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RESEARCH ARTICLE

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Comparisons of reanalysis and measured lower-troposphere winds over a portion of equatorial Africa

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Abstract

Despite lower-troposphere wind flow being a major control of rainfall in equatorial Africa, no studies have systematically compared winds from multiple reanalyses nor have attempted to validate the wind directions. Therefore, the objectives of this study are to assess differences in wind directions among multiple reanalysis products and compare reanalysis winds with wind measurements made at weather stations. The study region is western Uganda, part of the transition region between western equatorial Africa (WEA) and eastern equatorial Africa (EEA). Four-times daily (i.e., 0Z, 6Z, 12Z and 18Z) 10-m and 850-hPa winds from 1980 to 2021 are obtained for ECMWF Reanalysis v5 (ERA5), Japan Meteorological Agency 55-year Reanalysis (JRA55), Modern-Era Retrospective analysis for Research and Applications Version 2 (MERRA2), NCEP-NCAR Reanalysis 1 (R1) and NCEP/DOE Reanalysis II (R2). Wind measurements at 10 m and 850 hPa are obtained for six weather stations and two weather stations, respectively. Agreements between pairs of products and between measurements and reanalysis estimates are determined. In addition, differences between reanalyses and measurements with respect to wind vectors are calculated. Results show that the majority of reanalyses have western Uganda within the prevailing easterly flow over EEA and east of the prevailing westerly flow over WEA. Ten-meter wind measurements also show easterly flow being prevalent throughout western Uganda. R1 is unique among the products due to a relatively large number of westerly days. However, much of the westerly flow is likely artificial, based on station data. MERRA2 has large easterly biases. JRA55 is much more accurate than the other products at reproducing the intra-annual frequencies of wind directions. JRA55 and ERA5 are the least biased products based on the magnitudes of difference vectors. Therefore, it is recommended that JRA55 and ERA5 continue to be used in examinations of winds in western Uganda.

KEYWORDS

equatorial Africa, ERA, JRA, lower troposphere, MERRA, NCEP, reanalysis, winds

1 | INTRODUCTION

Lower-troposphere wind flow is a major control of rainfall amount and timing in equatorial Africa and thus that flow is of great importance to smallholder farmers. Flow from the Atlantic Ocean and Congo Basin is generally westerly and results in humid, unstable air, while the flow from the Indian Ocean is mostly northeasterly and southeasterly (i.e., the monsoons) and results in thermally stable air that is generally drier than the Congo air mass (Nicholson, 1996). Eastern equatorial Africa (EEA) is presumed to be dominated by easterlies with few incursions of westerlies (Finney et al., 2020). Westerlies prevail across western equatorial Africa (WEA) (Dezfuli, 2017) and are stronger in boreal autumn than in boreal spring (Creese & Washington, 2016; Dyer et al., 2017). The confluence zone between the Atlantic/Congo air masses and the Indian Ocean air mass is the Congo air boundary (CAB) (Nicholson, 2000). Since there is a seasonality to the position and intensity of convection within both the CAB and the tropical rainbelt, a biannual (i.e., bimodal) rainfall regime prevails across much of equatorial Africa, with the two rainy seasons in boreal spring and autumn (Creese & Washington, 2018; Nicholson, 2017). The onset and duration of these rainy seasons structure the agricultural practices of millions of rural households in equatorial Africa (Cooper et al., 2008; Zougmoré et al., 2018). Farmers typically make on-farm decisions based on observations of seasonal rainfall (Crane et al., 2011; Salerno et al., 2019; Wilkie et al., 1999), and use multiple environmental markers to estimate rainy season onset, including in some locations a change in wind direction that typically precedes the onset of rainy seasons (Okonya & Kroschel, 2013). Failure to notice changing patterns can adversely impact yields (Salerno et al., 2022). Households are further impacted by interannual variability that causes both drought (Nicholson, 2014) and excessive rainfall (Farrow et al., 2011; Ngecu & Mathu, 1999; Okonya et al., 2013).

Across equatorial Africa, except for the far eastern portion of EEA (Figure 1), studies involving reanalysis wind products have shown that westerly winds tend to be associated with enhanced rainfall either at the daily or seasonal timescale. Westerly anomalies—which may either represent anomalous westerly flow or reduced easterly flow—are present in EEA during boreal spring (Berhane & Zaitchik, 2014; Camberlin & Philippon, 2002; Pohl & Camberlin, 2006a, 2006b), boreal summer (Jury, 2018; Segele et al., 2009; Viste & Sorteberg, 2013) and boreal autumn (Berhane & Zaitchik, 2014; Mapande & Reason, 2005; Pohl & Camberlin, 2006a). The anomalies can extend up to 700 hPa (Segele et al., 2009). For the EEA-WEA transition zone, which includes western Uganda, Rwanda and Burundi, westerly anomalies are present across equatorial Africa to at least 500 hPa during rainfall days in the region in both boreal spring and autumn (Diem et al., 2019). Increased westerly flow contributes to increased seasonal rainfall throughout the year in WEA (Cook & Vizy, 2016; Dezfuli & Nicholson, 2013; Dyer et al., 2017, 2018; Nicholson & Dezfuli, 2013; Todd & Washington, 2004). Westerlies also have been associated with increased daily rainfall throughout the year in the WEA-EEA transition zone (Diem et al., 2019) and in EEA (Berhane & Zaitchik, 2014; McHugh, 2004; Mutai & Ward, 2000). Finally, westerlies have been shown to be the dominant wind direction during wet boreal springs in the WEA-EEA transition zone (Ngarukiyimana et al., 2018) and in EEA during relatively wet Augusts (Berhane et al., 2014).

Despite the findings of westerlies being an important aspect of rainfall production in equatorial Africa, there is a deficit in the understanding of the prevalence of westerly and other winds across the region. Little is known about the frequencies of specific winds (e.g., westerlies) from various reanalysis products. There also do not appear to be any systematic validation studies of lower-troposphere winds from reanalyses, and this is important because reanalyses are used to test the validity of climate models (Taguela et al., 2022). Therefore, the objectives of this study are to (1) assess differences in wind directions among multiple reanalysis products and (2) compare reanalysis winds with winds measured at weather stations.

2 | STUDY REGION

Western Uganda is on the far western edge of EEA and, as noted above, has rainfall that is transitional between that of EEA and WEA. The livelihoods of millions of western Ugandan households (with some of the most concentrated and fastest growing populations globally) depend on rainfed agriculture (Salerno et al., 2018). Northwestern Uganda has an annual (i.e., unimodal) rainfall regime, with rainfall occurring primarily during late March to late November while southwestern Uganda has a biannual rainfall regime, with rainfall occurring mostly from mid-March to Mid-May and again from early August through November (Diem et al., 2019) (Figure 1c). Based on teleconnections between rainfall and sea surface temperatures (SSTs), northwestern Uganda is more similar to EEA and southwestern Uganda is more similar to CEA; for example, only northwestern Uganda has increased rainfall associated with SST patterns resembling a positive Indian Ocean dipole or El Niño (Diem et al., 2021).

Western Uganda is an ideal region within equatorial Africa to initially examine potential biases in lower-

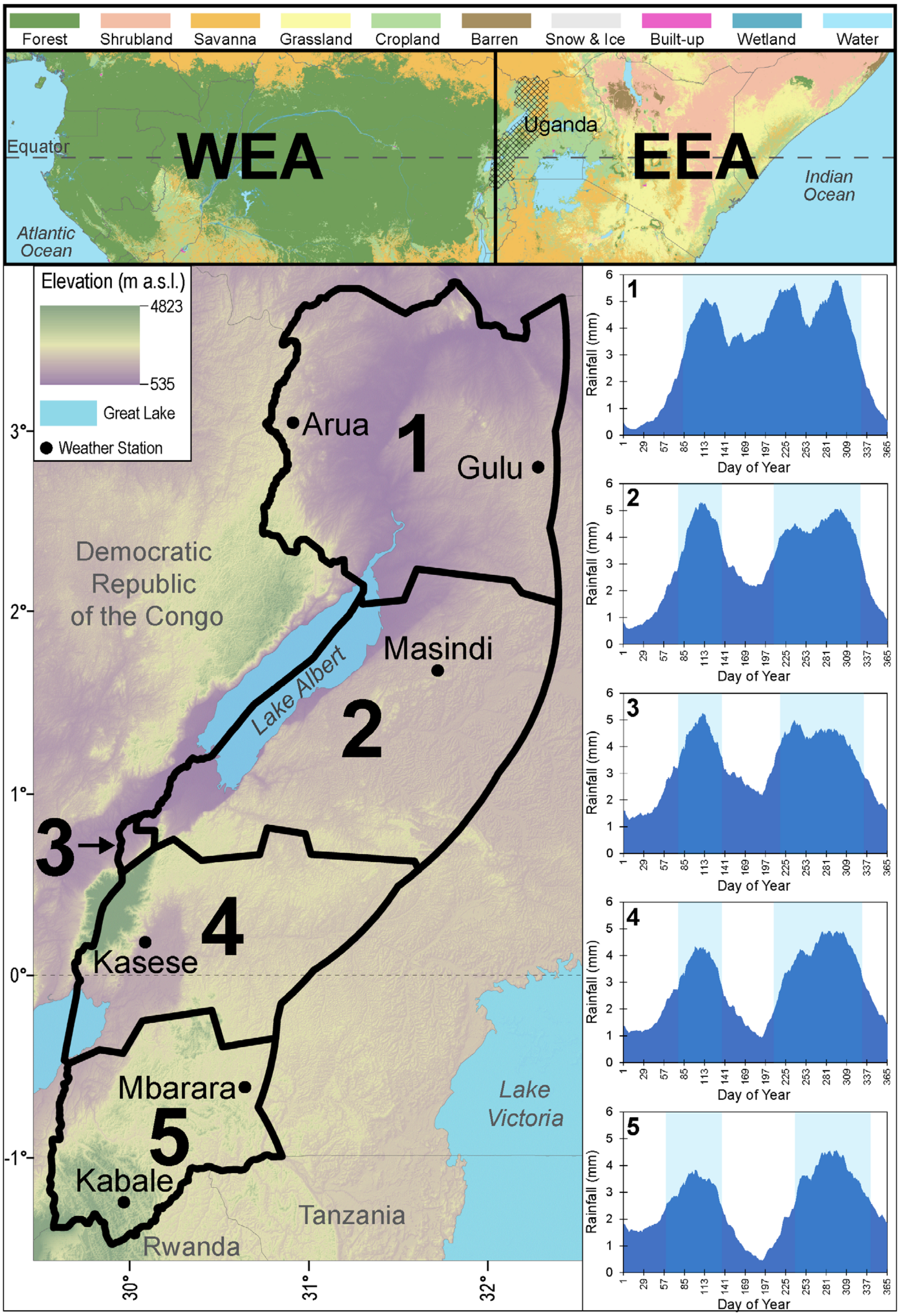

FIGURE 1 The location of western Uganda (hatched) within equatorial Africa, the five rainfall regions in western Uganda, and six weather stations, along with the mean daily rainfall totals of each region. WEA is western equatorial Africa and EEA is eastern equatorial Africa. Land-cover information in the top panel is derived from the Moderate Resolution Imaging Spectroradiometer land-cover type product (MCD12Q1). Rainfall regions and daily rainfall totals are after Diem et al. (2019). The rainy season(s) for each region are denoted by shading [Colour figure can be viewed at wileyonlinelibrary.com]

troposphere wind from reanalysis products. It is one of the most likely parts of East Africa to be impacted by Congo westerlies; for example, back trajectories extending over the Congo Basin have been shown to be the most frequent trajectories during the boreal-autumn rains (Diem et al., 2019). But easterlies are likely more prevalent than westerlies, since the mean 850-hPa flow over western Uganda has been shown to be easterly (e.g., Nicholson, 2016). Finally, subdaily measurements of near-surface winds at multiple weather stations have been done for the past several decades and some radiosonde measurements exist for a few years, thereby enabling an assessment of the reanalyses.

3 | DATA

Near-surface and lower-troposphere winds from five reanalysis products were obtained for 1980–2021. The five products were as follows: ECMWF Reanalysis v5 (ERA5; Hersbach et al., 2020), Japan Meteorological Agency 55-year Reanalysis (JRA55; Kobayashi et al., 2015), Modern-Era Retrospective Analysis for Research and Application Version 2 (MERRA2; Gelaro et al., 2017), NCEP-NCAR Reanalysis 1 (R1; Kalnay et al., 1996) and NCEP/DOE Reanalysis II (R2; Kanamitsu et al., 2002). Mean annual 10-m and 850-hPa zonal- and meridionalwinds data for equatorial Africa were obtained from Physical Sciences Laboratory of the National Oceanic and Atmospheric Administration (NOAA). ERA5, JRA55 and MERRA2 have much finer spatial resolutions than R1 and R2 (Table 1). R1 and R2 also are older reanalyses and should have more shortcomings than the other products (Fujiwara et al., 2017). Wind-vector data at both 10 m and 850 hPa were acquired 0Z, 6Z, 12Z and 18Z were acquired for all of western Uganda. Daily wind values were the mean of the values at the 4 h. In addition, 850-hPa wind data at 6Z and 12Z for 1973–1976 were acquired for ERA5, JRA55 and R1. Those data were needed for comparisons with radiosonde measurements made via balloons. MERRA2 and R2 were not used, because data for those products begins after the balloon campaign ended.

TABLE 1 Spatial resolutions and data sources of the wind data from the five reanalysis products

Product	10 m (°)	850 hPa (°)	Data source
ERA5	0.250 × 0.250	0.250 × 0.250	European Union's Earth Observation Program
JRA55	0.563 × 0.562	1.250 × 1.250	University Corporation for Atmospheric Research
MERRA2	0.500 × 0.625	0.500 × 0.625	National Aeronautics and Space Administration
NCEP1	1.875 × 1.904	2.500 × 2.500	National Oceanic and Atmospheric Administration
NCEP2	1.875 × 1.904	2.500 × 2.500	National Oceanic and Atmospheric Administration

Ten-meter winds measured at six weather stations in western Uganda (Figure 1) were obtained from NOAA's Integrated Surface Database for all days from 1980 through 2021. Nearly all the measurements at the six stations were between 4Z and 15Z, with the two most frequent measurement hours being 6Z and 12Z (Figure S1, Supporting Information). Therefore, daily values for this study were the mean of 6Z and 12Z values. The number of days with valid wind data (i.e., the day had both valid 6Z and 12Z measurements) ranged from 1524 to 3026 (Table 2).

850-hPa winds measured via radiosondes on pilot balloons were obtained from NOAA's Integrated Global Radiosonde Archive for all available days from 1973 through 1976. The balloons were launched at the Masindi and Kasese weather stations. Nearly all measurements occurred at either 6Z or 12Z. At Masindi, there were 303 days with 6Z measurements and 118 days with 12Z measurements. At Kasese, there were 148 days with 6Z measurements and 179 days 12Z measurements. Measurements at both 6Z and 12Z occurred on only 33 days at Masindi and 50 days at Kasese.

4 | METHODS

Near-surface and 850-hPa winds from the five products for 1980–2021 were examined at the mean annual scale at both the geographic scale of equatorial Africa and at the geographic scales of rainfall regions of western Uganda. Surfaces of mean annual 10-m winds were created for equatorial Africa. Product-specific wind data for each rainfall region were a weighted mean of the values of the grid cells that existed within the rainfall region. Grid cells with more coverage in a rainfall region received more weight than other grid cells. Wind roses showing the frequency and mean wind speeds of eight

TABLE 2 Weather stations in western Uganda where wind observations were made

Station	Longitude (°)	Latitude (°)	Elevation (m.a.s.l.)	First day	Last day	Total days
Arua	30.917	3.050	1211	1985/02/28	2021/12/25	3026
Gulu	32.272	2.806	1070	1982/11/01	2021/12/22	2218
Masindi	31.717	1.683	1147	1991/11/29	2021/12/25	2347
Kasese	30.100	0.183	961	1984/01/08	2021/12/25	2171
Mbarara	30.650	−0.617	1413	1981/10/13	2021/12/25	2717
Kabale	29.983	−1.250	1869	1992/03/06	2021/12/22	1524

Note: The first and last date and total days refer to days when there were valid observations at both 6Z and 12Z.

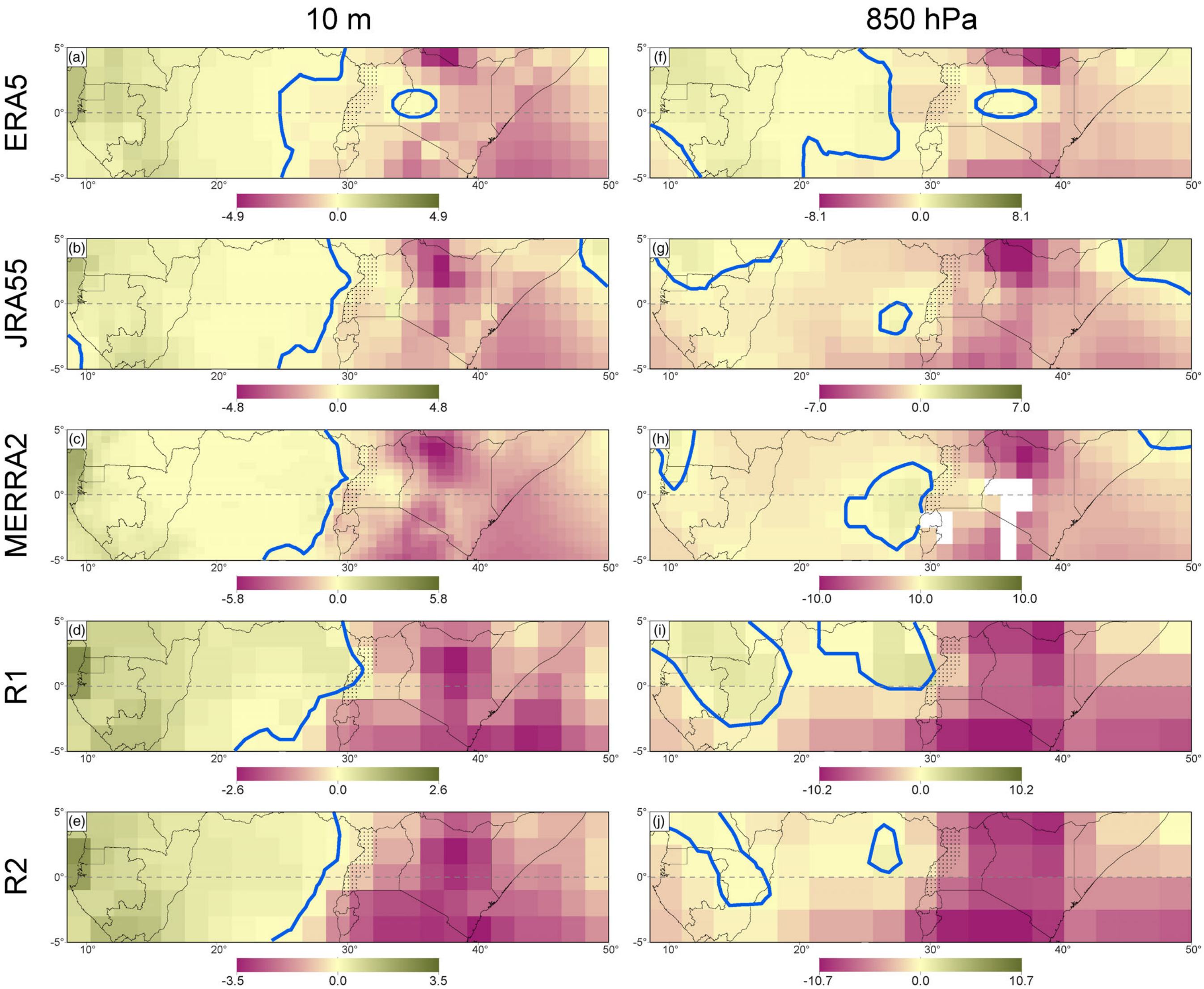

FIGURE 2 Mean annual zonal flow (in m·s^{-1}) across equatorial Africa for 1980–2021 at 10 m (a–e) and 850 hPa (f–j) for the five reanalysis products. Negative (positive) values are easterly (westerly) flow. The blue lines are the boundaries between easterly and westerly flow (i.e., locations where the u vector equals zero). Western Uganda is denoted by stippling [Colour figure can be viewed at wileyonlinelibrary.com]

wind directions were created for each rainfall region. The rainfall regions, which are described in detail (Diem et al., 2019), used in this study are Regions 1, 2, 4 and 5 (Figure 1). Region 3 was not used because it is also smaller than the grid cells of the reanalysis products. Region 1 has an annual rainfall regime, with the one long rainy season occurring from late March to mid-November, while the other regions have biannual rainfall regimes, with the first rainy season and second rainy seasons generally occurring during March–May and August–November, respectively (Diem et al., 2019).

Agreements among the reanalysis products for each region were calculated with respect to mean annual frequencies and mean monthly frequencies of the of the eight wind directions over 1980–2021. The eight wind directions were each 45° and were centred on north, northeast, east, southeast, south, southwest, west and northwest. Mean proportions of days for each of the eight wind directions (i.e., proportion of days with northerly winds, northeasterly winds, etc.) was used for the annual agreement calculations. This resulted in one index value calculated for each pair of products for each rainfall region. Mean proportions of days for each month of the year and each of the eight wind directions (e.g., the proportion of northerly winds in January, February, etc.) were used for the monthly agreement calculations; as a result, eight index values, corresponding to the wind directions, were calculated

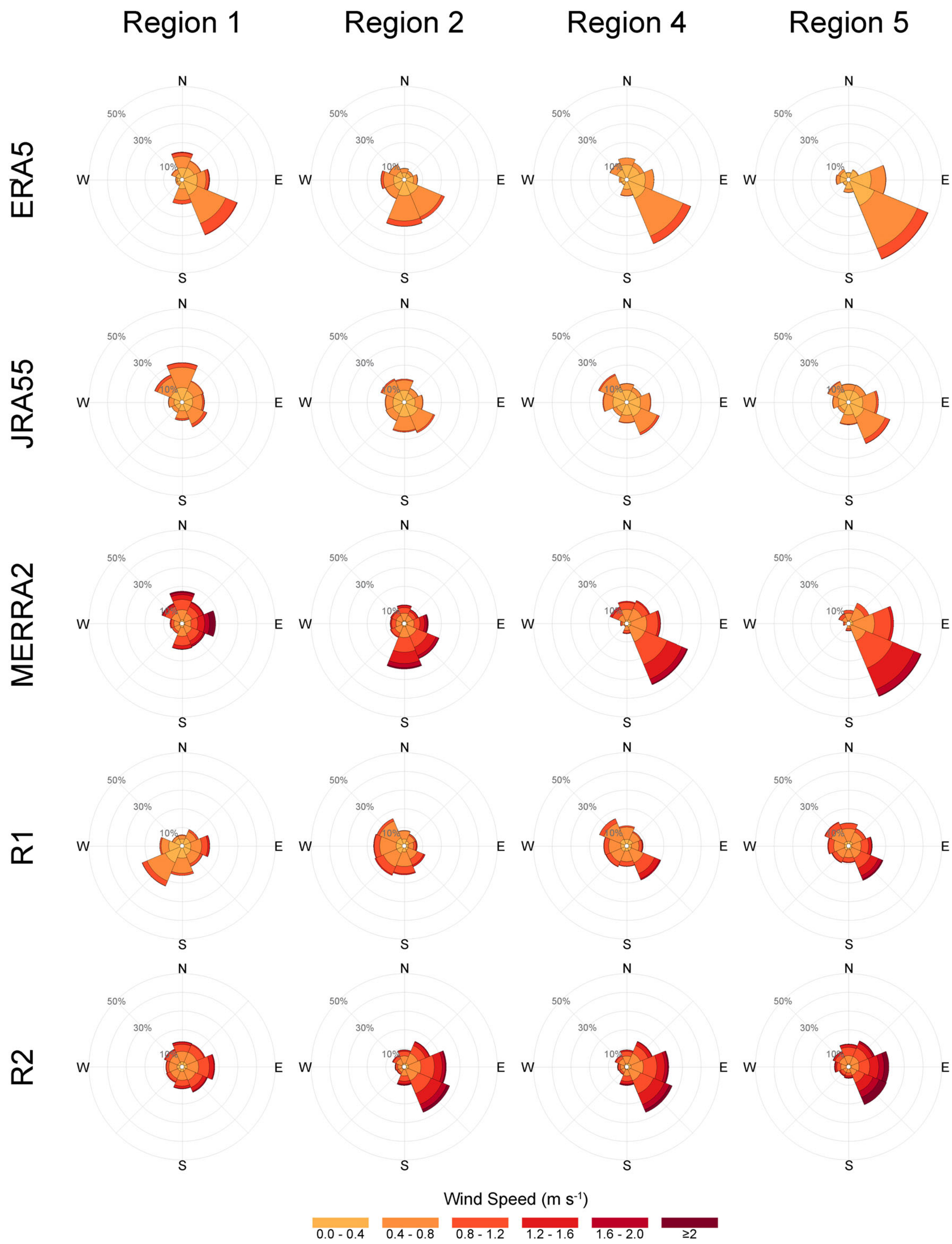

FIGURE 3 Wind roses with 10-m wind information from all days from 1980 to 2021 from the five reanalysis products for the four regions [Colour figure can be viewed at wileyonlinelibrary.com]

for each pair of products for each rainfall region. The revised version of Willmott's index of agreement (Willmott et al., 2012) was used, and the calculation of the index (d_r) is shown below,

$$d_r = 1 - \frac{\sum_{i=1}^{n} |P_i - O_i|}{2\sum_{i=1}^{n} |O_i - \overline{O}|}, \quad (1)$$

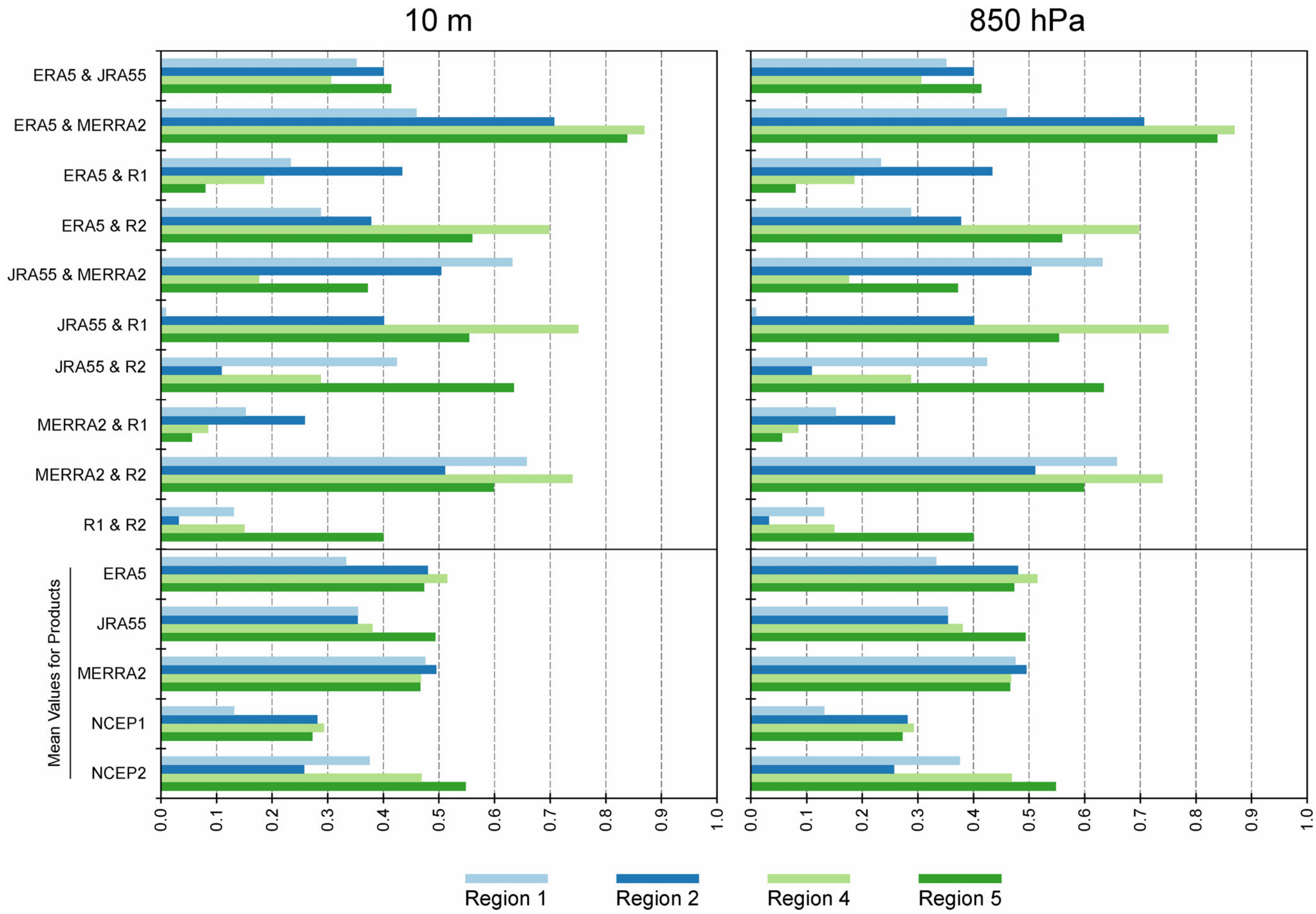

FIGURE 4 Indices of agreement (d_r values), based on annual frequencies of the eight wind directions, for all pairs of reanalysis products for 10 m and 850 hPa. The mean d_r values for the products also are included. The more positive the values the stronger the agreement [Colour figure can be viewed at wileyonlinelibrary.com]

when

$$\sum_{i=1}^{n}|P_i-O_i|\le 2\sum_{i=1}^{n}|O_i-\overline{O}|, \tag{2}$$

$$d_r=\frac{2\sum_{i=1}^{n}|O_i-\overline{O}|}{\sum_{i=1}^{n}|P_i-O_i|}-1, \tag{3}$$

when

$$\sum_{i=1}^{n}|P_i-O_i|>2\sum_{i=1}^{n}|O_i-\overline{O}|, \tag{4}$$

where O is observed, P is predicted and n is the number of cases. The index ranges from −1 to +1, with +1 indicating perfect agreement and negative values indicate strong disagreement. For each pair of products, the index was calculated with one product as the observed and the other as predicted and then calculated again with the roles of the products reversed the index was calculated twice, and the mean of the two values was used.

Reanalysis estimates of 10-m winds were compared with 10-m wind measurements at the six weather stations. The reanalysis data that corresponded to a station were those data in the grid cell in which the station existed. For each station and wind-direction sector, the number of measured and reanalysis-predicted days in each month of the 12 months with that wind direction were tabulated. Using those data, d_r values were calculated for each combination of station, sector and reanalysis product. In addition, differences between the reanalyses and the measurements with respect to the u and v components of the wind vectors were calculated, thereby yielding difference vectors.

Estimates of 850-hPa winds by ERA5, JRA55 and R1 were compared with 850-hPa wind measurements at

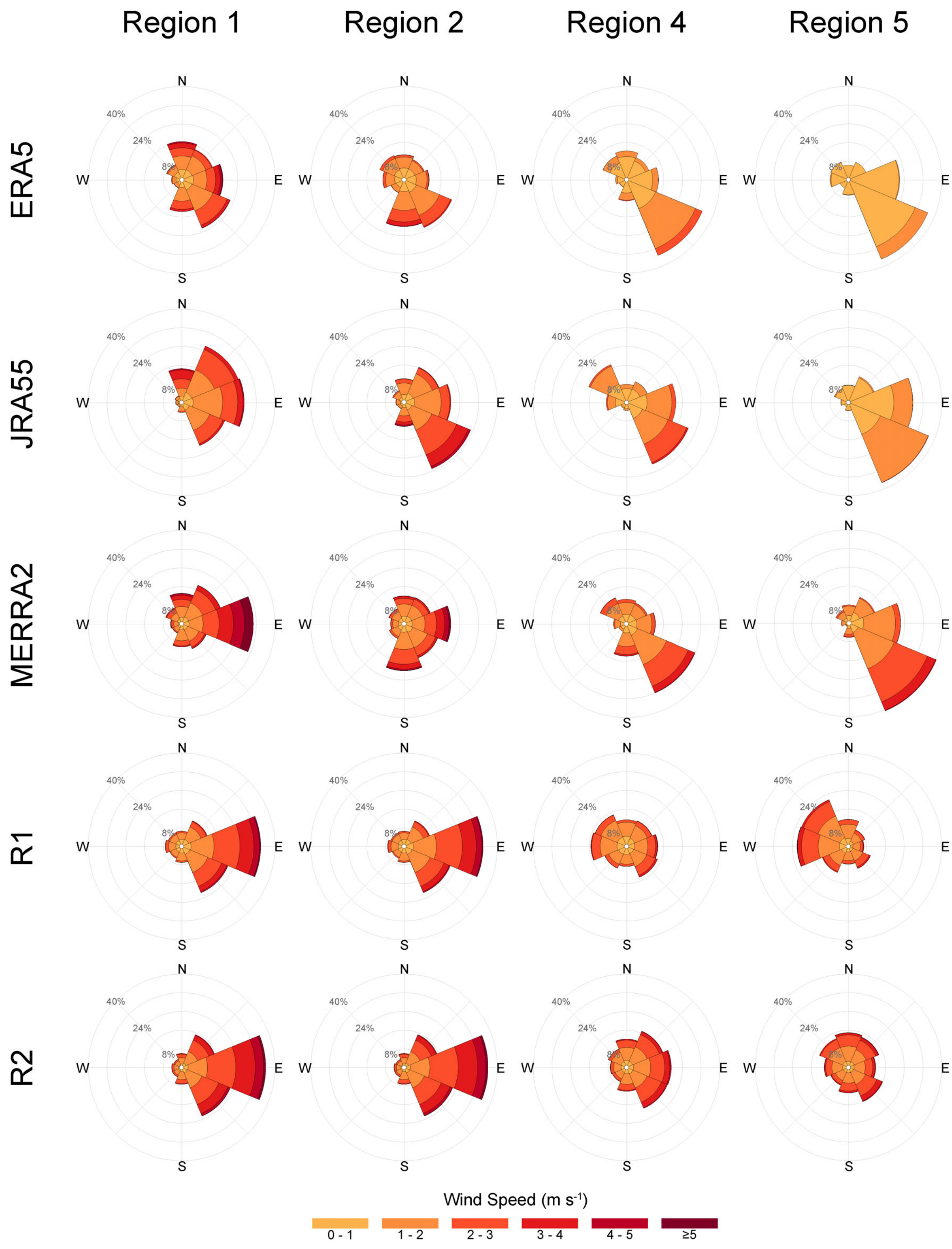

FIGURE 5 Wind roses with 850-hPa wind information from all days from 1980 to 2021 from the five reanalysis products for the four regions [Colour figure can be viewed at wileyonlinelibrary.com]

Masindi and Kasese. The reanalysis data that corresponded to each weather station were those data in the grid cell in which the station existed. For 6Z and 12Z data separately, differences between the reanalyses and the measurements with respect to the *u* and *v* components of the wind vectors were calculated.

5 | RESULTS

5.1 | Reanalysis winds at the annual scale

Based on near-surface winds from all reanalysis products, western Uganda was typically east of the prevailing westerly flow over WEA and within the prevailing easterly flow over EEA (Figure 2). The magnitude of easterly flow over EEA was on average four times the magnitude of westerly flow, which represents Congo westerlies, over WEA. The *u*-vector zero contour for all five products was situated either immediately west of or over western Uganda. R1 had the westerly flow extending the farthest eastward, with the westerly winds over parts of western Uganda. ERA5 had westerly flow constrained within the Congo basin and thus up to 700 km west of the extent of the westerly flow in R1. But ERA5 did have some westerly flow east of western Uganda: it was the only product that had a small area of westerly flow in EEA over western Kenya. The westerly flow is presumably a meso-scale phenomena from Lake Victoria (Woodhams et al., 2022).

Western Uganda was typically well within the easterly 850-hPa flow zone over equatorial Africa (Figure 2b). Similar to 10-m winds, easterly flow dominated over EEA and the magnitude of the flow over EEA was much larger than the magnitude over WEA. However, in contrast to 10-m winds, westerly flow only existed in portions of WEA. Therefore, all products show the Congo westerlies for the most part confined to below 850 hPa. Finally, the flow over WEA was considerably weaker than the flow over EEA.

R1 was the most different product with respect to frequencies of 10-m wind directions in northwestern Uganda, and considerable differences among the reanalysis products make it difficult to generalize typical frequencies of 10-m wind directions in the region (Figures 3 and 4). The most similar products for Region 1 were JRA55, MERRA2 and R2, and those products had little variation in frequencies among wind directions. ERA5 and R1 were the outlier products: ERA5 had southeasterly winds as the most frequent, while R1 had southwesterly winds as the most frequent. There was a large difference in the frequencies of northeasterly to southeasterly winds (i.e., "easterly" winds) and southwesterly to northwesterly winds (i.e., "westerly" winds) between ERA5 and R1: ERA5 had four times as many "easterly" days while R1 had more "westerly" days than "easterly" days. The most similar products at Region 2 were ERA5, JRA55, MERRA2 and R2, and those products had either southeasterly or southerly winds as the most frequent. Similar to the wind directions at Region 1, R1 had southwesterly as the most frequent wind direction.

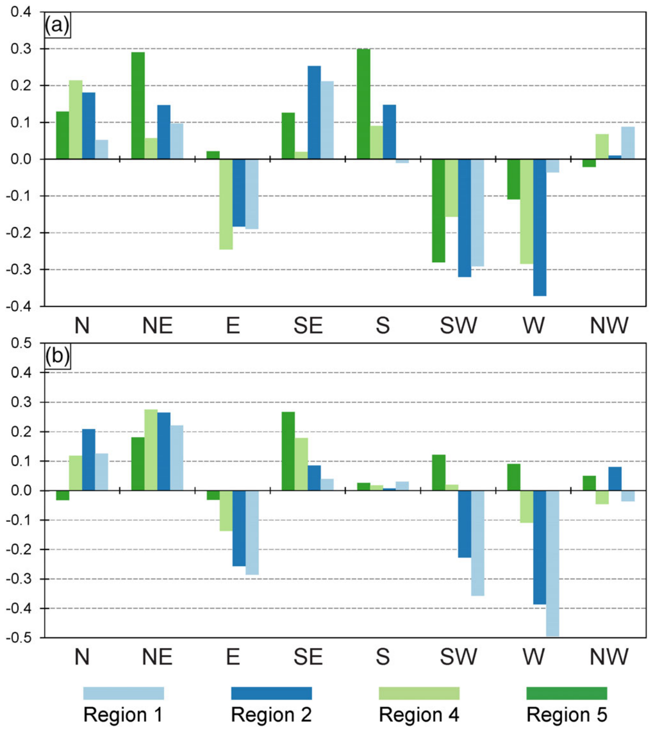

FIGURE 6 Deviation from mean d_r values for (a) 10-m winds and (b) 850-hPa winds. The mean d_r values, which were calculated using all pairs of reanalysis products, were 0.29 and 0.41 for 10-m winds and 850-hPa winds, respectively. Large positive values indicate that the products agree about the intra-annual variability of the frequency of a wind direction [Colour figure can be viewed at wileyonlinelibrary.com]

In southwestern Uganda, R1 was again the most different product with respect to frequencies of 10-m wind directions, but—compared to northwestern Uganda—there was more agreement in 10-m wind directions among the products (Figures 3 and 4). Southeasterly was the most frequent wind direction for all products. ERA5 and MERRA2, which were two extremely similar products, had large frequencies of southeasterly winds: those winds occurred on more than 40% of days. The major difference among the products involved the frequencies of "easterly" winds (i.e., northeast to southeast) and "westerly" winds (i.e., southwest to northwest): ERA5, MERRA2 and R2 had at least three times as many easterly days, while JRA55 and R1 had nearly equal frequencies of easterly and westerly days.

There was strong agreement among the products with respect to 850-hPa winds in northwestern Uganda, with "easterly" winds prevailing (Figures 4 and 5). For most products, easterly was the most frequent direction in Region 1. Differences among the products increased when moving to Region 2, but easterly and southeasterly winds were still the dominant directions.

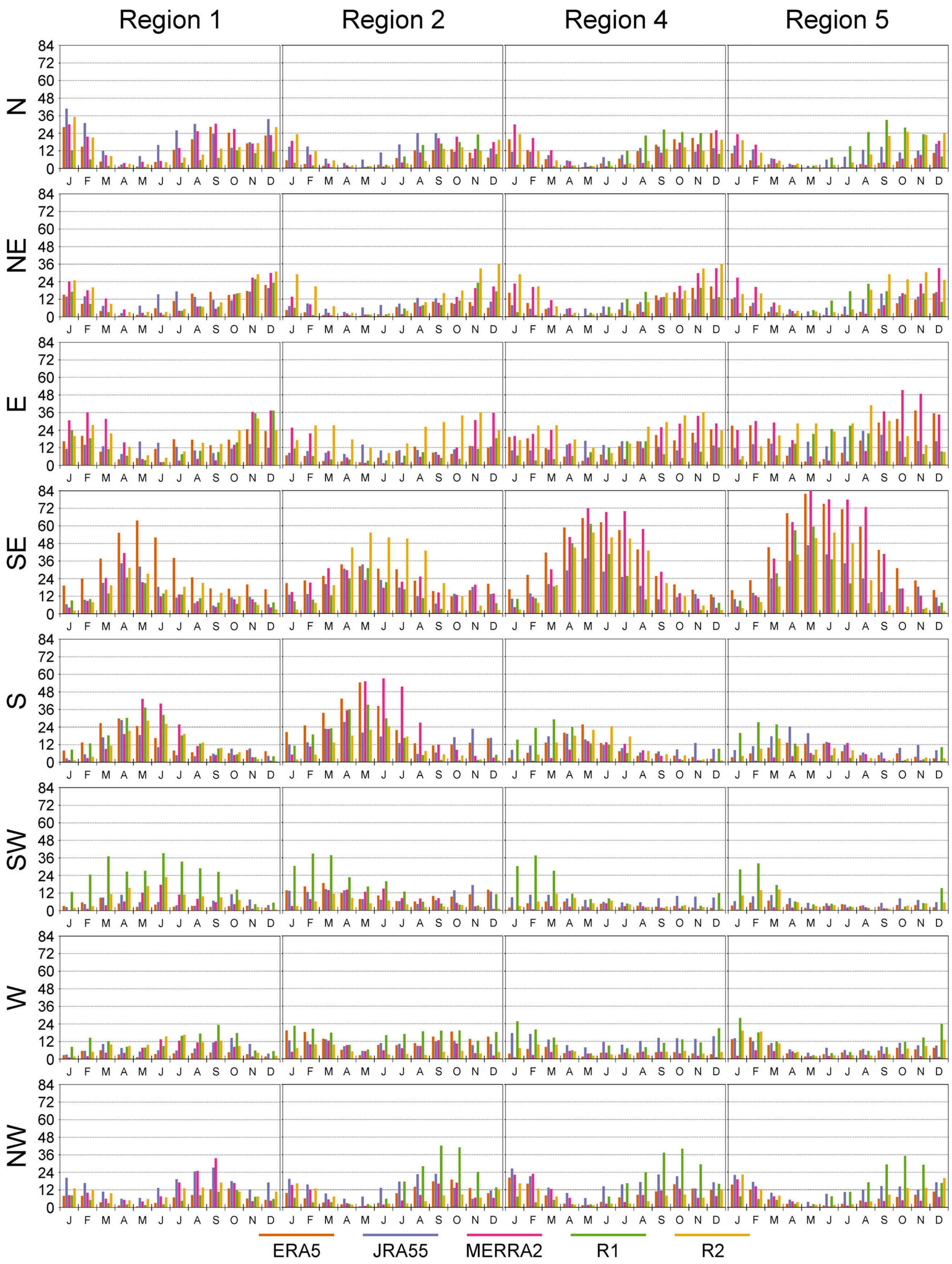

FIGURE 7 Percentage of days in each month that have 10-m winds from each of the eight directions [Colour figure can be viewed at wileyonlinelibrary.com]

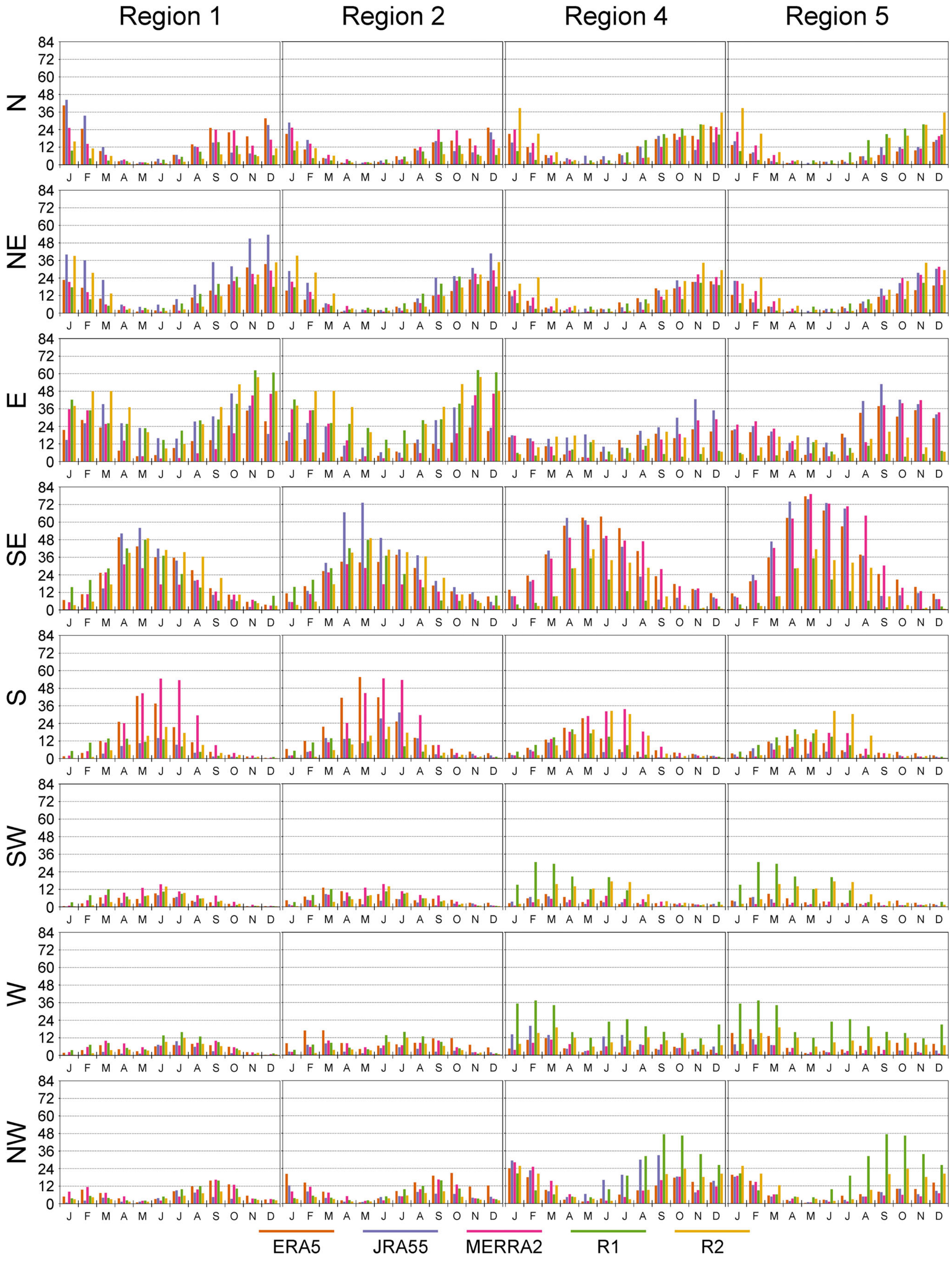

FIGURE 8 Percentage of days in each month that have 850-hPa winds from each of the eight directions [Colour figure can be viewed at wileyonlinelibrary.com]

Contrary to 10-m winds, there was more disagreement about 850-hPa winds in southwestern Uganda compared to northwestern Uganda, and R1 and R2 differed from the other products (Figures 4 and 5). ERA5, JRA55, and MERRA2 had strong agreements in both Regions 4 and 5, with southeasterly as the prevailing wind direction. Southeasterly winds occurred on approximately 35% of days. In Region 5 (i.e., far southwestern Uganda), R1 and R2 were very dissimilar to the other products and to each other: R1 had over 40% of the days with either westerly or northwesterly and R2 had relatively equal representation from all the wind directions.

5.2 | Intra-annual variation in reanalysis winds

The best agreement among the products with respect to the intra-annual variability of both 10-m and 850-hPa winds occurred for northerly, northeasterly, southeasterly, southerly, and northwesterly winds (Figures 6–8). Across the four rainfall regions, northerly winds and northeasterly winds were most frequent during September–January, while southeasterly and southerly winds were most frequent during April–July. The occurrence of northwesterly winds differed between northwestern Uganda, where they occurred mostly during July–October, and southwestern Uganda, where they occurred mostly during September–February.

The worst agreement among the products with respect to the intra-annual variability of 10-m and 850-hPa winds

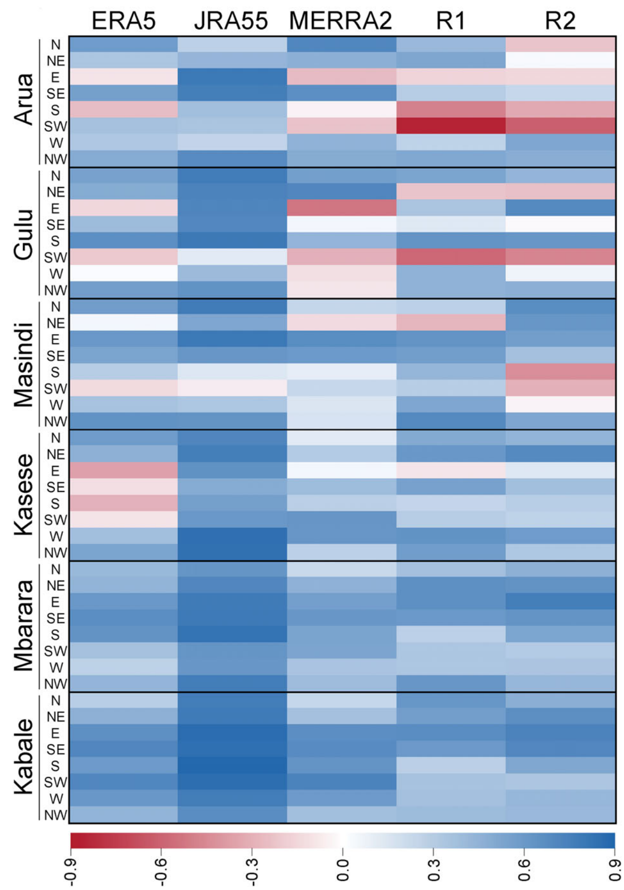

FIGURE 10 Wind-direction specific d_r values for each reanalysis product at each weather station. The more positive (negative) the values the stronger (weaker) the agreement [Colour figure can be viewed at wileyonlinelibrary.com]

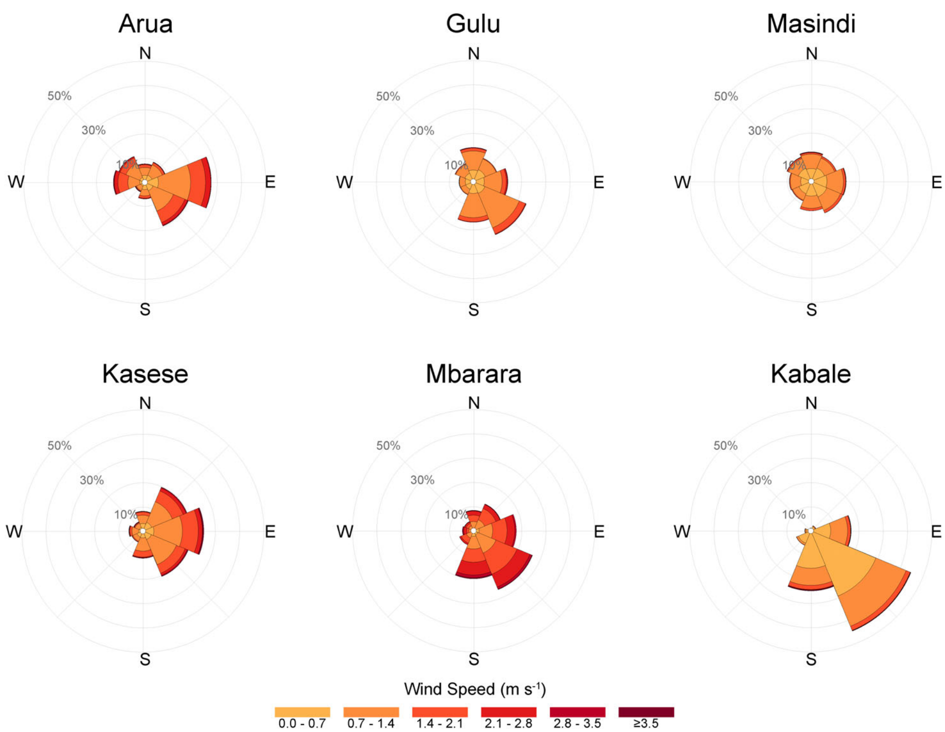

FIGURE 9 Wind roses with 10-m wind information for six weather stations in western Uganda [Colour figure can be viewed at wileyonlinelibrary.com]

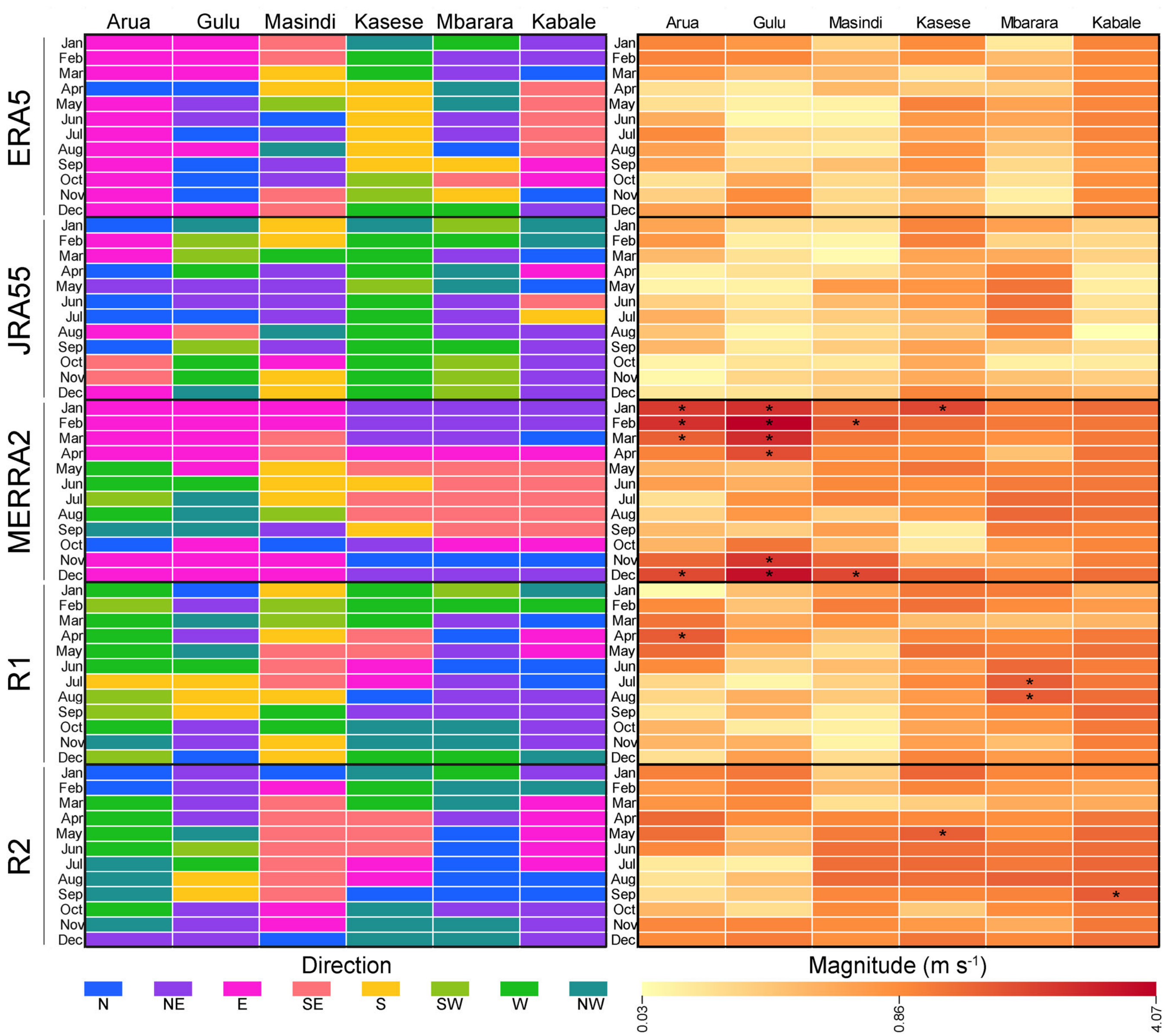

FIGURE 11 Directions (left panel) and magnitudes (right panel) of month-specific vectors produced by subtracting observed winds at weather stations (Arua, Gulu, Masindi, Kasese, Mbarara and Kabale) from reanalysis winds. The top 5% of magnitudes are denoted by asterisks [Colour figure can be viewed at wileyonlinelibrary.com]

occurred for easterly, southwesterly, and westerly winds (Figures 6–8). The peak periods for easterly winds, southwesterly winds and westerly winds were different for all products in both northwestern Uganda and southwestern Uganda. In general, easterly winds were most frequent during November–January in northwestern Uganda and southwestern Uganda during August–December. For 10-m winds, JRA55 did not have the peak in boreal autumn and winter that most of the other products had and thus was the main contributor to the small d_r values for easterly winds. Southwesterly winds occurred mostly during March–July in northwestern Uganda, but, in southwestern Uganda, the peak period for most products included February–March. The large frequencies of R1 southwesterly winds caused the small d_r values. Peak periods for most products for westerly winds in northwestern Uganda were March and July–September and February–March for southwestern Uganda. With respect to 10-m westerly winds, MERRA2, with its low frequencies and a lack of boreal-winter peak, was the cause of the small d_r values in southwestern Uganda. The small d_r values for 850-hPa westerly winds was caused by ERA5 and R1: ERA5 had an anomalous winter peak in northwestern Uganda, and R1 had large frequencies in southwestern Uganda.

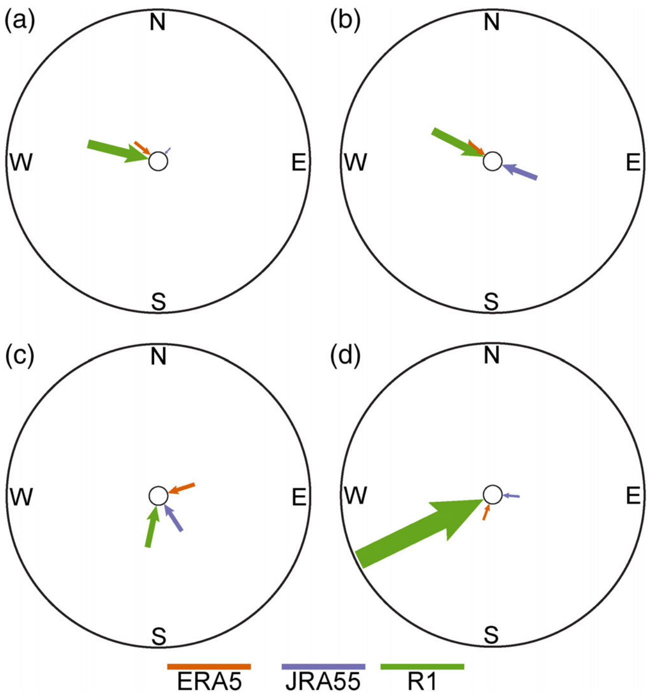

FIGURE 12 Difference vectors for ERA5, JRA55 and NCEP1 winds at 850-hPa for (a) Masindi at 6Z, (b) Masindi at 12Z, (c) Kasese at 6Z and (d) Kasese at 12Z. The length and width of the vectors are proportional to the magnitude of the vectors [Colour figure can be viewed at wileyonlinelibrary.com]

5.3 | Comparison of reanalysis winds with measured winds

"Easterly" near-surface winds prevailed at nearly all the weather stations in western Uganda (Figure 9). At Arua, Gulu, Kasese, Mbarara and Kabale, over 50% of days had "easterly" winds. The most frequent wind-direction sector at the five stations was either easterly or southeasterly. Arua, Gulu, and Masindi, the three stations in northwestern Uganda, were the only stations with more than 20% of days with "westerly" winds.

Among the five reanalyses, JRA55 best matched the measured monthly frequencies in near-surface wind directions at the six stations, and the reanalyses in general tended to perform the best in southwestern Uganda (Figure 10). JRA55 had a mean d_r value of 0.62, while ERA5, MERRA2, R1 and R2 had mean values of 0.35, 0.32, 0.34 and 0.31, respectively. The mean d_r values for all products combined increased with a decrease in latitude, with the mean d_r values at Arua, Gulu, Masindi, Kasese, Mbarara and Kabale being 0.22, 0.28, 0.34, 0.39, 0.53 and 0.58, respectively.

The reanalyses had a variety of directional biases for near-surface winds, with MERRA2 having the largest biases (Figure 11). ERA5 and MERRA2 tended to be biased towards "easterly" winds, while JRA55 and R1 tended to be biased towards "northerly" and "westerly" winds. R2 did not have a tendency towards certain directional biases. MERRA2 was the most biased product based on the magnitude of difference vectors, while JRA55 and ERA5 were the least biased products. MERRA2, which had a mean magnitude of 1.34, had most of the largest difference vectors, and those vectors were almost entirely easterly biases in northwestern Uganda during boreal winter and spring. The mean vector magnitudes for ERA5, JRA55, R1 and R2 were 0.60, 0.47, 0.84 and 1.04 $m \cdot s^{-1}$, respectively.

Compared to ERA5 and JRA55, R1 winds at 850 hPa were in general much more biased (Figure 12). R1 had a strong westerly bias at both Masindi and Kasese during at least one of two radiosonde measurement times. ERA5 and JRA55 had relatively weak biases, with neither product having a definitive directional bias.

6 | DISCUSSION

6.1 | Reanalyses and measurements show southwestern Uganda at the western edge of the prevailing near-surface easterly flow over EEA

Southwestern Uganda is east of the boundary of the prevailing near-surface easterly flow over EEA and the prevailing near-surface westerly flow over WEA. All reanalyses have southeasterly as the most frequent 10-m wind direction. Moreover, measured easterly flow is prevalent at the weather stations. While R1 does have a substantial proportion of days with westerly flow at 850 hPa, comparisons with measured winds indicate that R1 is biased towards westerly winds. On an annual basis, the typical wind direction in southwestern Uganda is more similar to that for EEA than WEA. This is an interesting finding, because southwestern Uganda is more similar to WEA than EEA based on correlations between rainfall and sea-surface temperatures (Diem et al., 2021).

6.2 | Congo westerlies may only be common in northwestern Uganda

Both reanalyses and measurements at weather stations show that Congo westerlies may only be common in parts of northwestern Uganda. Unfortunately, the weather-station data do not include evening and night-time hours, so conclusions from only examining the station data are not as robust as they could be. Westerly occurrence in northwestern Uganda is uncertain: the products had differing typical wind directions, and the three weather stations in the region had different wind characteristics. But the substantial rainfall and peak in estimated westerlies during boreal summer in northwestern Uganda provide evidence that westerlies might be common during boreal summer. Far northwestern Uganda is located just 500 km from Ethiopia, which has boreal-summer rainfall driven by Congo westerlies (Gleixner et al., 2017).

6.3 | Newer reanalyses generally outperformed older reanalyses

The best products for analysing lower-troposphere winds in western Uganda are JRA55 and ERA5, while the worst product is R1. JRA55, along with ERA5 and MERRA2, has a relatively fine spatial resolution. It is much more accurate than the other products at reproducing the intra-annual frequencies of wind-direction sectors. Moreover, JRA55 has the smallest mean bias in 10-m wind direction among the products. ERA5 has the same accuracy as MERRA2, R1 and R2 in estimating intra-annual frequencies of wind-direction sectors and does not have large 10-m wind-direction biases. Both JRA55 and ERA5 had relatively small biases with 850-hPa winds. The main deficiency of MERRA2 is an extremely large easterly bias. R1 and R2 are the oldest reanalyses and thus have the coarsest spatial resolution (e.g., the 10-m data are 57 times coarser than ERA5 data and 11 times coarser than JRA55 and MERRA2 data). While the performance of R2 is surprisingly similar to that of ERA5, the poor spatial resolution of R2 makes it undesirable for use in assessing winds in relatively small regions. For example, values for each rainfall region in western Uganda are derived from one to two R2 cells, while values for the smallest rainfall region are derived from approximately 30 ERA5 cells. All the analyses in this study show R1 having much more westerly flow than the other products, and, as noted earlier, much of that westerly flow appears to be artificial.

7 | CONCLUSIONS

This study investigates lower-troposphere winds through the comparison of reanalysis products and assessment against station-based measurements in western Uganda. The reanalyses show near-surface easterlies and near-surface westerlies prevailing over EEA and WEA, respectively. Most reanalyses have western Uganda being within the prevailing easterly flow over EEA. Measurements of near-surface winds also show easterly flow being prevalent throughout western Uganda. Steady occurrences of Congo westerlies—which have been associated with increased rainfall in previous studies—are probably limited to northwestern Uganda; thus, those westerlies are likely rare in southwestern Uganda. Previous research using R1 has shown Congo westerlies to be common in southwestern Uganda, but this study shows that R1 is biased towards westerly winds. MERRA2, conversely, has large easterly biases. Based on comparisons with wind measurements at weather stations over several decades, JRA55 is more accurate than the other products at reproducing the intra-annual frequencies of wind directions. In addition, JRA55 and ERA5 are the least biased products based on the magnitudes of difference vectors (i.e., differences in mean wind vectors between the reanalyses and measurements). JRA55 and ERA5 appear to be the most appropriate products for use in western Uganda, while R1—because of its poor performance and coarse spatial resolution—is not an optimal product to use to examine winds in the region and possibly equatorial Africa as a whole.

AUTHOR CONTRIBUTIONS

Jeremy E. Diem: Conceptualization; methodology; data curation; investigation; formal analysis; funding acquisition; visualization; writing – original draft; writing – review and editing. **Jonathan Salerno:** Methodology; writing – original draft; writing – review and editing. **Karen Bailey:** Methodology; writing – original draft. **Bronwen Konecky:** Writing – original draft.

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CONFLICT OF INTEREST STATEMENT

The authors declare no potential conflict of interest.

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