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Importance in Shifting Circulation Patterns for Dry Season Moisture Sources in the Brazilian Amazon

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Key Points:

- Dry season rainfall declined in a key agricultural region of the Amazon
- During drought years, forest and oceanic sources of dry season precipitation both fell
- Upwind forests maintain evapotranspiration during droughts, but atmospheric circulation changes reduce moisture transport

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Water is redistributed from evaporation sources to precipitation sinks through atmospheric moisture transport. In the Brazilian Amazon, the spatial and temporal variability of dry season moisture sources for key agricultural regions has not been investigated. This study investigates moisture sources for dry season rainfall in the state of Rondônia in Brazil, especially during drought years. Using a precipitationshed framework, we quantified the variability of moisture contributions to rainfall in the state of Rondônia (Brazilian Amazon) and the influence of synoptic circulation patterns. Ocean evaporation accounts for 58% of mean dry season precipitation while continental recycling contributed 42%. During drought years, although forests maintain or increase evapotranspiration, the moisture contribution of both ocean and forests to dry season rainfall decreases due to the synoptic circulation changes, reducing the moisture transport into Rondônia.

Plain Language Summary The evaporation from upwind ocean and land surfaces can be recycled and transported to downwind locations as precipitation. The state of Rondônia in the Brazilian Amazon is a key agriculture region and its precipitation relies on moisture transport from upwind tropical forests and the Atlantic Ocean. We examined the moisture contribution of forests and ocean to dry season rainfall during normal and drought years. Over time, the dry season is getting drier with reduced forest and oceanic sources. This is linked to atmospheric wind changes that reduce moisture transport into Rondônia. Future deforestation and climate change can cause the dry season to become more intense in this part of the Amazon.

1. Introduction

Forests influence climate through exchanges of water, energy, and chemicals with the atmosphere (Bonan, 2008). Evapotranspiration (ET) from vegetation is recycled through the atmosphere as water vapor and reaches downwind locations as precipitation (Keys et al., 2012; Lettau et al., 1979). Globally, more than half of terrestrial evaporated moisture rains back again over land (Tuinenburg et al., 2020), and for the Brazilian Amazon, forest ET accounts for one-third to more than half of the total rainfall (Satyamurty et al., 2013). During the wet season, the southwestern region of the Amazon basin provides rainfall directly to the La Plata basin through moisture recycling, dispersing moisture from the Amazon basin to the La Plata basin (Zemp et al., 2014).

The Amazon Rainforest is experiencing deforestation, particularly in the southeastern border of the forest, called the "arc of deforestation." Forests have deep roots that access water in deeper soil layers and can maintain ET during droughts, buffering against precipitation variations (Da Rocha et al., 2009; Mu, Biggs, & De Sales, 2021; O'Connor et al., 2021). Pasture grasses, which account for most post-deforestation cover in the Amazon, have shallow roots and lower dry season ET, so deforestation may amplify drought conditions (Mu, Biggs, & De Sales, 2021; Sierra et al., 2022; Staal et al., 2020; Zemp et al., 2017). Moisture of Amazonian origin has strong diurnal cycles, annual and semi-annual signals with contrasting behavior between the northern and southern parts of the Amazon basin (Dominguez et al., 2022).

The "arc of deforestation" experienced severe droughts in 2005, 2010, and 2015–2016 (Panisset et al., 2018), as well as decreasing dry season rainfall in deforested areas (Mu, Biggs, & Shen, 2021; Mu & Jones, 2022). Over the southern Amazon, the length of the dry season and the number of dry days has been increasing, which may be due to a combination of deforestation and regional climate change driven by changes in energy transport (Espinoza et al., 2019; Wainwright et al., 2022). While reduced ET from deforested areas may play a role, changes in ocean conditions and synoptic circulation also play important roles in droughts. The 2005 drought was due to warm sea surface temperature (SST) anomalies in the tropical North Atlantic, while 2010 and 2015–2016 droughts were driven by a combination of the El Niño-Southern Oscillation (ENSO) and warm SST (Marengo & Espinoza, 2015; Marengo et al., 2011). Atmospheric moisture tracking suggests that forests mitigate drought severity for annual rainfall in the Brazilian State of Rondônia, at the western end of the arc of deforestation, as forests maintained annual ET during droughts (Mu, Biggs, & De Sales, 2021). Mu, Biggs, and De Sales (2021) only tracked moisture at the annual scale and the spatial resolution (1.5°) is relatively coarse compared to recent studies (0.5°, Theeuwen et al., 2022). The quantification of land and oceanic moisture sources during dry seasons and their changes during droughts remain unexplored, in particular the relative roles of changes in ET and in synoptic circulation. This is particularly important, as the dry season is a critical constraint on agricultural production in the southern Amazon. Using a modified Water Accounting Model-2layers (WAM-2layers) and ERA5 climate reanalysis at a higher resolution (0.25°), our study maps evaporation sources for precipitation in the Brazilian State of Rondônia and quantifies the land and oceanic moisture sources for 40 years (1981–2020). We aim to answer the questions: (a) How has the source of moisture for dry season rainfall changed during droughts and over time (1981–2020)? (b) What are the relative roles of changes in evaporation and changes in synoptic circulation for changing moisture sources?

2. Materials and Methods

2.1. Study Area

The state of Rondônia, located in the southwestern Brazilian Amazon, covers an area of 243,000 km^2 (Guild et al., 2004) and has a dry season from June to August (JJA). Rondônia is an important agricultural frontier for coffee, dairy, beef, and soybean. Mean annual rainfall ranges from 2,100 mm in the north to 1,800 mm in the south. Dry season rainfall, especially during droughts, is critical for water availability and agricultural production. The undisturbed vegetation includes both closed (*Floresta Densa*) and open (*Florest Obrofila Aberta*) moist tropical rainforest (RADAMBRASIL, 1978).

2.2. Tracking Model and Methods

Precipitationsheds represent the upwind land and oceanic regions that contribute evaporation to the dry season rainfall in Rondônia. The variations of precipitationshed is defined by a seasonal core precipitationshed where the long-term mean moisture contribution of a given region exceeds a threshold of 1 mm/month (Keys et al., 2014). WAM-2layers is a global Eulerian moisture tracking model that tracks the volume of evaporation and precipitation that enters and exits a column of air based on the atmospheric water balance (Equation 1) (van der Ent et al., 2010, 2014):

$$\frac{\partial S_k}{\partial t} = \frac{\partial (S_k u_k)}{\partial x} + \frac{\partial (S_k v_k)}{\partial y} + E_k - P_k + \varepsilon_k \pm Fv \tag{1}$$

where S_k represents the amount of atmospheric moisture stored in layer k, E is evaporation, P is precipitation, u represents zonal and v meridional wind speed, εk represents residual, and Fv is the vertical moisture transport (van der Ent et al., 2014). A modified offline version of WAM-2layers by Xiao and Cui (2021) was used to calculate the precipitationshed for Rondônia. ERA5 reanalysis data from 1981 to 2020 (Hersbach et al., 2020) was used as input to WAM-2layers. The ERA5 was downloaded at 0.25° × 0.25° resolution. Selected parameters were extracted, including specific humidity, u-velocity, v-velocity at 17 pressure levels, surface pressure, northern and eastern water vapor flux, total column water, and precipitation and evaporation. Precipitation and evaporation were downloaded at the 1-hourly resolution, and all other variables at the 6-hourly resolution, but both are interpolated to 10-min intervals in the model.

The vegetation types in ERA5 are specified from the Global Land Cover Characteristics database (GLCC) (Loveland et al., 2000) with a 1-km resolution classification of 20 land cover types, which we used in this study for land cover. The land cover has the base year of 1992–1993 and is static. The moisture tracking results are multi-annual (1981–2020) monthly averages with a spatial resolution of 0.25°, which were further aggregated by cover type: forest, non-forest natural vegetation (grassland, shrubland), agriculture, and ocean using the GLCC. The moisture contribution from each land cover j (f_m) is calculated as:

$$f_m = \sum_{1}^{n} f_{ri} \times f_{ji} \tag{2}$$

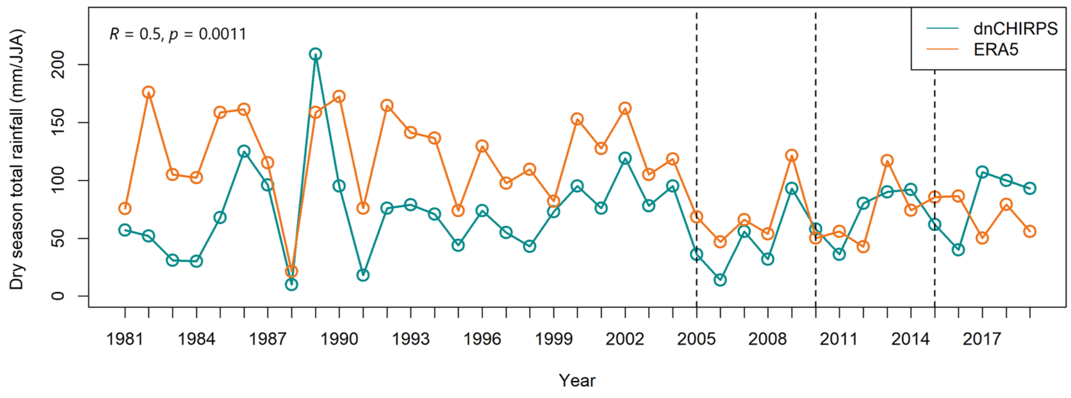

Figure 1. Time series of dry season total rainfall for ERA5 and dnCHIRPS from 1981 to 2019. The correlation (*R*) and *p*-value are indicated on the upper left. Vertical dashed lines are drought years (2005, 2010, 2015).

where f_{ri} is the fraction of dry season precipitation coming from cell *i*, and f_{ji} is the fraction of land cover *j* in cell *i*. Rainfall originating from cell *i* is divided by the sum of rainfall from all cells to calculate f_{ri}.

2.3. Statistical Analysis and Drought Years Conditions

Changes in moisture sources during droughts could represent either a change in the rate of evaporation from source areas or a change in atmospheric circulation that alters the transport into the target region. To investigate the changes in the precipitationshed and dry season synoptic circulation patterns during droughts, we compared four drought years: 2005, 2010, 2015, and 2020 (Jiménez-Muñoz et al., 2016; Papastefanou et al., 2022). ERA5 reanalysis data were used to calculate anomalies between drought and non-drought years (Hersbach et al., 2020), including 850 hPa winds, net radiation fluxes, 2m temperature, sea surface temperature (SST), vapor pressure deficit (VPD) and evaporation. ERA5 rainfall is validated by a satellite product for Rondônia calibrated with 73 rain gauges (dnCHIRPS) (Mu, Biggs, & Shen, 2021), showing an overestimation of the dry season rainfall by ERA5 (Figure 1). The implications of ERA5 precipitation and ET uncertainties will be explored in the discussion. Time series trend analysis is based on a Bayesian model averaging algorithm to decompose time series into individual components for trends and periodic variations, as described in Zhao et al. (2019). The statistical significance of drought year anomalies is calculated with the *t*-test of the difference between the means, and p-value less than 0.1 for minimum 90% confidence intervals.

3. Results and Discussion

3.1. Climatology and Spatiotemporal Variability

The major moisture source regions for dry season rainfall in Rondônia are the Amazon basin and the Southern Atlantic Ocean (Figure 2a). Moisture evaporation from these source regions is transported by easterly winds and some falls as rainfall downwind in Rondônia. The dry season moisture source region contrasts with the Northern Atlantic source observed for annual rainfall (Mu, Biggs, & De Sales, 2021). The Southern Atlantic source regions are more significant near South America, while the land moisture contribution core is to the northeast of Rondônia in the Amazon basin.

Ocean evaporation accounts for an average of 58% of JJA precipitation in Rondônia (Figure 2), while continental recycling contributed approximately 42%. From 1981 to 2020, Bayesian test showed both land and oceanic moisture contributions have negative trends at the 99% confidence interval ($p < 0.01$), while relative contributions of land and ocean show no overall significant trend (Figure 2b). During drought years, compared to the long-term average, the oceanic relative moisture contribution increased (+0.03%–+8.3%), and land contribution decreased, except for 2020 when the relative land contribution increased (+11.4%).

3.2. Moisture Contribution by Land Cover

The land moisture source is divided into a core region, defined as grid cells that contribute more than 1 mm of JJA rainfall on average, and a noncore region (contribution <1 mm per grid cell). The non-core region is mainly

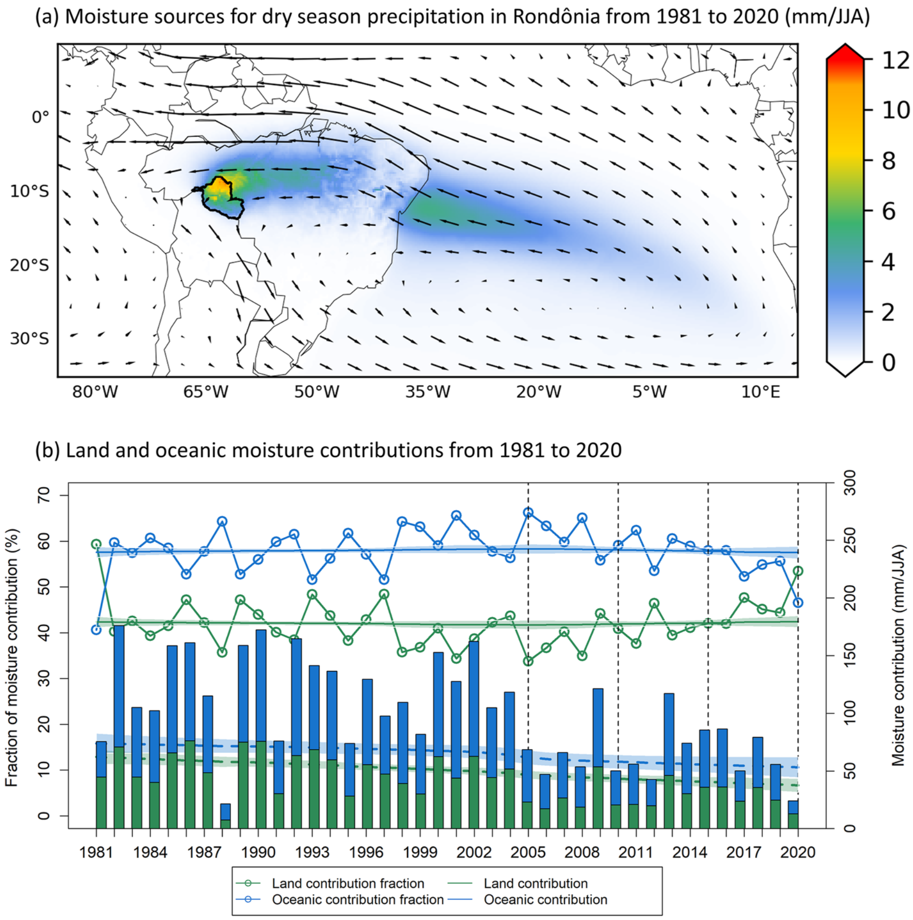

Figure 2. (a) Moisture sources for dry season precipitation in Rondônia from 1981 to 2020 (mm/JJA); Highlighted sink region is the State Boundary of Rondônia. Arrows indicate the average horizontal (vertically integrated) moisture flux. (b) Time series of land and oceanic actual and relative moisture contribution. The lines with circle markers are the relative contribution (%) and the bars are the actual moisture contribution (mm/JJA). Shaded lines indicate Bayesian model trends and the standard deviation of the trend component. Vertical dashed lines are drought years (2005, 2010, 2015, and 2020).

in the arid and semi-arid northeast of coastal Brazil. The core region contributes 32% of JJA rainfall compared with 42% from all land sources. The core is further broken down into forests, non-forest, and agriculture. Figure 3 shows the total dry season moisture contribution for each subregion, where forests contributed the most, accounting for 66% of moisture from the core and 22% of the total JJA rainfall (Figure 3). Non-forest and agriculture contributed the least moisture from the core (4.3% and 6.2%). Forests dominate the relative contribution of moisture during drought years (Figure 3), and forest contributions increased by 8.6% in 2020 compared to the long-term mean, while other land cover types had lower relative contributions (3.7%–10.4%).

3.3. Synoptic Patterns

During droughts, easterly winds (850-hPa) are enhanced over the equatorial Atlantic Ocean (Figure 4a) but have southerly components. In South America, an anomalous anti-cyclonic circulation is observed from Bolivia to central and northeast Brazil during drought years. Southerly wind anomalies are also noted over Colombia. Vertically integrated moisture fluxes divergence calculation followed (Seager & Henderson, 2013), showing divergence of moisture flux to the north and south of Rondônia (Figure 4f). This circulation pattern suggests divergence over Rondônia, which would decrease moisture supply to the region. While wind anomalies are not statistically significant over the forested core, the pattern also suggests wind divergence and decreased moisture transport into Rondônia. VPD and net radiation over land increased during droughts (Figures 4b and 4c), especially over the forest core region, which coincides with regional warming (Figure 4e). Oceanic evaporation and

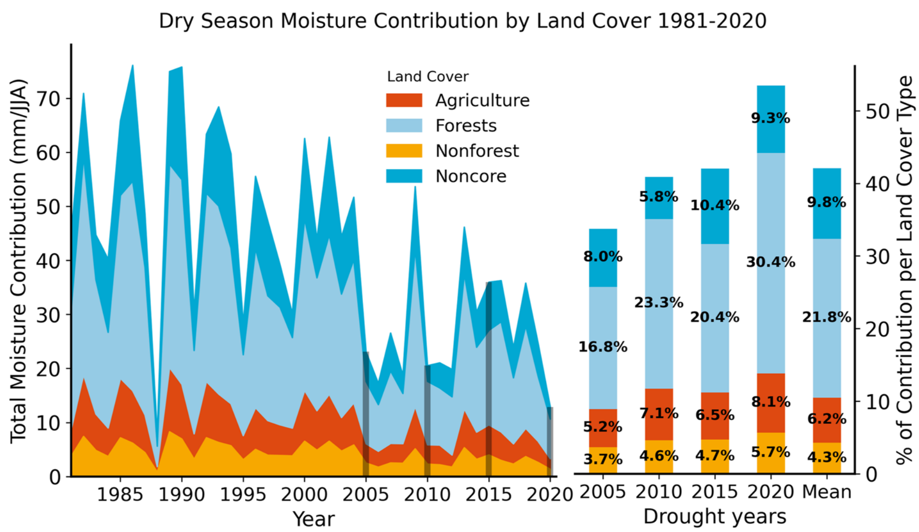

Figure 3. Total dry season moisture contribution to rainfall in Rondônia by land cover for each year. Actual moisture contribution is on the left (mm/JJA). Relative contribution (%) during drought years and the mean of non-drought years ("Mean") is on the right. The core is defined as all cells that contribute at least 1 mm of rainfall on average during the JJA dry season.

SST anomalies (Figures 4d and 4f) are both positive during droughts, while forest core regions have slight reductions or similar ET compared to non-drought years (Figure 4g).

The relative moisture contribution from the ocean increased and from land decreased in all drought years except for 2020, but forests maintained their relative contribution during droughts (Figure 3). Increased net radiation

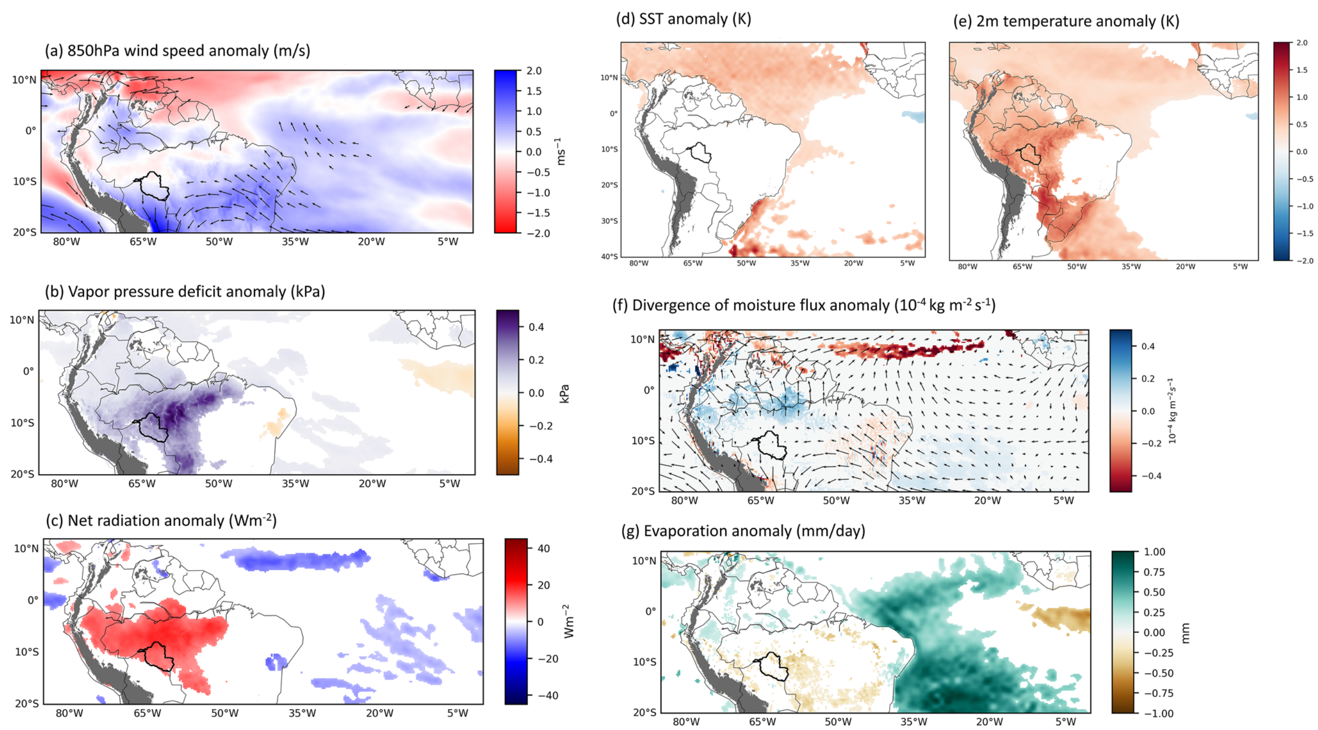

Figure 4. Mean drought years anomalies of (a) 850 hPa wind; (b) Vapor pressure deficit; (c) Net radiation; (d) Sea surface temperature; (e) 2m air temperature; (f) vertical integral of divergence of moisture flux and 850 hPa wind vectors; Positive moisture flux divergence anomalies indicate diverging of moisture and negative anomalies indicate converging of moisture and (g) Evaporation. The outlined region indicated the sink region Rondônia. Gray shading represents the Andes Mountains. Only statistically significant values in the *T*-test at 90% confidence intervals at 0.1 level ($p < 0.1$) are shown.

and VPD during droughts results in higher potential evapotranspiration (PET), while forest actual ET increased slightly in the northern Amazon but decreased slightly (−0.7% to −8% in the core, Table S1 in Supporting Information S1) in the southern Amazon during drought years, indicating moisture stress (Figure 4). Although forests dominate the relative contribution of moisture during drought years (Figure 3 right), and ET from forests only decreases slightly (<8%), the contribution of forests (Figure 3 left) to rainfall decreased markedly from non-drought years (−24% to −68%, Table S1 in Supporting Information S1), reflecting the importance of changes in circulation for decreased moisture transport into Rondônia. VPD increases are linked to warmer air temperatures with higher saturation vapor pressure and lower actual vapor pressure (Figure S1 in Supporting Information S1), which was also observed by Barkhordarian et al. (2019). Higher SST and stronger easterly wind anomalies during droughts favor the oceanic evaporation moisture contribution. While vegetation moisture stress is present in the core source area for some years, changes in circulation are likely contributing most to the decreasing moisture flux to Rondônia from forests.

3.4. Limitations and Discussion

Unlike annual rainfall (Mu, Biggs, & De Sales, 2021), where forests buffer moisture variations during drought years, during dry seasons the moisture flux from forests to Rondônia decreases in a majority of drought years. Over the past 40 years, the actual amount of moisture contributions to dry season rainfall in Rondônia from land surfaces and ocean decreased, while (Mu, Biggs, & Shen, 2021) only observed reduced dry season rainfall over deforested regions in Rondônia. ERA5 overestimated dry season rainfall in Rondônia when compared to gauge-enhanced satellite precipitation data (Figure 1), while lower overestimation during the three drought years investigated in this study (2005, 2010, and 2015), which suggests that the actual moisture contributions from the precipitationshed are lower than estimated by the water accounting model. Baker et al. (2021) reported that at the seasonal scale, ERA5 ET performed well and mostly represented the factors controlling ET. However, misrepresentation in the spatial distribution and trends of precipitation over the Amazon has a negative impact on ERA5 ET. ET in southwestern Amazonia is significantly controlled by vegetation which is coupled with cumulative water deficits (von Randow et al., 2012; Numata et al., 2021). Trends in ERA5 may be exaggerated due to its bias, but the changes in sources during drought years as anomalies from the trend are still robust. Our results showing no or small ET reduction of forest core regions agree with other studies, where forests can access deep soil moisture (Oliveira et al., 2005), and increase in leaf area due to reduced water circulation while utilizing built-up water resources during the wet season to sustain their own biomass production (Cui et al., 2022; Staal et al., 2023).

The dry season rainfall reduction is partially linked to the regional drought-deforestation feedback (De Sales et al., 2020; Khanna et al., 2017; Staal et al., 2020). At the regional scale, deforestation-induced surface roughness change causes low-level moisture convergence downwind and divergence upwind of the deforested regions (Eiras-Barca et al., 2020; Khanna et al., 2017). This could cause a decrease in local water availability but increased water availability downwind of Rondônia, as observed in the La Plata basin (Cui et al., 2022; Staal et al., 2018; Zemp et al., 2014). The trend of the drier dry season in South America may also be influenced by the more northerly position of the tropical rain belt due to warm SSTs in the North Atlantic (Hodson et al., 2022; Wainwright et al., 2022). Our results demonstrated that although overall upwind forest ET rates are maintained during droughts, precipitation still declined due to changes in atmospheric synoptic circulation. We conclude that reduced moisture transport into Rondônia during drought years is associated with changes in winds with anomalous anti-cyclonic circulation patterns that decrease moisture supply to inhibit precipitation.

Commar et al. (2023) also reported synoptic-scale circulation change from deforestation that delayed the wet season onset in the southern Amazon. The synoptic conditions in studies that model the impact of land cover changes on precipitation globally are often assumed to be constant. Recent studies (Hoek van Dijke et al., 2022; Tuinenburg et al., 2022) acknowledged that the shifting circulation patterns may partly compensate for the enhanced evaporation and affect the drought mitigation potential of forests.

4. Conclusions

Moisture contributions from both forest and ocean both fell during droughts and over time (1981–2020) in the agriculturally important Brazilian state of Rondônia. During drought years, both actual oceanic and forest moisture sources for precipitation decreased, while the relative oceanic contribution to rainfall increased and the relative land contribution decreased during three out of four drought years. A combination of natural and regional anthropogenic forcings could be responsible for the rainfall changes. Forests are the main relative contributor to rainfall in Rondônia during droughts. Forest maintains or increases water supply to the atmosphere through ET during droughts, but atmospheric circulation changes, in particular, anomalous anti-cyclonic atmospheric circulation, reduce the moisture transport into Rondônia. The current ability of forests to maintain ET during seasons and years with lower rainfall might be compromised under drier conditions, causing losses of moisture recycling which can be propagated downwind (Wunderling et al., 2022). With the ongoing extensive deforestation and increasing frequency of droughts in the Amazon forests, droughts could become worse in the future if the forest becomes moisture stressed. We document a long-term and consistent decrease in moisture transport into an agriculturally important region of Brazil, driven in part by a shift in winds. The causes of this shift in circulation during drought conditions are not known but are critical for the long-term stability of forest vegetation and agriculture. This research shows that changes in circulation should not be overlooked for a complete assessment of changes in precipitation due to deforestation and reforestation. Future work should document the interaction and relative importance of changes in ET and atmospheric circulation, and their potential changes under future warming, as drivers of agricultural drought in the region and throughout South America.

Data Availability Statement

The WAM-2layers model data is available through Van der Ent et al. (2014). The original modified WAM-2layers is available on Zenodo (http://doi.org/10.5281/zenodo.4796962). ERA5 data are available at the Copernicus Climate Change Service (C3S) Climate Date Store (https://doi.org/10.24381/cds.bd0915c6), and Global Land Cover Characteristics (GLCC) data set is available through Loveland et al. (2000).

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