 dataset, averaged across the 2.5°S – 2.5°N equatorial belt. TRMM was selected because it offers sufficient temporal resolution (3-hourly) for tracking CCKWs, and was the basis for the original event database used in this study (Baranowski et al. 2016a). The longitude-time precipitation dataset is then subjected to a two-dimensional Fourier transform to decompose the data into wave number and frequency components. To isolate the Kelvin wave signal, we apply a filter that retains only eastward-propagating waves with equivalent depths between 12 and 50 m, zonal wave numbers between 1 and 10, and periods ranging from 2.5 to 20 days. This spectral filter is designed to capture the typical characteristics of convectively coupled Kelvin waves, distinguishing them from other equatorial disturbances such as the Madden–Julian Oscillation (MJO) and inertia-gravity waves (Wheeler and Kiladis 1999; Kiladis et al. 2009).

After spectral filtering, an inverse Fourier transform reconstructs a filtered longitude-time precipitation field, highlighting the eastward-propagating precipitation anomalies associated with CCKWs. Individual CCKW events are then identified by tracking coherent precipitation maxima along these eastward trajectories. Each identified event is represented as a Lagrangian trajectory, describing the evolution of the wave's convective center as it propagates eastward (Baranowski et al. 2016a, b).

For this study, we restrict our analysis to CCKWs crossing the entire 90°E – 110°E sector, ensuring that only events relevant to the West Sumatra region are retained. For each event, the day on which the wave reaches 100°E is defined as Day 0, which serves as the reference point for all composite analyses.

Each CCKW event in the database consists of a trajectory: a set of time-longitude paired values, indicating the central position (longitude) of the CCKW at each time (with 3 h resolution). In order to be considered in this study, a CCKW trajectory had to exist between 90 and 110°E longitude. As a result, 261 CCKW events were identified and analyzed. For each CCKW trajectory, a reference date (Day 0) was a day it passed 100°E longitude.

2.6 Climatology and anomalies calculation

To analyze the variability of CCKWs, we compute anomalies relative to the seasonal cycle. The mean seasonal variability is derived from multi-year (2001–2019) data and approximated using the long-term mean and the first three annual harmonics. Anomalous fields are then computed by subtracting this seasonal cycle from the raw data at each grid point. This approach ensures that the anomalies reflect sub-seasonal departures from the mean state while

preserving variability associated with large-scale tropical wave dynamics.

3 Results

3.1 Typical atmospheric environment over eastern Indian Ocean and western MC during extended boreal winter

The mean conditions derived from multi-year average of ERA5 and IMERGv6 data (Fig. 1a) during extended boreal winter over the eastern IO show steady north-westerly horizontal flow in the range of 3–4 m/s in the lower troposphere (850 hPa height) that turns clockwise into more north/north-westerly flow over the western MC. This turn begins along the west coast of Sumatra and the low-level flow direction is parallel to the elongated island with significant coastal orography. While the theoretical low-level flow structure in CCKWs (see black arrows in Fig. 1a) has been derived assuming the zero background flow (Matsuno 1966; Kiladis et al. 2009; Matthews 2021), this condition is not satisfied over the region of interest. CCKW events during the extended boreal winter seasons between 2001 and 2019 account for approximately 40% of all CCKW events across all seasons. The CCKW-filtered precipitation variance is large in a relatively wide meridional band between 5°N and 10°S in the Indian Ocean, with maximum centered near 5°S . Over the western MC, enhanced precipitation variance shows more narrow bands around 5°S in the southern hemisphere and between 2.5°N and 7.5°N in the northern hemisphere, indicating two potential pathways for CCKW propagation across that region. This clear deviation from the theoretical description (Matsuno 1966) is likely related to the background flow as well as distribution of land and ocean within the MC, as these pathways tend to favor regions with less land masses (e.g. Java Sea in the southern hemisphere and sea regions spanning around Borneo in the northern hemisphere).

The vertical structure of horizontal winds over West Sumatra (Fig. 1b, c) show a shear in both zonal and meridional wind throughout the troposphere. Although vertical variability in zonal wind is larger than in meridional wind, the latter is not negligible. In the lower troposphere (below 550 hPa height) westerlies in zonal wind (around 4 m/s) and northerlies in meridional wind (around 1 m/s), consistent with the overall wind pattern over these regions (Fig. 1a), are observed. At higher altitudes both wind components reverse (meridional wind around 400 hPa height, zonal wind around 500 hPa level) and become much stronger. Upper troposphere (above 200 hPa height) is dominated by easterlies in zonal wind (around 12 m/s) and southerlies in meridional

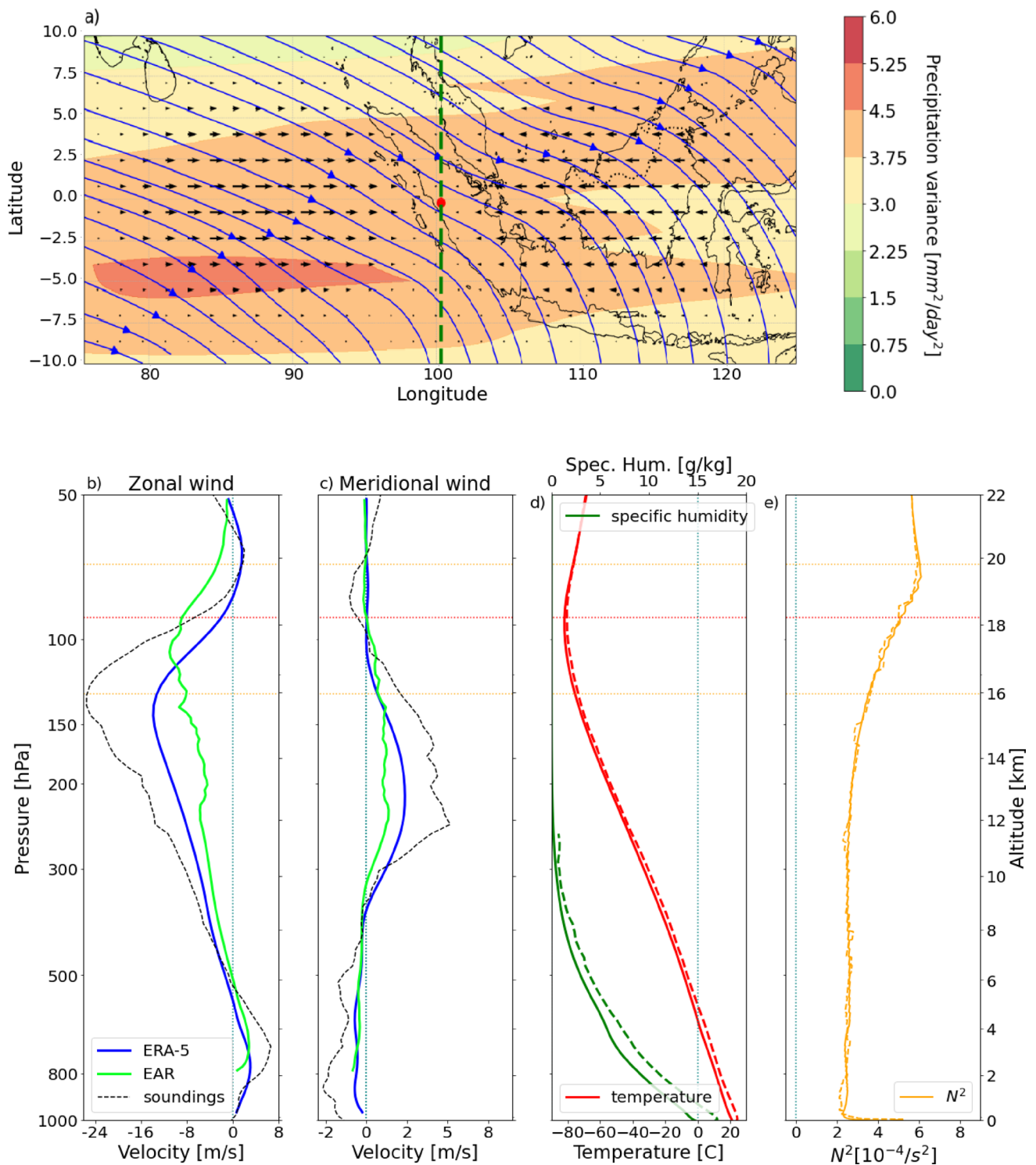


Fig. 1 **a** Mean precipitation variance for Kelvin wave filtered data over the eastern Indian Ocean and the western MC. Red dot indicates EAR location. Green dashed line indicates EAR longitude. Blue lines are streamlines of mean horizontal wind around 850 hPa height from ERA5. Black arrows correspond to the analytical solution structure of zonal wind in Kelvin wave. **b** Mean zonal wind profiles from EAR

(green line), ERA5 (blue line), and soundings from Padang (black dotted line). **c** Similar to **b**), but for meridional wind. **d** Mean profiles of specific humidity (green lines) and temperature (red lines) from soundings (dotted lines) and ERA5 (solid lines). **e** Mean N^2 profile for sounding data (solid line) and ERA5 (dotted line)

wind (around 3m/s). It is noteworthy to observe that the strongest easterlies are observed higher (around 150 hPa height) than the maximum of southerlies (around 200 hPa height). In the lower stratosphere, above 80 hPa height, the magnitudes of zonal and meridional winds are much smaller than in the troposphere. Hence, the mean, background horizontal wind structure is clearly non-zero, which is assumed in derivation of theoretical model of CCKWs and other tropical waves (Matsuno 1966). In particular, background meridional winds can contribute to off-equatorial maxima in filtered precipitation variance (Fig. 1a).

The typical temperature profile (Fig. 1d) shows cold point tropopause around 18km. Mean temperature decreases with altitude at 5.25K/km from 22C near the ground (note that only 00UTC, that is 7am local time, was used from both soundings and ERA5 data) down to -80C around altitude of 18-19km. Above that level temperature rises with altitude, however the rate of growth is smaller than the rate of decline in the troposphere. Such stratification results in a profile of Brunt-Väisälä frequency (N^2), which is nearly constant with height up to 16km (value around $2 \times 10^{-4} 1/s^2$). Above 16km a clear increase in value is observed and around 20km the frequency reaches $6 \times 10^{-4} 1/s^2$. Such growth in Brunt-Väisälä frequency leads to the change in stability and impacts wave properties, including its propagation. In fact, stratospheric and tropospheric equatorial waves are characterized by different spatial structure (Wheeler and Kiladis 1999). However, theoretical solutions have been derived for troposphere and stratosphere independently, assuming different constant values of static stability. Here, this transition is continuous from low tropospheric values to larger values in the lower stratosphere. An impact of such stratification on propagation of CCKWs will be investigated.

3.2 CCKW structure over eastern Indian Ocean and western MC during extended boreal winter

The dynamical structure of a CCKW across three levels of the atmosphere (850 hPa height, 200 hPa height and 100 hPa height) as well as its precipitation footprint based on composite analysis of 261 events is presented in Fig. 2. CCKW events were composited relative to a day when they passed over EAR location (longitude marked by a black vertical dashed line in each panel), which we refer to as Day 0. An eastward propagating signal can be seen across all fields. The precipitation composite shows a single, coherent structure for negative lags as well as Day 0, that is while a CCKW propagates over eastern IO and approaches Sumatra. For positive lags precipitation anomalies decrease with time. The anomalous rainfall pattern splits into two branches: south-west of Sumatra and over Karimata Strait and western Borneo on Day 1. On the following day (Day+2) over

ocean areas north, south and east of Borneo, while the next day the pattern of increased precipitation is located to the east of 125E and it is shifted towards the northern hemisphere with increased precipitation between 5S and 10N. While the evolution of precipitation pattern for negative lags is consistent with the canonical evolution derived from theory and observations over the ocean (Matthews 2021), the composite rainfall anomalies during CCKW propagation across the western MC is consistent with pathways identified in CCKW-filtered precipitation patterns (Fig. 1a).

An evolution of dynamical structure at 850 hPa height associated with a composite CCKW is dominated by zonal wind variability with eastward propagating anomalous easterlies followed by anomalous westerlies and a convergence zone between them (Fig. a3–g3). Over the eastern IO (negative lags) this structure closely follows the theoretical evolution of wavelength equal to 54 degrees longitude (c.a. 6000km) propagating at a constant 10 m/s velocity (green and blue contours). However, once a CCKW passes over Sumatra (positive lags), a composite CCKW structure starts moving faster than the theoretical one, which is manifested by an eastward shift of composite convergence zone in comparison to theoretical convergence zone (marked by a dashed green line in each panel). Furthermore, differences between the observed and the theoretical spatial structure of low-level zonal winds begins to emerge. On Day+1 westerly wind anomalies extend meridionally around Sumatra, particularly in the southern hemisphere, while easterly anomalies ahead of CCKW convergence maximize in the northern hemisphere over South China Sea and northern Borneo. As a result, convergence region splits into two: one along southwest coast of Sumatra dominated by anomalous westerlies and the other in the Karimata Strait and west Borneo dominated by anomalous easterlies. These two regions well match areas of enhanced rainfall observed at that time (Fig. 2e1) slightly north and the other slightly south of the equator. On the following days (Day+2 and Day+3) observed zonal wind structure shows convergence areas in regions where enhanced precipitation is found as well. Also, at that time widespread westerly anomalies are observed over the IO, which may be associated with sequential CCKW events activity (Baranowski et al. 2017) in the region where oceanic Kelvin waves are found to originate in a wake of an atmospheric event (Azaneu et al. 2023).

In the upper troposphere an eastward propagating pattern with zonal and meridional components is observed as well. It is a divergent pattern which is shifted westward with respect to 850 hPa height structure. At 200 hPa height on lag 0 days maximum divergence is observed about 8 degrees westward (at 94 degE), while at 100 hPa height it can be seen 12 degrees westward (at 90 degE), from the maximum convergence at 850 hPa height (at 102 degE). This structure

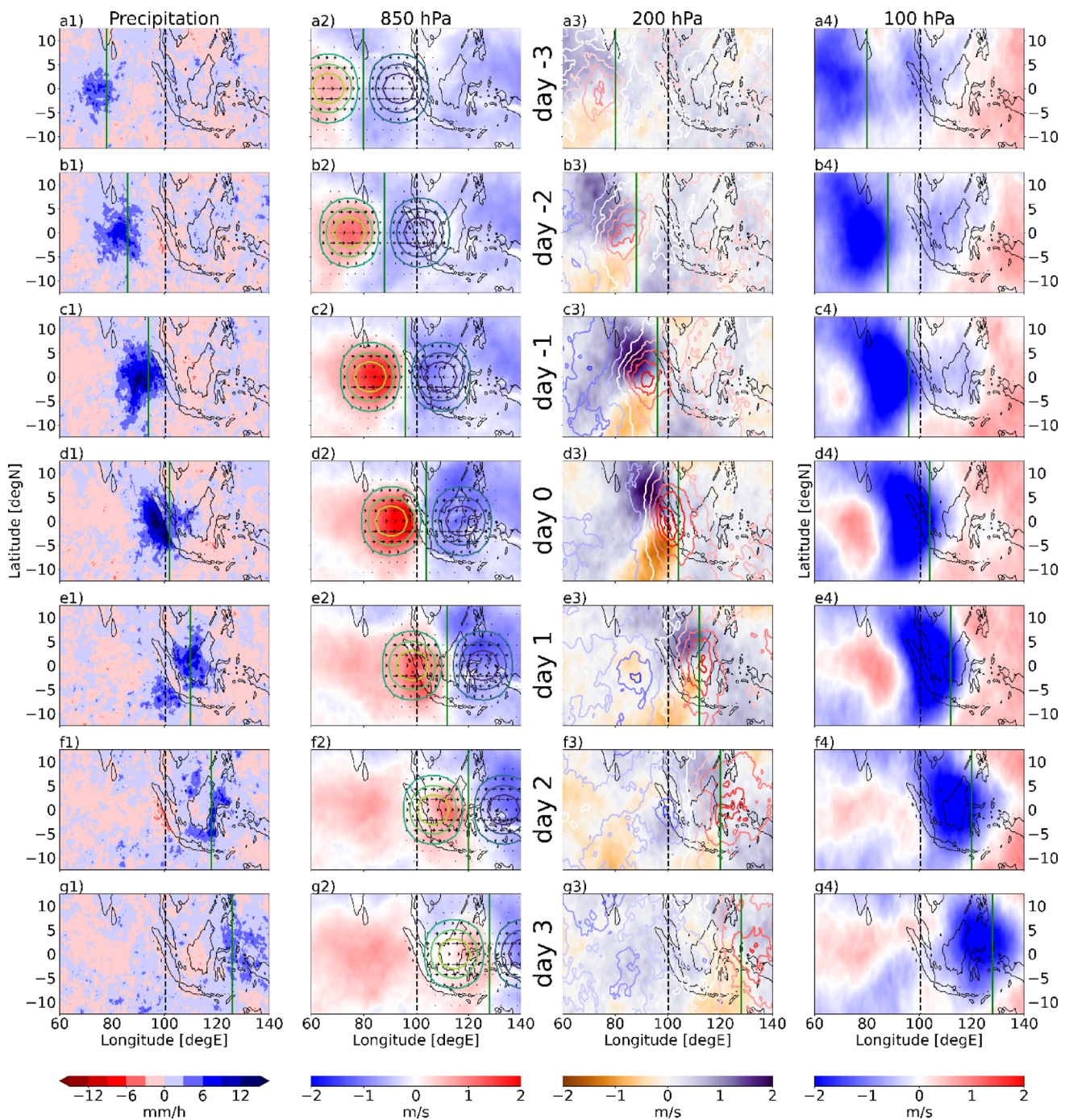


Fig. 2 Time lagged composites of CCKW structure in GPM rainfall anomalies (first column) and ERA5 850 hPa height zonal winds (second column), 200 hPa height zonal and meridional winds (third column) and 100 hPa height zonal and meridional (fourth column) relative 261 strong CCKW events passing over EAR location (longitude of EAR marked by black dotted line in each panel). All data show anomalies relative to climatology with seasonal cycle removed. The first three rows show results for negative lags from Day -3 to Day -1. The fourth row shows composites for a day when CCKW is active over EAR (lag 0 day) and rows five to seven show composites for positive lags from Day 1 to Day 3. In panels representing 850 hPa height zonal winds (second column) shadings indicate zonal wind anomalies (red is westerly, while blue indicate easterly anomalies), contours indicate

theoretical structure of a Kelvin wave fitted to zonal wind anomalies at 850 hPa height on Day 0 and propagating at 10 m/s phase speed (calculated by fitting theoretical structures to data on Day 0 and Day 1). Convergence zone in the theoretical Kelvin wave structure is marked with green dashed line in each panel. In panels representing 200 hPa height (third column) shading indicates meridional wind anomalies; yellow is for northerly wind anomaly, while purple represents southerly wind anomaly (contour interval is 0.5 m/s). Contour lines represent zonal wind anomalies—red indicates westerly and blue indicates easterly wind anomalies. In panels representing 100 hPa height (fourth column) shading indicates zonal wind anomalies (red is for westerly and blue for easterly anomalies)

represents westward tilt in a vertical structure of a CCKW. The divergence at 200 hPa height shows significant eastward propagating anomalies in both zonal and meridional wind components, which likely results from a projection of an upper-level convective outflow onto the mean meridional wind (Szkolka et al. 2023). Although the meridional outflow shows nearly symmetrical pattern with southerlies in the northern hemisphere and northerlies in the southern hemisphere, the southerlies show higher magnitudes throughout the evolution. The strength of the observed anomalous outflow fluctuates significantly during its evolution. This may be linked to interactions with the mean flow at 200 hPa height and the evolving structure of both CCKW precipitation and the 850 hPa height structure over the western MC. These effects are further amplified by the negative interference between multiple CCKW events moving at slightly different phase speeds. It is also noteworthy that on Day 0 the 200 hPa height structure appears to be slightly rotated counterclockwise in comparison with previous days, which may be related to the possible turn of CCKW trajectory southward from the equator. On the following days (positive lags) the spatial structure of the 200 hPa height outflow changes. It expands in size as manifested by a larger distance between extrema in anomalous zonal flow and shift in meridional anomalies: stronger southerlies dominate over north east part of the domain, while weaker northerlies remain over the southwest region. At the same time, anomalous easterlies become stronger while westerlies expand southward. Hence, anomalous meridional outflow appears coupled to anomalous westerlies near a region of enhanced precipitation around Borneo, while the southern branch near the southern part of Sumatra and Java has a support at 200 hPa height outflow from anomalous northerlies. It is noteworthy that Fig. 2 represents an average of multiple events, which may include cases with varying spatial patterns. The discussion presented here considers this averaged structure; however, individual events may exhibit differences from this composite representation.

An eastward propagating structure, dominated by zonal wind variability, is observed also at the 100 hPa height level (Fig. 2, fourth column). This structure appears more coherent than the structure at 200 hPa height, which indicates that anomalies project better onto a mean flow which is weaker than at the lower level. At the same time, propagation properties, such as a phase speed, are consistent with analyses of horizontal winds at lower levels and precipitation anomalies. The structure at 100 hPa height appears more pronounced in anomalous easterlies which is related to the fact that anomalous westerlies project onto the mean westerly flow over the region at this altitude (Fig. 1b). As a result, the structure shows both divergence at the leading edge of anomalous easterlies and convergence behind them.

Divergence at 100 hPa is observed near the area of low-level convergence, giving support to enhanced convection and anomalous precipitation. For negative lags, as well as Day 0, the structure appears symmetrical around the equator with a ‘butterfly’ pattern when variability poleward follows changes on the equator consistent with theoretical, dynamical CCKW structure (Kiladis et al. 2009). For positive lags, anomalous easterlies appear rounder and more shifted to the north. They occupy a region where the northern branch of CCKWs appear to have its precipitation footprint. The described evolution of the zonal wind anomaly at 100 hPa height agrees with the theoretical stratospheric Kelvin wave (Kiladis et al. 2009). Because it follows the tropospheric wave it can be concluded that the wave in the stratosphere is a response to variations in the troposphere.

The analysis presented above highlights the dynamical structure of CCKWs at different atmospheric levels and their relation on precipitation patterns. As we have seen, the evolution of precipitation anomalies during CCKW propagation is closely linked to the zonal wind variability. 850 hPa height, 200 hPa height, and 100 hPa height levels exhibit distinct patterns of convergence and divergence corresponding to areas of enhanced rainfall. Our analysis shows how zonal wind anomalies evolve differently across these layers, with a westward tilt in the upper levels, indicating a complex interaction between different atmospheric components. It is noteworthy that while the CCKW pattern over the Indian Ocean closely resembles the theoretical structure, over the Maritime Continent, it is more complex due to the intricate characteristics of the region.

In order to provide a deeper understanding of the vertical structure and the role of zonal wind dynamics in shaping the behavior of CCKWs we will investigate now the evolution of zonal wind anomalies across all altitudes along the equator during the CCKW events.

3.3 CCKW activity: vertical structure

In order to better elucidate dynamics of a CCKW event, a vertical structure of horizontal winds across the entire troposphere and lower stratosphere is investigated.

The evolution of zonal wind anomalies in the troposphere, as shown in Fig. 3, reveals a clear progression during CCKW activity. Two days prior to the event (Day -2), anomalous westerlies appear in the upper troposphere and easterlies in the lower troposphere between longitudes 85°E and 130°E. On Day 0, a distinct baroclinic Kelvin wave structure becomes evident, characterized by westerly anomalies in the middle troposphere (70°E–90°E) and upper troposphere (90°E–110°E), and easterly anomalies in the adjacent regions at the same altitude. The lower troposphere shows westerly anomalies between 90°E and 100°E,

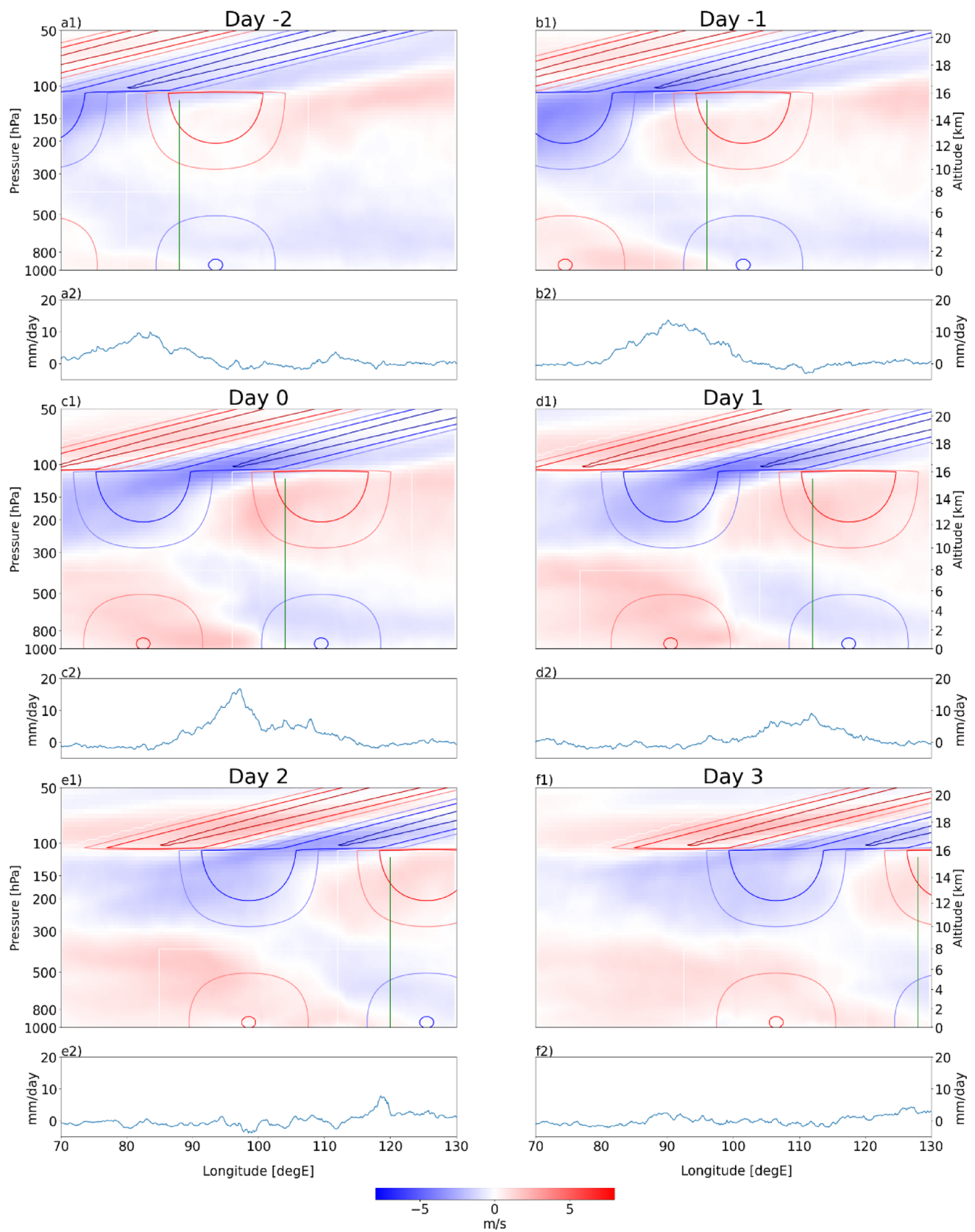


Fig. 3 Evolution of zonal wind anomalies (ERA5) in the equator-height plane and rainfall (IMERGv6) at the equator during Kelvin wave activity. Panels correspond to successive days before and after the passage of wave over Sumatra (composite for days with active Kelvin waves). Red (blue) shading indicates westerly (easterly) anomalies. The green line indicates the same longitude as the green line in Fig. 2. Contours correspond to the Kelvin wave structures fitted to the data on Day 0 in the troposphere and stratosphere, shifted to other days with an assumed speed of 10 m/s eastward. In these calculations we assumed: horizontal wavelength 6000 km; this fitting results in a wave in the troposphere centered at 94°E and stratospheric vertical wavelength of 6.4 km

creating a convergence zone over 100°E. These wind anomalies coincide with significant precipitation increases between 95°E and 100°E.

When comparing the real tropospheric evolution with the theoretical structure, a strong similarity in the overall pattern and propagation is observed. However, the theoretical convergence zone is slightly shifted in comparison to the real data, as seen in Fig. 2. This discrepancy may result from a tilt between anomalous westerlies and easterlies in the lower troposphere. As a result, the Kelvin wave in the free atmosphere appears to be shifted westward relative to the maximum precipitation, whereas the precipitation aligns more closely with the behavior in the lower troposphere.

In the stratosphere, a sequence of tilted structures of zonal wind anomalies is observed on Day -2, with these structures moving progressively eastward over time. On Day 0, the stratosphere exhibits westerly and easterly anomalies located at around 70 hPa height and 100 hPa height. These patterns fit well with the theoretical structure of stratospheric Kelvin wave with horizontal wavelength of 6000 km and vertical wavelength of 6.4 km (Fig. 3). By Day 1, the pattern becomes more distinct, with easterly anomalies between 90°E–100°E and 110°E–120°E, and westerly anomalies in adjacent regions. The stratospheric Kelvin wave response is evident, reinforcing the notion of a vertically coupled system during CCKW activity.

The comparison of the stratospheric evolution with theoretical structures (Kiladis et al. 2009) shows a remarkably close match, particularly in terms of the propagation speed. Both the observed and theoretical stratospheric patterns propagate eastward at approximately 8 degrees per day, consistent with the tropospheric speed, even though stratospheric Kelvin waves typically propagate faster than their tropospheric counterparts (Matthews and Madden 2000). This alignment between the theoretical and observed data suggests that, despite known differences in wave speeds, the propagation of CCKW composite events follows a more synchronized pattern across both atmospheric layers.

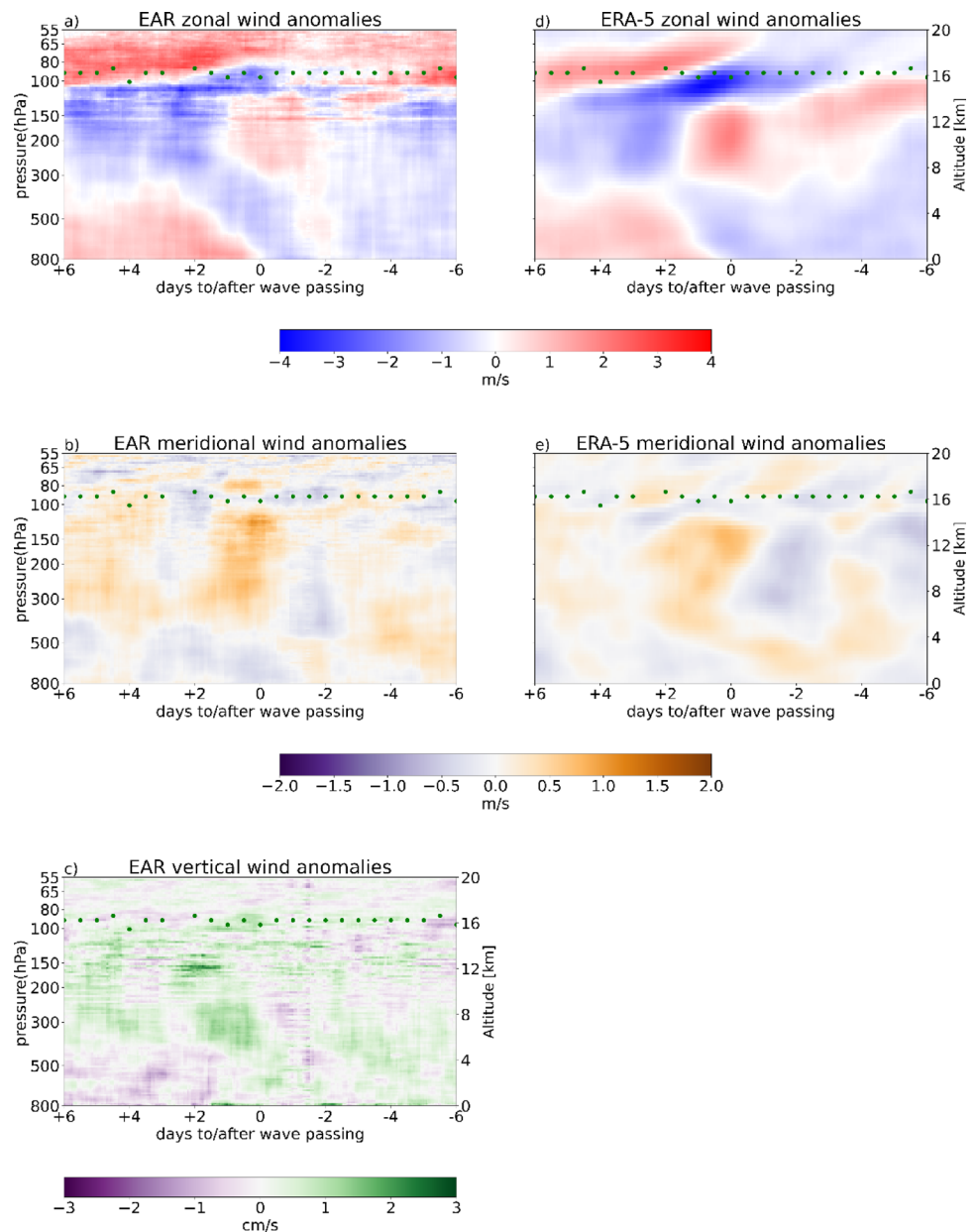
3.4 CCKW activity: time series of winds over Sumatra

A different perspective of an evolution of tropospheric structure of the troposphere and lower stratosphere comes from observations over a particular location. Figure 4 presents the typical evolution of zonal, meridional and vertical wind anomalies during CCKW activity based on data from EAR and ERA5. Because ERA5 vertical winds show significant biases (Szkolka et al. 2023) they are excluded here.

Below 150 hPa height EAR zonal winds show variability consistent with propagation of CCKW structure between Day -2 and Day +3 (Fig. 4a). The time scale of observed variability (approx. 6 days) aligns with the time required for the theoretical Kelvin wave pattern (Fig. 2) to traverse the specified longitude. Over a longer period, a shift from low-level easterlies to low-level westerly flow can be seen. While variability in meridional wind has much smaller magnitude, consistent patterns to that of zonal winds are observed between Day -2 and Day +3 as well. Before Day -3, southerly anomalies dominate the troposphere, with northerly anomalies appearing above 500 hPa height between Day -3 and Day -1. An inverse pattern occurs from Days -1 to 2; by Day +4, southerly anomalies extend across the troposphere.

Although the theoretical Kelvin wave lacks a meridional wind component, the analyzed data clearly show coherent structures in meridional wind anomalies. Previous studies have also documented the presence of meridional wind perturbations associated with the passage of Kelvin waves (Matthews 2021). While meridional wind anomalies are significantly weaker than those in the zonal wind, their presence indicates that variations in the background flow in the meridional direction may influence the propagation of Kelvin waves. Moreover, the meridional wind anomalies appear to be phase-shifted relative to the zonal wind. This structure indicates an eastward propagating convective envelope located south of the EAR site, with low-level inflow and upper-level outflow. Hence, observed horizontal wind anomalies are consistent with a convectively coupled Kelvin wave passing to the south of the observation point (Szkolka et al. 2023). Vertical wind data (Fig. 4c) show that before Day -2 upward anomalies dominate below 300 hPa height and the downward anomalies are present between 300 hPa height and the tropopause. Between Day -2 and Day +2, a pattern of westward-tilted structures in vertical velocity, downward anomalies followed by upward anomalies in the middle and upper troposphere, can be observed. This pattern of upward anomalies coincides with westward tilted easterly anomalies, indicating enhanced convection along the area of enhanced zonal wind convergence, with convection progressing from shallow to deep over time. The

Fig. 4 Composites of zonal (left column), meridional (middle column) and vertical (right column) wind anomalies from EAR for all analyzed CCKW events at EAR location. Vertical axis corresponds to altitude, while horizontal axis corresponds to time, from 6 days prior (Day - 6) to 6 days after (Day + 6) CCKW event. Top row show results for EAR data, bottom row—for ERA5 data. Green dots represent the altitude of cold point tropopause calculated for the composite temperature profile from soundings data



pronounced downward anomalies below 400 hPa height, observed later (after Day + 2), indicate suppressed convection in a wake of a propagating convective system. However, it is noteworthy that despite this, between 400 hPa height and the tropopause, after the period of downward anomalies on Day + 3, we again observe upward anomalies from Day + 4 onwards, likely related to stratiform clouds that can persist at those altitudes (Szkolka et al. 2023).

In the lower stratosphere, EAR data show a structure consistent with stratospheric Kelvin wave, as indicated by tilted anomalies in zonal wind above cold-point tropopause (Fig. 4a). This structure comprises tilted easterly anomalies below westerly anomalies. This pattern shows downward phase propagation. For example, easterly anomaly in Day

0 can be seen at 80–100 hPa height level, while it is found below 100 hPa height on Day + 2, merging with upper tropospheric easterlies. In vertical wind, alternating structures of downward and upward anomalies are observed, propagating downward over time (Fig. 4c). Importantly, around Day 0, these structures coincide with similar patterns in the zonal wind. Moreover, the downward anomalies correspond with easterly anomalies, while the upward anomalies align with westerly anomalies, consistent with theoretical structure of a stratospheric Kelvin waves (Kiladis et al. 2009).

ERA5 shows structures similar to EAR data across troposphere for both zonal and meridional winds variability (Fig. 4d, e). Zonal wind variability in the lower stratosphere is also well represented in reanalysis data. Structures in the

lower troposphere appear more coherent than in EAR observations—they are smoother and have larger spatial and temporal extension. Tilted easterly wind anomaly in ERA5 data appears to be preceded by a tilted westerly wind anomaly, with phase propagating downward at a rate consistent with other (easterly and westerly) crests, and merging with westerly wind anomaly in the upper troposphere on Day 0. The reanalysis shows variability in meridional wind in the lower stratosphere with the same time scale as EAR observations, but these structures in ERA5 are less regular and differently arranged.

The results presented in Fig. 4 indicate that although the CCKW is primarily a tropospheric phenomenon, and the theoretical Kelvin wave structure is evident in zonal and vertical winds, the CCKW is accompanied by stratospheric phenomena and disturbances in meridional wind. The stratospheric response appears to be a counterpart to the tropospheric structure of a CCKW, propagating in phase with it. This aligns with previous studies that have observed coherent troposphere-stratosphere structures in CCKWs (Straub and Kiladis 2002; Kiladis et al. 2009). Current composite analysis suggests dynamical coupling across the tropopause between tropospheric and stratospheric structures.

The easterly anomaly in the upper troposphere since Day 2 exhibits signs of interaction with both the westward tilt in the tropospheric component and the downward phase propagation in the stratospheric component. Similarly, westerly anomalies around the 200 hPa level appear to be linked to dynamical structures in both the troposphere and lower stratosphere. While a theoretical, uncoupled Kelvin wave in the stratosphere would be expected to propagate much faster than a tropospheric Kelvin wave, the observed coherence suggests that the stratospheric response may be continuously modulated by the CCKW rather than acting as an independent, freely propagating wave.

While composite analysis suggests this connection, it remains uncertain whether every CCKW has a stratospheric counterpart or whether the specific phase shift between tropospheric and stratospheric components plays a role in the evolution of a CCKW event. Additionally, the possibility that these structures arise from common external forcing, such as local invigoration of deep convection, should also be considered. Finally, it should be noted that ERA5 results show similar structures as EAR observations for horizontal winds. In the subsequent sections, we explore how stratospheric conditions and meridional wind shape the behavior of the CCKW as it propagates across the MC region.

3.5 Indices

The theoretical CCKW structure exhibits variations in tropospheric zonal and vertical winds which can explain

observed composite precipitation patterns. Our composites, however, reveal additional anomalies—particularly in tropospheric meridional wind and in the lower stratosphere—that deviate from this idealized scheme. To quantify these features for specific CCKW events during their passage across the EAR location, we introduce two indices designed to capture the strength of circulation in the troposphere and lower stratosphere, respectively. Each index is defined as the difference in wind anomalies between two layers. Hence, it represents a gradient of a specific wind component across those altitudes and its composite magnitude reflects the strength of circulation associated with a CCKW. The Stratospheric zonal wind Index (S_zI) quantifies zonal wind variations, and the Tropospheric meridional wind Index (T_mI) quantifies meridional wind variations (although either could be calculated from other wind components). For each index, two boxes in the time–altitude plane are selected for averaging, as shown in Fig. 5 and detailed in Table 1. Each box spans five EAR data levels during a specific day (24 h) relative to the CCKW event over the EAR location. S1 and S2 are the averaging regions for S_zI (Fig. 5a), while T1 and T2 define those for T_mI (Fig. 5b). These regions were chosen to quantify vertical shear in zonal and meridional winds. The indices were defined as the difference between box averages (S1–S2) on Day -2 for S_zI and the difference between box averages (T1–T2) on Day 0 for T_mI. Details of index definitions are provided in Table 1. Since these indices are defined based on wind anomalies, their long-term means are very small in comparison to their long-term standard deviations. The specific days for calculating each index were selected to yield the most distinct results, with the largest differences between CCKW events characterized by positive and negative index values. While S_zI index is based on observations prior to CCKW arrival, it can also provide the prognostic properties for CCKW behavior following interaction with weather over Sumatra.

CCKW events were divided into distinct groups based on the T_mI and S_zI indices, CCKWs that occurred when an index value exceeded half of its long-term standard deviation were qualified as positive index events, while those that showed values lower than negative half of its long-term standard deviation are considered negative index events. The choice of a threshold is designed to distinguish between opposing index values while providing enough cases for subsequent compositing. Out of 261 events (the total number), there were 80 positive S_zI and 61 negative S_zI events. The breakdown for T_mI shows 49 positive and 39 negative events. It should be noted that events within each group were evenly distributed over time, allowing us to exclude the effect of anomalous years or months as a potential cause of the differences in the results.

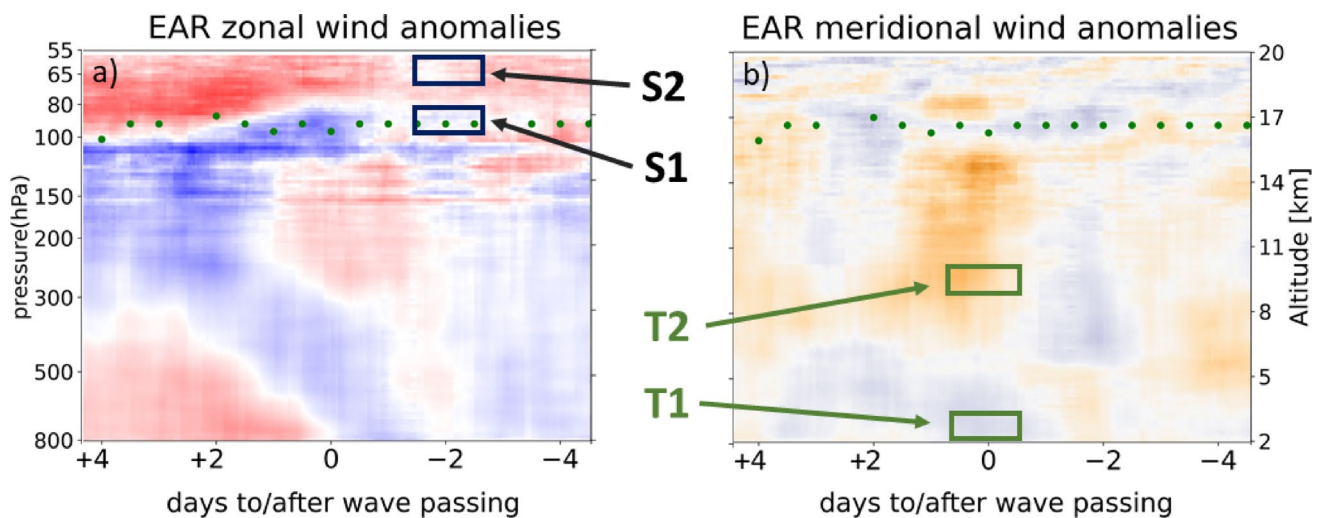


Fig. 5 Section of Fig. 4a) (left) and of Fig. 4b) (right) with marked boxes used to calculate tropospheric and Stratospheric zonal wind Index

Table 1 Details about stratospheric and tropospheric indices

Index	Day	Box 1 altitudes	Box 2 altitudes	NDJFM std
Stratospheric zonal wind Index (SzI)	Day -2	S1: 80–90 hPa height	S2: 55–65 hPa height	11.4 m/s
Tropospheric meridional wind Index (TmI)	Day 0	T1: 770–790 hPa height	T2: 240–260 hPa height	3.6 m/s

These event groups were used to calculate precipitation composites associated with them. Precipitation data for this analysis were smoothed spatially using 1-degree running average in both latitude and longitude. The patterns of intense rainfall defined as the precipitation that exceeds 0.5 standard deviation from the local mean were investigated for positive and negative SzI and TmI values.

3.6 Stratospheric zonal wind index

Figure 6 illustrates the evolution of indexed waves with intense precipitation defined as anomalies exceeding half of the standard deviation of precipitation filtered for CCKWs.

It is worth noting that for about 80% of grid points over the region of interest (the Maritime Continent), standard deviation is in the range of 15 and 25 mm/day during NDJFM.

For both groups, on Days -1 and 0, intense precipitation approaching Sumatra from the west is observed, which on Day 0 aligns along its western coast. In the following days, for positive SzI events, no extreme precipitation is observed over the MC. In contrast, for waves in negative SzI group, there is a distinct area of propagating heavy rainfall, which on Day +1 is located over central and eastern Borneo, and to the north of the Borneo island. By Day +2, the precipitation anomalies are reduced and located south of Borneo

and north of Sulawesi. Three days after the passage of the CCKW over Sumatra, a larger area of intense precipitation reappears between 0°N and 5°N and between 125°E and 135°E. In the subsequent days, this area shrinks but remains present and continues to propagate eastward.

These results indicate that the value of the Stratospheric zonal wind Index defined two days before the CCKW's arrival over Sumatra is related to propagation properties of the event and subsequent evolution of rainfall across the MC. Negative values of the index, corresponding to westerlies overlaying easterlies, i.e. stronger stratospheric response to a CCKW results in the intense rainfall likely propagating further across the MC towards the western Pacific. On the other hand, significantly higher values of SzI imply weakening of rainfall intensity associated with the CCKW in the following days.

Figures 7 and 8 are the same as Fig. 4 but for positive SzI events and negative SzI events. They present altitude–time cross-sections at the EAR location to examine the relationship between the strength of stratospheric circulation and CCKW propagation characteristics. An evolution of wind components reveals significant differences between positive and negative SzI events. It is especially true for the zonal and vertical wind. In the zonal wind within the troposphere, similar structures are observed in both groups for Day 0. However, magnitudes are different as easterly anomalies in the troposphere are smaller for positive SzI than for negative SzI events. In the stratosphere, a structure of a stratospheric Kelvin wave can be observed in both composites, but clearly phase-shifted between them. Near the tropopause at negative lags, positive zonal wind anomalies are present in positive SzI events, while negative zonal wind anomalies are observed for negative SzI events. This is consistent with

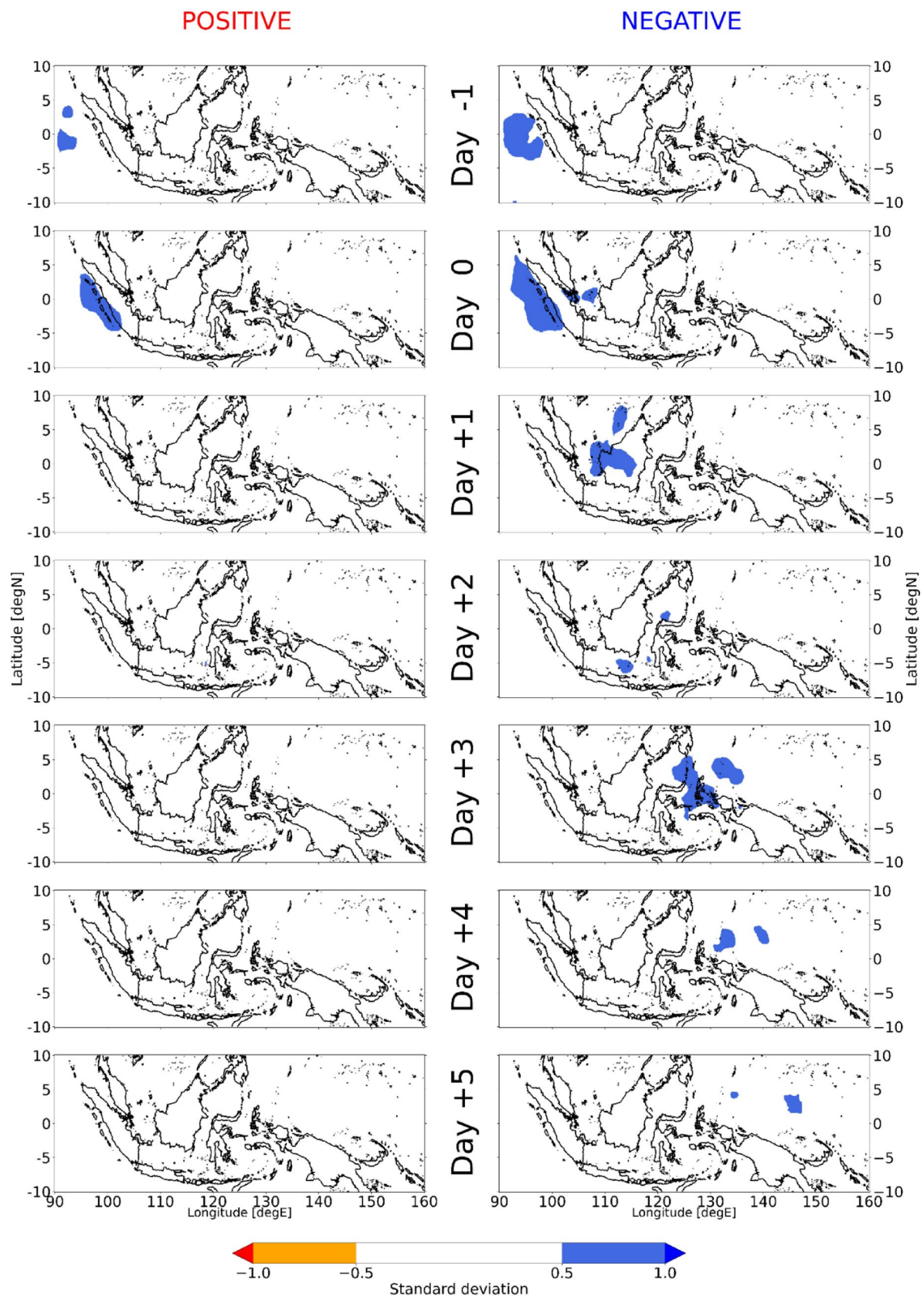


Fig. 6 Precipitation during the activity of the CCKW wave on consecutive days before and after the wave passage (rows from top to bottom correspond to Days from -1 to $+5$). Left column: results for waves with significantly higher Stratospheric zonal wind Index for zonal wind two days before the wave passage. Right column: same, but for waves with negative Stratospheric zonal wind Index. Precipitation exceeding ± 0.5 standard deviations from the mean at specific locations are highlighted

the classification of waves based on the stratospheric zonal wind index.

Easterly anomalies are observed around the tropopause for negative SzI events and show downward phase propagation. After Day $+1$ they merge with easterlies in the mid and upper troposphere. This could potentially affect the intensity of the tropospheric structure, particularly by enhancing zonal circulation, as reflected in the strong vertical shear of zonal winds, which appears to persist until Day $+6$ (Fig. 8a). On the other hand, positive SzI events show no such enhancement of zonal circulation behind a CCKW event. Hence, stronger circulation over EAR for positive lags indicates that the wave remains strong. Moreover, distinct vertical wind patterns in the mid and upper troposphere are observed for both groups prior to the arrival of a CCKW. Positive SzI events are characterized by downward anomalies (Fig. 7c), while negative SzI events show upward anomalies for negative lags (Fig. 8c). These results are consistent with theoretical structure of a stratospheric Kelvin wave, for which easterly anomalies coincide with downward anomalies, while westerly anomalies are associated with upward anomalies. Therefore, the phase of the stratospheric wave relative to the tropospheric CCKW component, at the time of its arrival over Sumatra, can influence the evolution of CCKW in the following days. CCKW remain stronger when SzI index is negative, which is characterized by easterly and upward wind anomalies. These anomalies can influence upper troposphere by bringing positive vertical wind anomalies before and during passage of an event (more intense convection) and upper-level zonal easterly anomalies in a wake of an event (stronger circulation).

3.7 Tropospheric meridional wind Index

Figure 9 presents the evolution of precipitation for positive TmI CCKW events (left column) and negative TmI CCKW events (right column). For both analyzed groups of waves we observe an approach of intense rainfall from the west towards Sumatra on Day -1 and Day 0 , with higher precipitation values for the positive TmI events. On Day $+1$, differences in precipitation evolution emerge: for the positive TmI events, the rainfall occurs predominantly on the southern side of Borneo, for the negative TmI group, a pattern of intense rainfall on the western side of Borneo is observed. On the following day, precipitation evolves

over the sea between Borneo and Sulawesi, with the positive TmI group precipitation located north of the equator, while for the negative TmI group, it is positioned south of the equator. Additionally, in the negative TmI group of waves, the area of intense rainfall has shifted further and significantly altered its latitude. For this group of waves, on Day $+3$, intense precipitation remains present over the MC—between Sulawesi and New Guinea, as well as near 3°N , 135°E —while for the positive TmI group, no patterns of intense rainfall are observed over the analyzed region. It is noteworthy that on Day $+4$, for both positive and negative TI, we observe a small area of enhanced precipitation to the northwest of New Guinea.

These results indicate that, even though idealized Kelvin wave has only zonal component, here the influence of meridional variations on the propagation of CCKWs is evident, as evidenced by the location of rainfall over the MC region in the days following the CCKW event passage over Sumatra.

To gain a better understanding of how tropospheric circulation can affect the propagation characteristics of a CCKW, Figs. 10 and 11 show altitude-time cross-sections at the EAR location (comparable to the results in Fig. 4) for positive and negative TmI events. We observe a distinct difference on the day of wave transition in the meridional wind: for the positive TmI group of waves, we have southerly anomalies below 500 hPa height and northerly anomalies above this level in the troposphere. An inverse structure occurs for the waves in the negative TmI group. It is noteworthy that these structures extend back to earlier days, starting from Day -2 . At the same time, for the positive TmI events, we observe easterly anomalies in the lower troposphere and upward anomalies in the layer below 500 hPa height during these days. In contrast, for the negative TmI events, there are northerly anomalies, and downward anomalies—which clearly differ from the results shown in Fig. 4 for all CCKWs.

In both cases, these anomalies are aligned with the Barisan Mountains in the horizontal plane—for the positive TmI group, the wind is oriented toward the northwest, while in the negative TmI group, it is directed toward the southeast. The vertical wind effect may be caused by changes in the diurnal propagation of precipitation over Sumatra itself, where anomalous easterlies hinder the propagation of precipitation from the mountains toward the land (Mori et al. 2004; Szkolka et al. 2023) and anomalous westerlies favor this propagation.

By combining the results for the lower tropospheric wind with the findings on precipitation propagation for both analyzed wave groups, we see that northwesterly winds favor the propagation of precipitation north of the equator, while winds in the opposite direction shift this precipitation to the

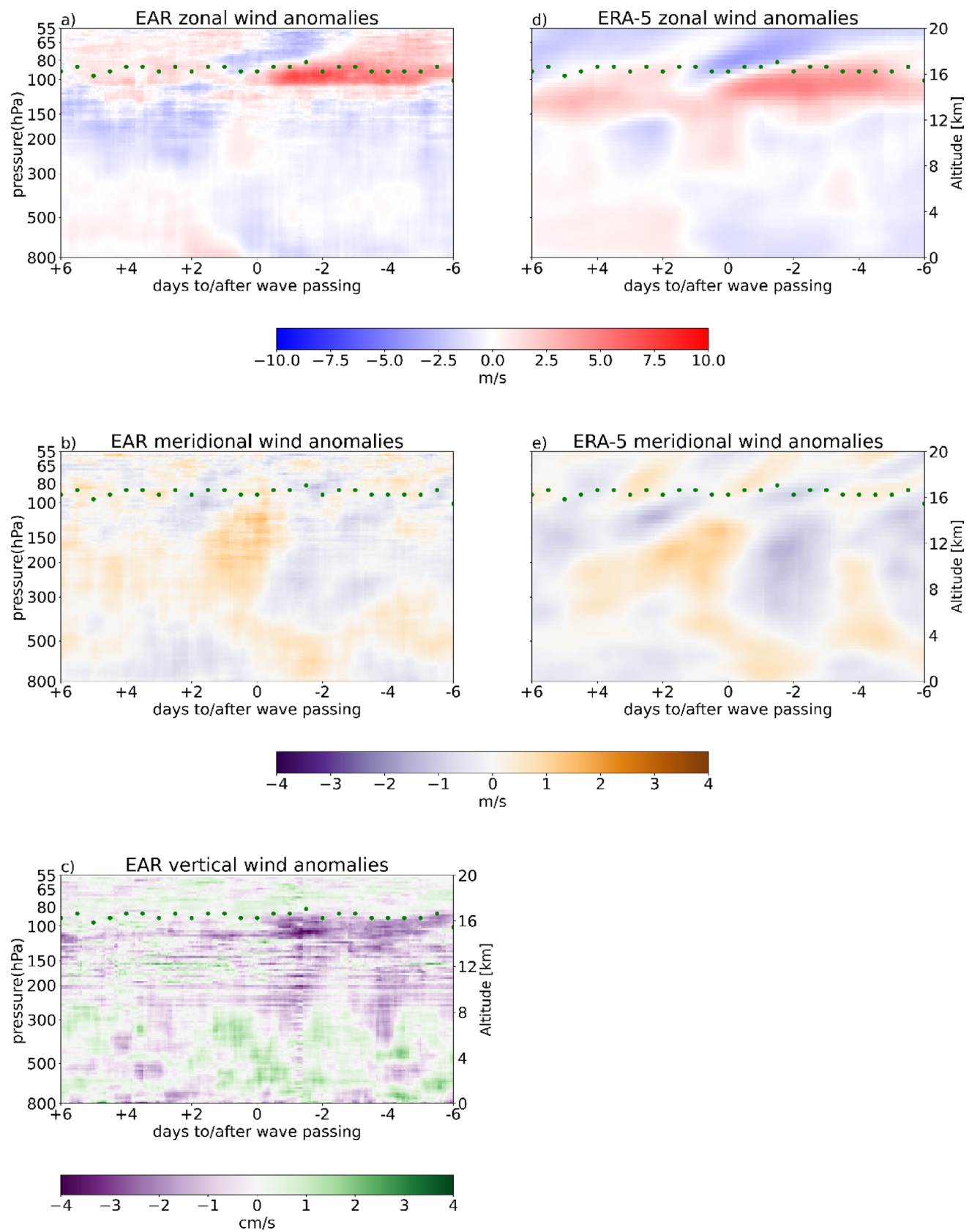


Fig. 7 Same as Fig. 4, but for composites of positive SzI CCKW events

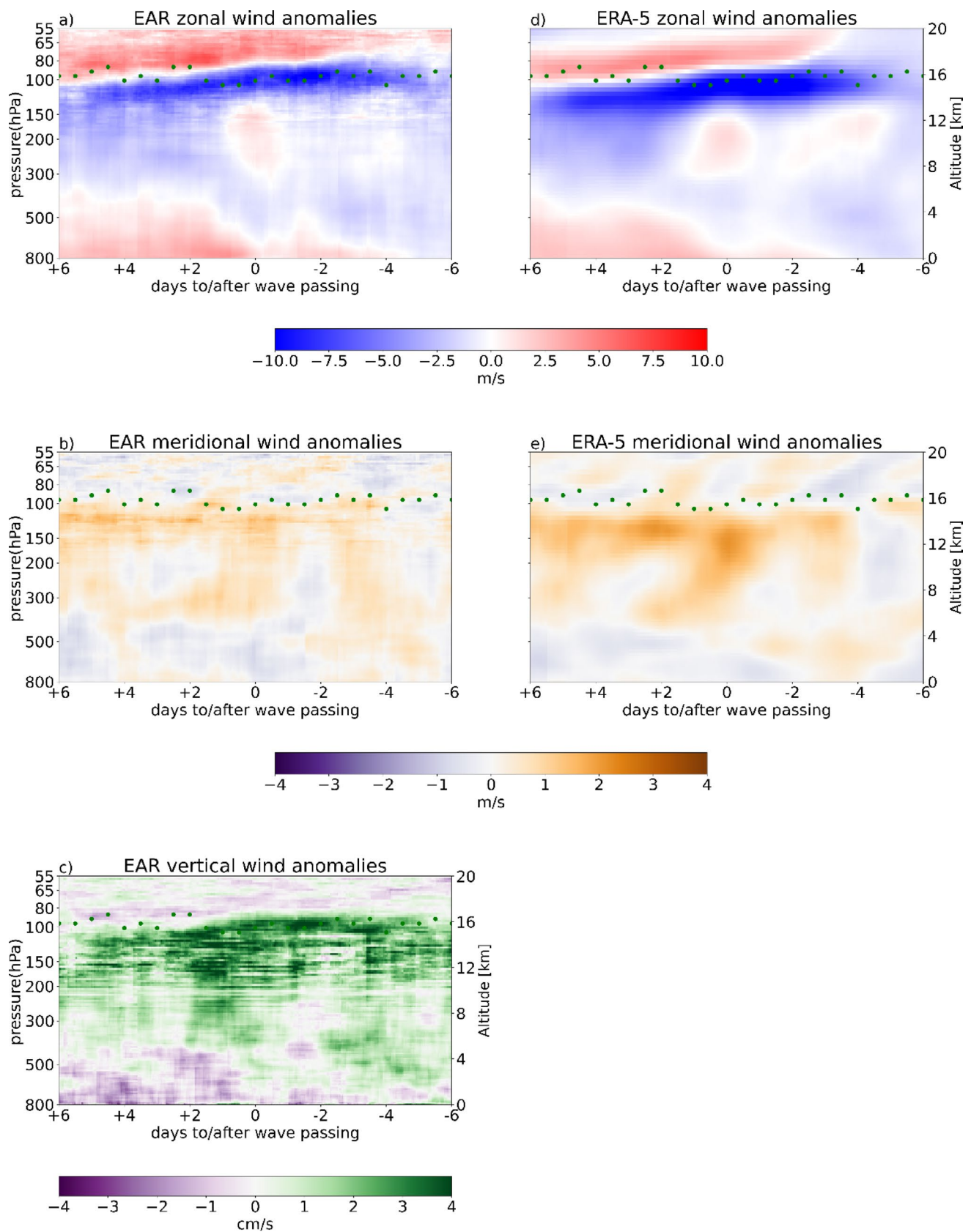


Fig. 8 Same as Fig. 4, but for composites of negative SzI CCKW events

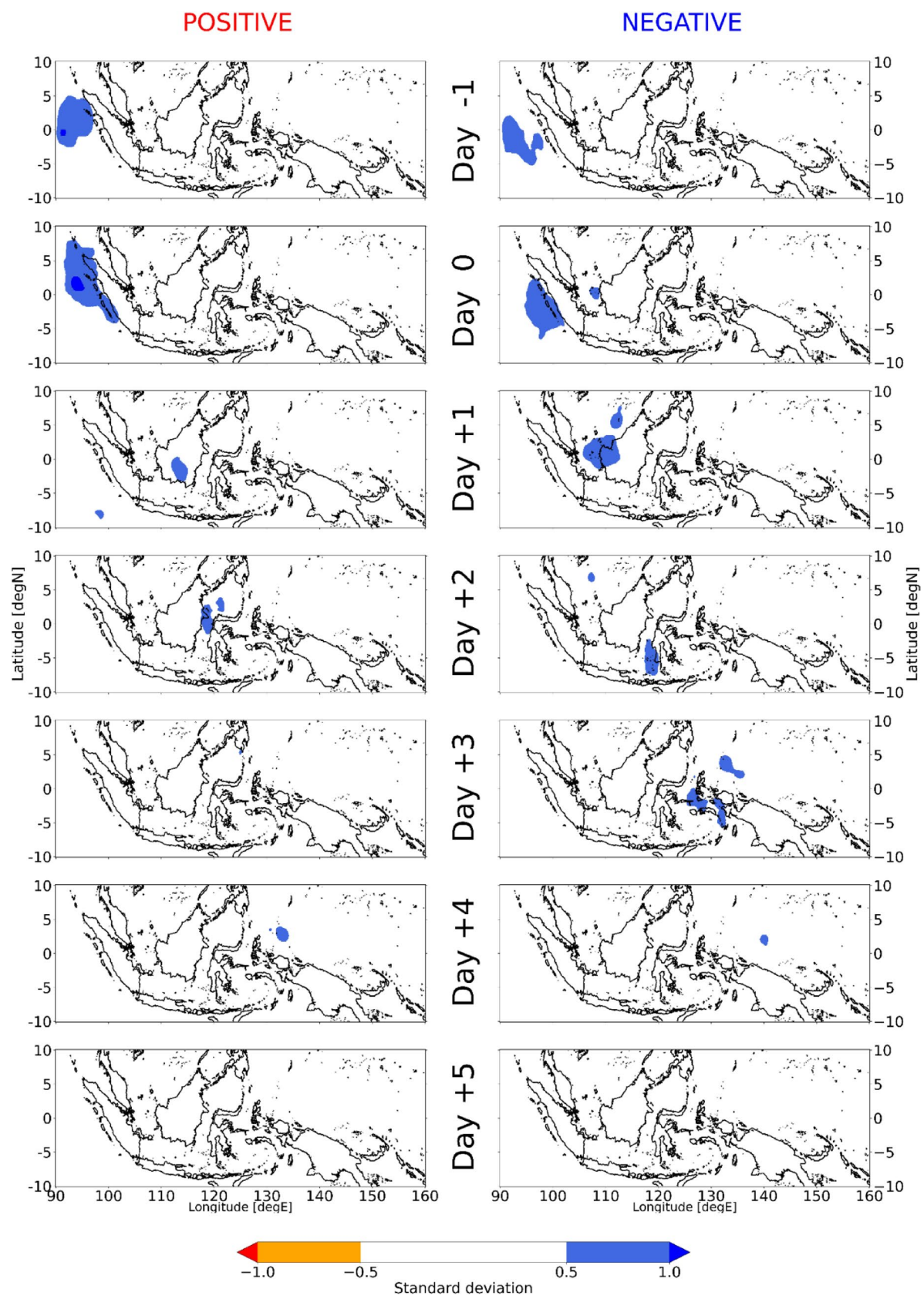


Fig. 9 Same as Fig. 6, but for Tropospheric meridional wind Index of meridional wind on the day of the CCKW event on Sumatra. Left column corresponds to the results for positive TmI group of waves, right—for the negative TmI group

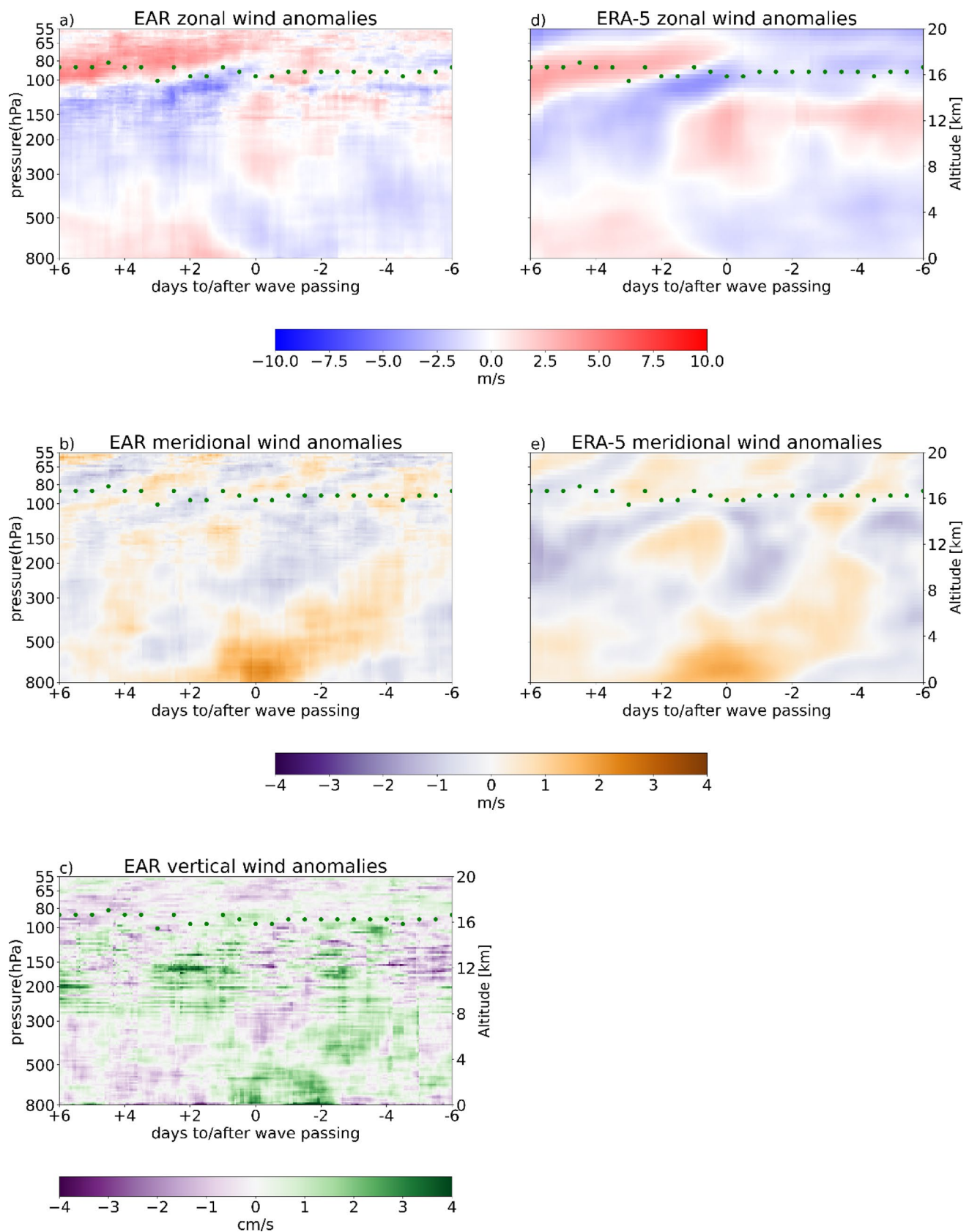


Fig. 10 Same as Fig. 4, but composites are made for positive TmI CCKW events

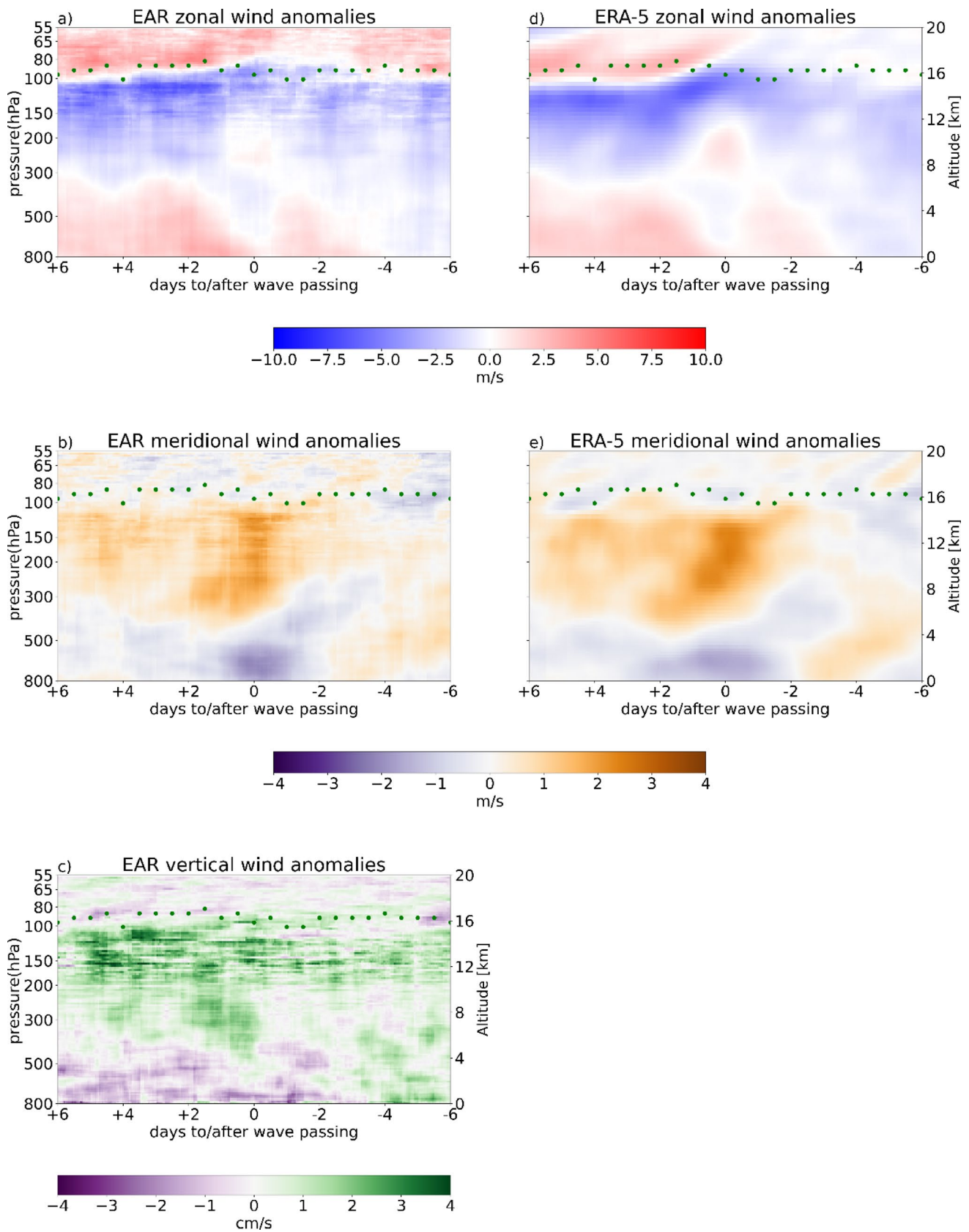


Fig. 11 Same as Fig. 4, but composites are made for negative TmI CCKW events

south of the equator (Day +2, Fig. 9). It is also worth noting that the probable influence of horizontal wind anomalies is visible as early as Day 0, when precipitation in the positive TmI group is displaced northward compared to that of the negative TmI group.

4 Summary

This study investigates dynamical structure across the troposphere and lower stratosphere associated with CCKWs as they propagate over Sumatra. On the basis of long-term (19 years) measurements from EAR, a Doppler radar facility in West Sumatra, ERA5 reanalysis and IMERGv6 precipitation estimates, variability in the zonal, meridional and vertical wind components is analyzed in the context of CCKW's precipitation footprint across the MC region. The results show that coherent dynamical structures across troposphere and lower stratosphere exist at a time of CCKW activity over the western flank of the MC, while their variations can constitute a predictor for CCKW characteristics, such as trajectory and rainfall amount, over the broader region. The key results are summarized below. The observed evolution of zonal wind in the lower troposphere closely matches the theoretical structure of a Kelvin wave propagating at a speed of approximately 10 m/s (Fig. 2). In addition, a coherent response is also evident in the lower stratosphere. While this stratospheric response exhibits a structure consistent with the theoretical stratospheric Kelvin wave pattern (Kiladis et al. 2009), our results show that this pattern propagates at the same speed as its tropospheric counterparts, and more than 2 times slower than a free, uncoupled stratospheric Kelvin wave (Pan et al. 2020). Hence, stratospheric structure observed here appears forced by the tropospheric CCKW.

Although theoretical Kelvin wave structure has been derived assuming zero background flow, particularly in a meridional direction, such conditions are clearly not present over eastern Indian Ocean and western MC during the extended boreal winter (Fig. 1). Therefore, CCKW dynamical structure projects onto meridional winds as well (Fig. 4). Northerlies in the lower troposphere tend to magnify at a time of CCKW propagation (Fig. 4) which can contribute to southward migration of a CCKW, as indicated by the fact that filtered precipitation variance is larger over the Java Sea rather than over the equator in proximity of the central MC (Fig. 1).

Results indicate that these two features can contribute to propagation properties of a CCKW as it traverses past Sumatra. Two indices were defined: the Stratospheric zonal wind Index which is a measure of a strength of zonal circulation in the lower stratosphere two days before a CCKW arrival at EAR location and the Tropospheric meridional wind Index,

which is a measure of meridional circulation over EAR on a day of CCKW arrival. It is shown that the Stratospheric and Tropospheric Indices constitute good prognostics of trajectories and precipitation progression across the entire MC region. Specifically, negative Stratospheric zonal wind Index leads to stronger than typical rainfall over the MC following the CCKW's passage over Sumatra. The Tropospheric meridional wind Index values can be used to prognose trajectories of CCKWs past Sumatra. Positive Tropospheric meridional wind Index values show precipitation primarily north of the equator, negative index values are associated with enhanced rainfall diverted to the southern hemisphere. This finding underscores the importance of both stratospheric and meridional wind dynamics in modulating the precipitation response to CCKW events, suggesting a more complex interaction between atmospheric layers than previously understood. Potentially, tropospheric and Stratospheric zonal wind Index can serve as prognostic tools in forecasting precipitation footprint of CCKW events based on observations. These results also highlight a need for further investigation into the mechanisms driving coupling between tropospheric and stratospheric circulations in CCKWs as well as interactions with background flow.

The use of EAR data has proven highly beneficial in capturing detailed wind structures during the CCKW events. Such observations are beneficial for improving weather forecasting over the MC. By providing high-resolution wind variability data, particularly in the lower and upper atmosphere, EAR helped to better understand the complex dynamics of wave-precipitation interactions. This, in turn, enhances the predictability of rainfall patterns associated with CCKWs in the Maritime Continent region.

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Continent” program managed by Eric T. DeWeaver and by National Science Centre (NCN) of Poland, grant no. 2022/45/B/ST10/03836.

Data availability Equatorial Atmosphere Radar data are provided by Research Institute for Sustainable Humanosphere of Kyoto University and available on: <http://www.rish.kyoto-u.ac.jp/ear/data/data/ver02.0212/>. The ERA-5 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>). The IMERG (Integrated Multi-satellite Retrievals for GPM) v6 daily database is part of the Global Precipitation Measurement (GPM) mission, managed by NASA. You can access the IMERG v6 data through NASA's Goddard Earth Sciences Data and Information Services Center (GES DISC).

Declarations

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

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