Synoptic variability in the tropical oceanic moist margin

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Key Points:

- The moist margin displays strong variance on synoptic scales, and its movement is strongly related to precipitation variability.
- Variability in the moist margin is related to mid-tropospheric humidity, and is uncorrelated with sea surface temperature.

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Abstract

Recent research has described a 'moist margin' in the tropics, defined through a total column water vapor (TCWV) value of 48 kg m^{-2}, that encloses most of the rainfall over the tropical oceans. Diagnosing the moist margin in the ERA5 reanalysis reveals that it varies particularly on synoptic time scales, which this study aims to quantify. We define 'wet and dry perturbation' objects based on the margin's movement relative to its seasonal climatology. These perturbations are associated with a variety of features, such as tropical cyclones and lows, tropical waves, and extrusions of moisture towards the extratropics. Wet (dry) perturbations produce substantially more (less) rainfall compared to the seasonal average, confirming the clear link between moisture and precipitation. On synoptic scales we suggest that mid-tropospheric humidity plays a key role in creating these perturbations, while sea surface temperatures (SSTs) are relatively unimportant.

Plain Language Summary

Rainfall over the tropical oceans tends to be confined within a large-scale, highly humid region enclosed by the 'moist margin'. This work aims to describe how the moist margin varies from one day to another. We find that shifts of the moist margin strongly control rainfall variability around the boundary of the tropics. Therefore, understanding the processes leading to shifts in the moist margin is an important component of understanding precipitation variability. We suggest that water vapor in the middle levels of the atmosphere, rather than sea surface temperatures, play a key role in controlling the moist margin.

1 Introduction

Water vapor is a key ingredient for moist convection and precipitation, particularly in the tropics where the Coriolis force is small and horizontal temperature gradients are generally weak. The relationship between moisture and precipitation has long been studied in a range of contexts from convective modeling and parameterizations to large-scale variability and anthropogenic climate change (Arakawa & Schubert, 1974; Kain & Fritsch, 1990; Sherwood, 1999; Holloway & Neelin, 2009; Sherwood et al., 2010). There is a well-documented nonlinear relationship between total column water vapor (TCWV) and precipitation over tropical oceans, including the 'convective pickup' where precipitation rapidly increases above a critical humidity threshold (Zeng, 1999; Bretherton et al., 2004; Peters & Neelin, 2006; Holloway & Neelin, 2009; Neelin et al., 2009; Ahmed & Schumacher, 2015; Schiro et al., 2016; Virman et al., 2018). Despite this, even areas deemed suitable for heavy convection still exhibit large variability on multiple spatial and temporal scales (Muller et al., 2009; Stechmann & Neelin, 2011; Gilmore, 2015).

A recent study by Mapes et al. (2018) defines the tropical 'moist margin' as a sharp boundary at a TCWV value of 48 kg m^{-2} over the oceans. This boundary separates broad areas of a wet regime, where heavy rainfall sporadically occurs, from a dry regime where rainfall is suppressed. Simple observation of the moist margin on synoptic scales demonstrates its 'meandering' behavior through time and space. This includes excursions of the wet regime towards higher latitudes, and incursions of dry air into the deep tropics. The movement of the moist margin is therefore expected to change the region where heavy convective rainfall is permitted.

However, no comprehensive analysis of the variability of the tropical moist margin has been performed. Therefore, this study seeks to extend on the work of Mapes et al. (2018) by examining how the tropical moist margin varies on synoptic scales. An object-based approach will be taken here to define perturbations of the moist margin from its basic seasonal cycle.

The paper will be structured as follows. Section 2 first describes the observational and reanalysis data used throughout the study. Section 3 then examines the relationship between TCWV and precipitation over tropical oceans in the context of the moist margin, demonstrating the suitability of reanalysis data for analysis of the moist margin. Section 4 presents the main analysis of variability in the moist margin, beginning with the seasonal cycle (part 4.1) and following with synoptic variability (part 4.2). In Section 5, we examine some large-scale conditions associated with wet and dry perturbations, including the vertical structure of the troposphere and sea surface temperatures (SSTs). A discussion and conclusion are presented in sections 6 and 7 respectively.

2 Data

Total column water vapor (TCWV), specific humidity, temperature and vertical motion data are taken from the ERA5 reanalysis, provided by the European Centre for Medium-Range Weather Forecasts (Hersbach et al., 2020). All variables have been resampled to daily means over 1979-2021 at 1° horizontal resolution, providing 43 years of data for analysis. Unless otherwise indicated, the analysis is performed between 30°N-S.

Rainfall data is taken from the Global Precipitation Climatology Project (GPCP) version 1.3 (Adler et al., 2020), an observational dataset that provides daily rainfall at 1° resolution, the same as the downsampled ERA5 data. Note that the GPCP record begins in October 1996, so any joint analysis between TCWV and precipitation is taken over the overlapping period Jan 1997 – Dec 2021.

We use daily SST data from the Optimum Interpolation SST version 2.1 (OISST) provided by NOAA (Huang et al., 2021). OISST data has a resolution of 0.25° and begins in September 1981; once again overlapping periods with ERA5 are used.

3 The relationship between total column water vapor, the moist margin, and rainfall in ERA5

In their study, Mapes et al. (2018) used instantaneous satellite-based observations for TCWV. Here, we repeat the analysis with ERA5 by first evaluating the representation of TCWV distributions over the tropical oceans, shown in Figure 1a. A bimodal distribution of TCWV is clearly evident, including a 'dry mode' at 30 kg m^{-2}, a 'moist mode' at around 55 kg m^{-2}, and a local minimum between the two which defines the 'moist margin'. Overall, the distribution is remarkably similar to the results of Mapes et al. (2018) (see their Figure 1). Some slight differences exist; for example, the minimum is at a slightly lower value of around 45-46 rather than 48 kg m^{-2} (e.g. for 25 °N-S), and the 'shoulder' is slightly less clear for narrower latitude bands (e.g. for 15 °N-S), picking up at slightly lower values. However, these differences are minor, and we conclude that reanalysis datasets such as ERA5 are suitable for analyzing the moist margin. For all subsequent analysis, we take the moist margin to be the TCWV = 48 kg m^{-2} contour, as in Mapes et al. (2018). We have repeated all analysis with a lower threshold of 45 kg m^{-2}, and the differences in results are minor and qualitatively identical.

Conditionally sampling on the presence of rainfall highly skews the TCWV distribution, as shown in Figure 1b. Even a small rainfall threshold of 1 mm day^{-1} dramatically shifts the distribution to its moist mode and removes a large fraction of TCWV values below 48 kg m^{-2}. This suggests that the 'dry mode' is mostly associated with rain-free conditions, and would likely include oceanic desert regions such as the tropical cold tongues and the subtropical high-pressure regions. As the rainfall threshold increases, the distribution becomes more skewed and the TCWV of the moist mode increases slightly, approaching 60 kg m^{-2}. All distributions for TCWV for differing rainfall thresholds become similar beyond around 60 kg m^{-2}, suggesting that high rainfall amounts are as-

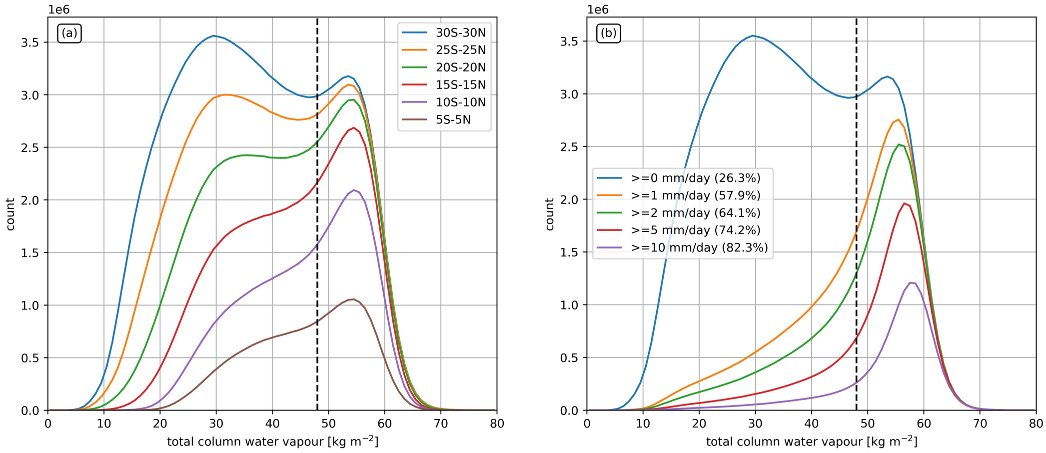

Figure 1. Histogram of ERA5 daily-mean TCWV values over tropical oceans, filtered by latitude band (a) and daily rainfall (b). The moist margin at 48 kg m^{-2} is labelled as the vertical dashed line

sociated with the highest TCWV. This is likely because the atmosphere is approaching its limit of saturation and must therefore produce rainfall. The proportion of TCWV points above 48 kg m^{-2} increases from 57.9% at 1 mm day^{-1} to 82.3% at 10 mm day^{-1}, both of which are well above the unconditional value of 26.3%. However, heavy rainfall still occasionally occurs at low TCWV values, which may be due to strong dynamical forcing, for example through the intrusion of extratropical Rossby waves into the tropics (Kiladis & Weickmann, 1992) or development of land-sea breezes (Bergemann & Jakob, 2016).

Overall, this section supports the idea that being inside the moist margin is an important but insufficient condition for heavy rainfall over tropical oceans. The next section examines how this margin and therefore the region in which heavy rainfall occurs evolves through time.

4 Variability in the moist margin

4.1 Seasonal cycle

We begin by investigating the seasonal cycle of the moist margin. Figure 2 shows the position of the moist margin along with the mean TCWV and variance for all months (top), austral summer (middle), and boreal summer (bottom). In the annual mean, the margin is confined within 20° N-S, displaying multiple climatic features such as the tropical warm pool over the Maritime Continent, and the intertropical convergence zones (ITCZ) over the Pacific and Atlantic Oceans. A strong monsoonal migration is evident, particularly the Asian-Australian monsoon which migrates from northern Australia during austral summer to India and Southeast Asia in the boreal summer. Seasonal differences are also present in the western Indian Ocean, which is only covered by the margin during austral summer, and the central Pacific, which is only continuously inside the margin during boreal summer. The South Pacific convergence zone (SPCZ) is also somewhat evident as a southward extension of the margin near the dateline, particularly during austral summer.

It is important to note that the use of ERA5 allows us to also display the moist margin over land, while the original definition of the moist margin is only over oceans (Mapes et al., 2018). The applicability of the 48 kg m^{-2} contour over land is therefore

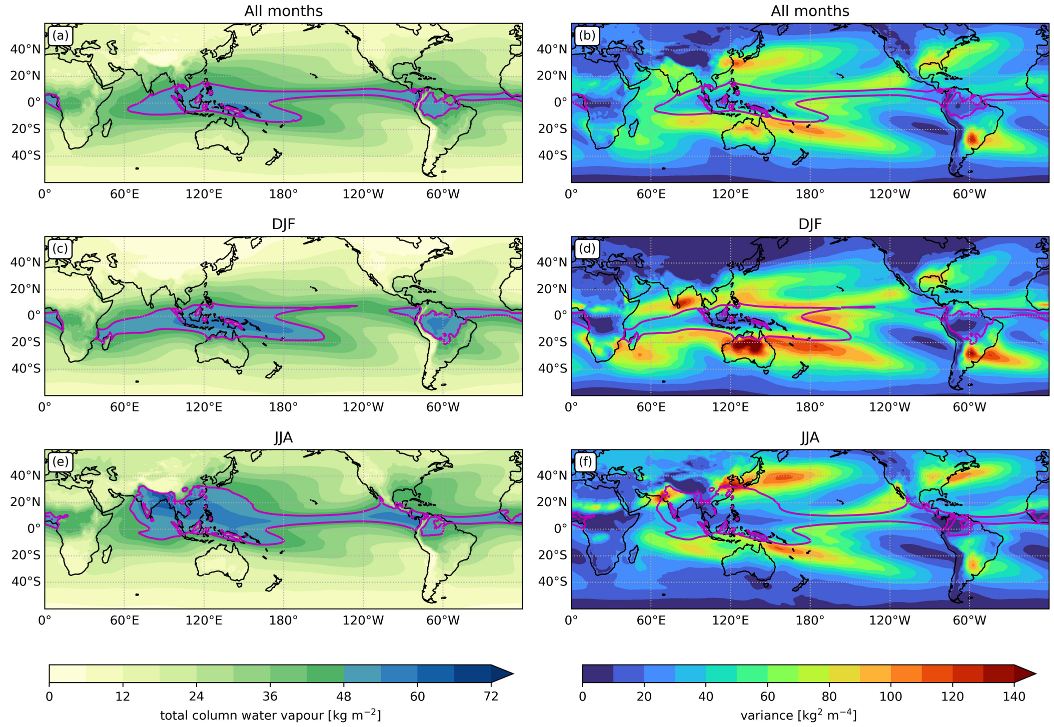

Figure 2. TCWV mean (left) and daily variance (right) for all months (top), DJF (middle), and JJA (bottom). The purple contour in all panels denotes the moist margin at 48 kg m^{-2}.

an open question. Interestingly, the moist margin is clearly identifiable over South America, but is absent over tropical Africa, indicating important differences in the rainfall behavior over the two continents. This will be further discussed in Section 6.1.

The daily variance plots in Figure 2 show that variability is largest in the regions straddling the edges of the mean moist margin in all seasons. This suggests that these areas are hotspots for activity on synoptic and longer timescales. Interestingly, the SPCZ and other diagonal convergence zones are even more easily identifiable in the variance compared to the mean state. This suggests that these climatic features are the result of transient activity rather than mean conditions, consistent with dynamical studies of the SPCZ (Matthews, 2012; van der Wiel et al., 2015). Also prominent are the dominant tracks for tropical lows and cyclones in the Northwest Pacific and North Atlantic, as well as north-central Australia and south-central South America. The former is likely due to moisture variations between tropical disturbances such as cyclones and the clear periods between, while the large variance over Australia during austral summer may indicate the strong disparity between monsoon burst and break conditions (Troup, 1961; Pope et al., 2009; Berry & Reeder, 2016; Narsey et al., 2017)

Areas inside the climatological margin tend to have smaller variance, and are therefore more consistently humid compared to regions outside the margin. This allows us to create a conceptual framework where the area contained by the margin acts like a reservoir of moisture (i.e. the 'deep tropics'), where moisture is high and variability is small. Transient activity periodically moves this moisture to higher latitudes outside the climatological margin, which is interspersed by dry periods, creating high TCWV variance. This will be further analyzed in the next section.

4.2 Synoptic variability

As stated in the introduction, strong 'meanders' in the moist margin can be observed in snapshots of TCWV, and understanding its movement provides the main motivation for this study. An example of this for 28 Jan 2019 is shown in Figure 3a. Here, the margin shows considerable perturbations from the basic austral summer state shown in Figure 2c. This includes features such as Tropical Cyclone Riley in the southeast Indian Ocean, a monsoon low over northeast Australia, a frontal-like structure on the southwest Indian Ocean with a dry intrusion to its east, and a wet-dry-wet wave pattern in the West Pacific in both hemispheres. The overlaid rainfall in Figure 3a shows that it is mostly confined to areas within the margin, with some exceptions. Possible reasons for these exceptions are further discussed in Section 6.1.

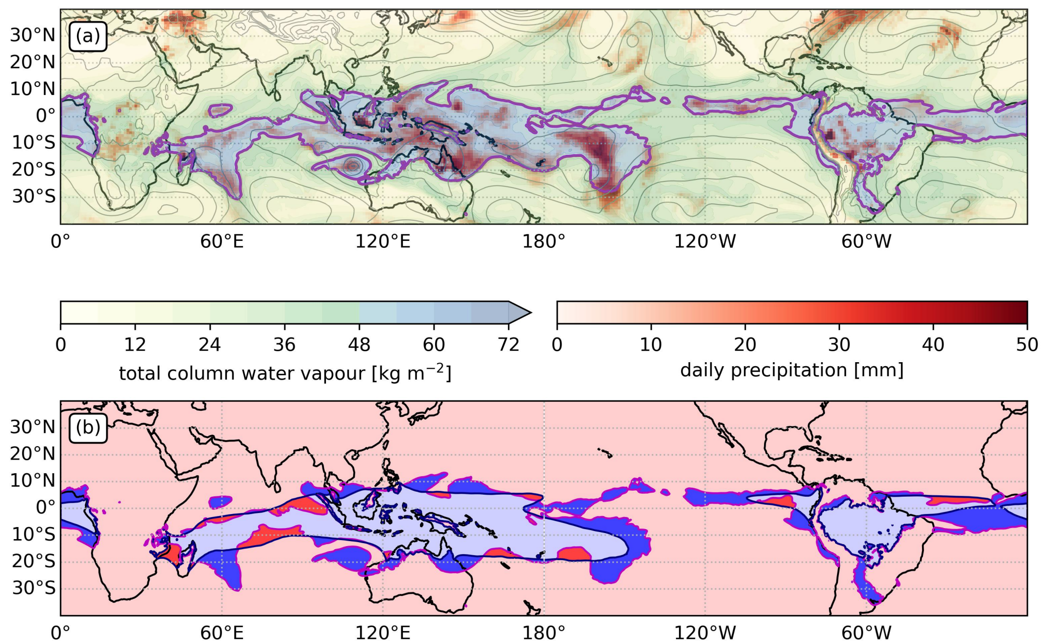

Figure 3. Daily mean TCWV (shading), moist margin (purple contour), mean sea level pressure (thin gray contours) and precipitation (red shading) for 28 Jan 2019 (a). Corresponding moisture categories are shown in panel b, where the navy contour denotes the basic state moist margin. Wet perturbations are in dark blue, dry perturbations are in dark red, wet normal is in light blue, and dry normal is in light red.

4.2.1 Wet and dry perturbations

To effectively analyze the synoptic variability of the moist margin, we seek a method to define anomalously wet and dry areas. We create four categories based on the movement of the margin in relation to its annual cycle, calculated as a centered 15-day moving average over 1979-2021:

1. 'Wet perturbations' are areas above 48 kg m^{-2} that are below in the climatology,
2. 'Dry perturbations' are areas below 48 kg m^{-2} that are above in the climatology,
3. 'Wet normal' are areas that are above 48 kg m^{-2} at that timestep as well as the climatology,

4. 'Dry normal' are areas that are below 48 kg m^{-2} at that timestep as well as the climatology.

Figure 3b shows objects for these four categories for 28 Jan 2019. The wet perturbations, shaded in dark blue, are largely outward extensions of the moist margin, and the dry perturbations, shaded in dark red, are generally inward intrusions of the margin. Some isolated wet perturbations exist, such as near 60 °E, 0-5 °N; these have been termed 'atmospheric lakes' by Mapes and Tsai (2021). Heavy rainfall is common in the wet perturbations (see Figure 3a), and largely absent in the dry perturbations.

4.2.2 Object properties

We now turn our attention to some basic properties of the objects introduced above, in particular the wet and dry perturbations. Figure 4 shows the frequency of occurrence of wet and dry perturbations for austral summer (top) and winter (bottom). In the following discussion, note that by definition, wet perturbations must occur outside the climatological margin, and dry perturbations must occur inside it.

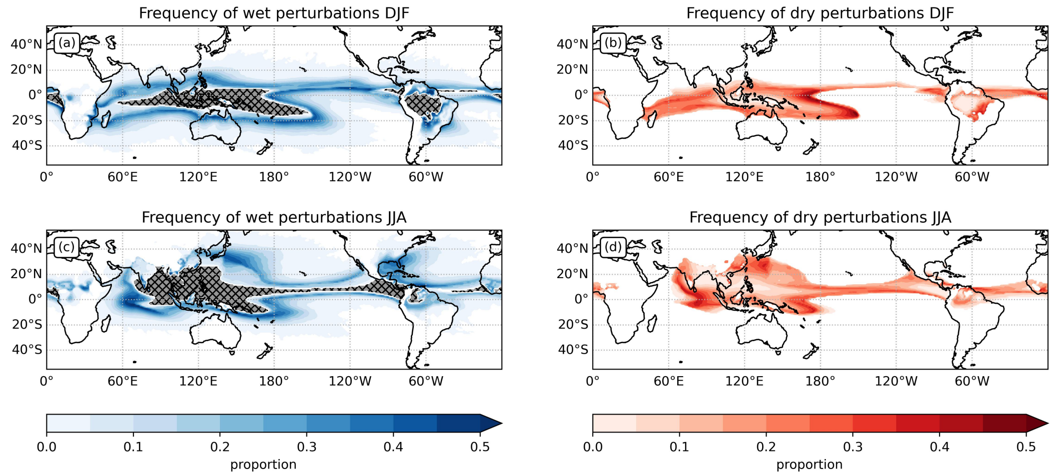

Figure 4. Frequency maps of wet perturbations (left) and dry perturbations (right) for DJF (top) and JJA (bottom). Regions which never experience perturbations are in white. The hatched area in the left panels denote where the climatological TCWV is above 48 kg m^{-2}, and therefore by definition no wet perturbations can occur.

Wet perturbations occur most often in the shoulder regions of the tropics, especially around the ITCZ and SPCZ, and occur less frequently moving away from the climatological margin, which shifts by season. This is unsurprising, as areas close to the climatological margin would be expected to have TCWV go above 48 kg m^{-2} more often. Wet perturbations can occasionally extend past 40 °N/S in the summer hemisphere, especially in the Northwest Pacific and North Atlantic. This is likely due to tropical cyclones or strong midlatitude interactions which transport tropical moisture to higher latitudes.

Dry perturbations are most frequent in regions just inside the climatological moist margin, particularly around the ITCZ, SPCZ, and central Indian Ocean. Although less common, they can extend all the way into the central Maritime Continent during austral summer and the Bay of Bengal and South China Sea during boreal summer. Therefore, any location inside the climatological moist margin is prone to dry perturbations.

Figure 5 shows that there is a clear seasonal cycle of the total area covered by wet and dry perturbations by month. The summer hemisphere has a greater area covered by both wet and dry perturbations, peaking in August for the Northern Hemisphere and March for the Southern Hemisphere. This suggests that there is more synoptic 'activity' in the summer hemisphere; for example, a series of tropical cyclones will create multiple large wet interspersed by dry perturbations. Wet perturbations also cover a larger area than dry perturbations; this will be expanded on in the following paragraphs.

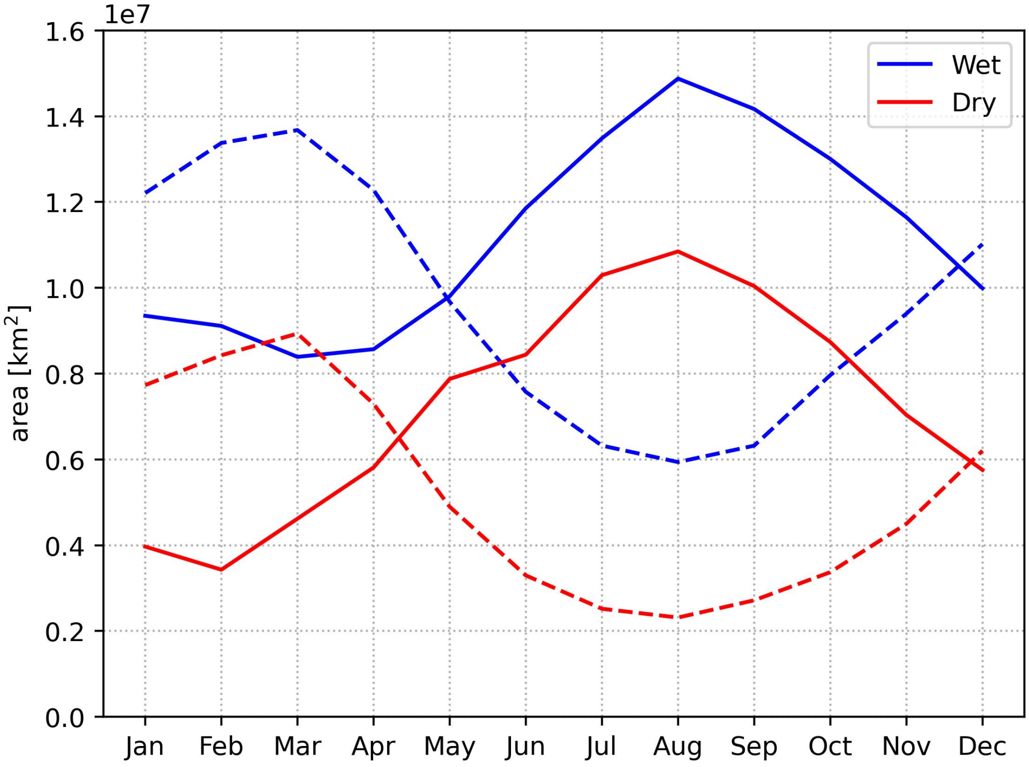

Figure 5. Average area covered by all wet (blue) and dry (red) perturbations in each month by hemisphere. Solid lines show the Northern Hemisphere and dashed lines show the Southern Hemisphere.

Figure 6 shows more properties of wet and dry perturbations, including the number of objects per day, and distributions of object size and mean TCWV anomaly. Note that in this figure, we have removed all objects smaller than 500,000 km^2, so that we are only considering large perturbations. In general, there are more wet perturbations (mean of 10.4) on a given day than dry perturbations (mean of 6.4), though there is considerable spread in the number. Notably, there is always at least one wet and dry perturbation each day.

Both wet and dry perturbations have a gamma-like size distribution, meaning there are many more small objects than large objects. If the minimum area threshold is removed, the distribution keeps the same shape at small sizes (not shown). Although the distributions for wet and dry perturbations are very similar, there are slightly more large (above 1×10^6 km^2) wet objects compared to dry objects.

Also presented in Figure 6b is the mean TCWV anomaly of wet and dry perturbations, which could be considered a measure of the intensity of the object. Note that

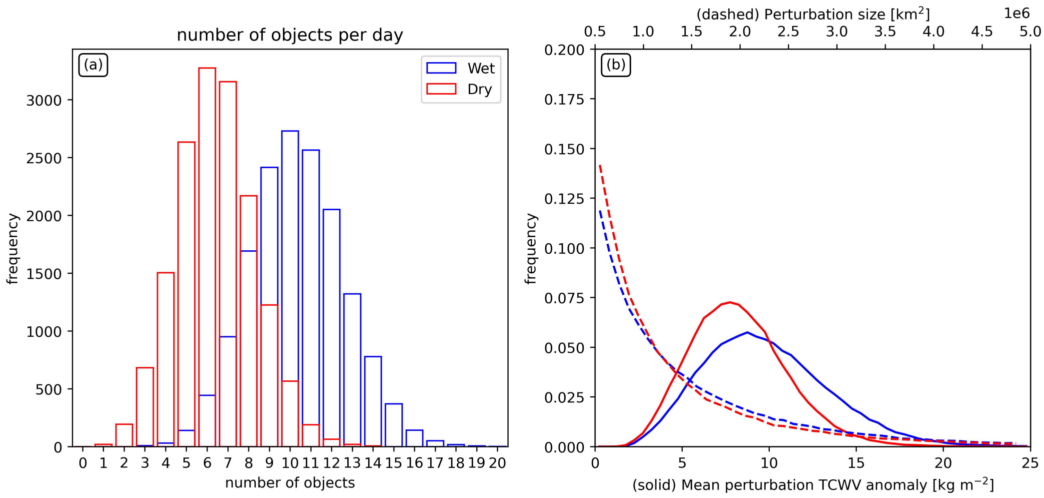

Figure 6. Distributions of the number of objects per day (left), size (right, dashed line) and mean TCWV anomaly (right, solid line) for wet (blue) and dry (red) perturbations. The anomaly for dry perturbations has been multiplied by -1 to make it a positive number.

dry perturbation values have been multiplied by -1 for easier display in the same graph. The mean TCWV anomaly is near-normally distributed for both wet and dry perturbations, though wet perturbations generally have larger anomalies (mean of 10 kg m^{-2}) compared to dry anomalies (mean of 8.5 kg m^{-2}). Wet perturbations also have a more prominent tail at high TCWV anomalies; for example, an anomaly of 15 kg m^{-2} is much more common for wet perturbations compared to dry perturbations.

Overall, Figure 6 shows that wet perturbations are typically more frequent, larger, and more intense than dry perturbations. While this may seem contradictory at first glance, note that the calculations determining wet and dry perturbations are done by grid point. Therefore, a balance between wet and dry perturbations at a single snapshot is not required; rather, there must be a balance between the four categories (including 'wet normal' and 'dry normal') at each grid point. Wet perturbations being more frequent and intense is also consistent with large TCWV variability outside the margin, as shown in Figure 2. This implies that areas outside the margin are prone to strong undulations in TCWV, often pushing them above 48 kg m^{-2} and into the wet perturbation category. Meanwhile, areas inside the margin have smaller undulations and therefore fall below the 48 kg m^{-2} and into the dry perturbation category less frequently.

4.2.3 Relation of objects with rainfall

We now demonstrate that wet and dry perturbations are tightly linked with rainfall variability on synoptic scales. Figures 7a and b show the proportion of daily rainfall associated with wet and dry perturbations. Wet perturbations are associated with a large amount of rainfall along the shoulder regions of the moist tropics. This includes the northwest and southern Indian Ocean, northern inland Australia, and around the edges of the ITCZ and SPCZ. Many of these areas experience greater than 50% of their total rainfall during wet perturbations. Moving further away from the moist tropics, the proportion of rainfall during wet perturbations becomes smaller, likely due to the rarity of objects there. Some areas in the deep tropics (e.g. the Maritime Continent) experience little or no rainfall from wet perturbations; this is due to the climatological TCWV being above 48 kg m^{-2} for much of the year. Very little rainfall is associated with dry perturbations, with less than 10% of rainfall occurring during dry perturbations in most places.

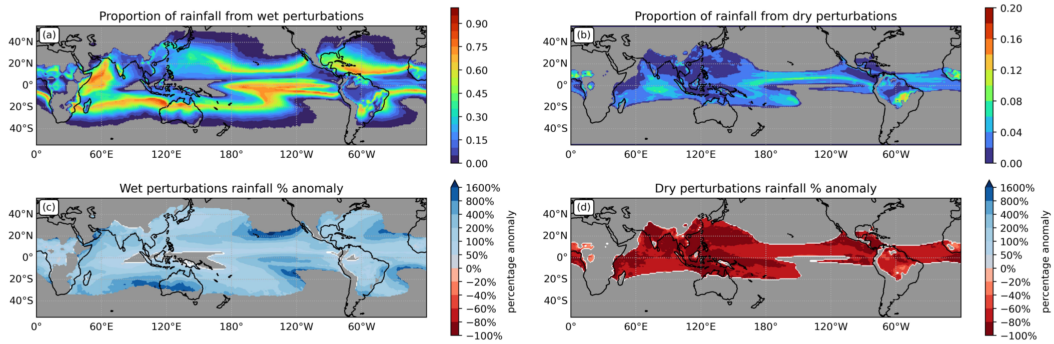

Figure 7. Total proportion of rainfall from wet (a) and dry (b) perturbations. Daily rainfall percentage anomaly compared to the seasonal mean for wet (c) and dry (d) perturbations. Regions where object frequency is below 0.1% are shaded gray. Note the difference in color scales between panels (a) and (b).

How large are the rainfall anomalies during wet and dry perturbations? The answer to this likely varies by location. For example, a climatologically dry area may receive far greater rainfall than usual in a wet perturbation compared to a climatologically wetter area. Figures 7c and d present daily rainfall percentage anomalies compared to the 15-day smoothed seasonal climatology. Wet perturbations (Figure 7c) produce over 50% more rainfall compared to climatology across the entire tropics, and this anomaly increases moving away from the moist tropics and towards drier regions. Some regions near the equatorial cold tongues and central Australia receive more than 800% of their mean daily rainfall in a wet perturbation. In comparison, rainfall in the deep tropics is strongly reduced (less than 40% of usual over most areas) when experiencing a dry perturbation. This emphasizes the importance of the moist margin as a strong predictor of heavy rainfall.

5 Large-scale conditions leading to perturbations

So far, we have presented properties of wet and dry perturbations in the moist margin, but have not considered the large-scale conditions that these objects form in. In this section, we will explore what relates to TCWV variance, in particular sea surface temperature and mid-tropospheric humidity.

5.1 Role of sea surface temperatures

Sea surface temperatures (SSTs) may be expected to strongly relate to TCWV, due to increased evaporation over warm waters. Previous research has shown that low-level relative humidity over the oceans remains near-constant with global warming, meaning low-level specific humidity and TCWV closely follows Clausius-Clapeyron scaling with temperature on long timescales (Trenberth et al., 2005; Sherwood & Meyer, 2006; Held & Soden, 2006; Willett et al., 2007; Mears et al., 2007; O'Gorman & Muller, 2010). Does this also apply on synoptic scales?

Figure 8 shows 2D histograms of daily-mean SST and TCWV for wet and dry perturbations. There is considerable spread in SST for both wet and dry perturbations, however, wet perturbations tend to have colder SSTs (mean: 27.7 °C) than dry perturbations (mean: 28.6 °C) (Figure 8a). This is the opposite of our hypothesis, which would predict that wet perturbations tend to occur with *warmer* SSTs. However, the difference between wet and dry perturbations is simply related to the geographical distribution of these objects. Wet perturbations occur in the shoulder regions of the tropics, where SSTs are typically cooler; and dry perturbations occur in the deep tropics, where SSTs are typically warmer.

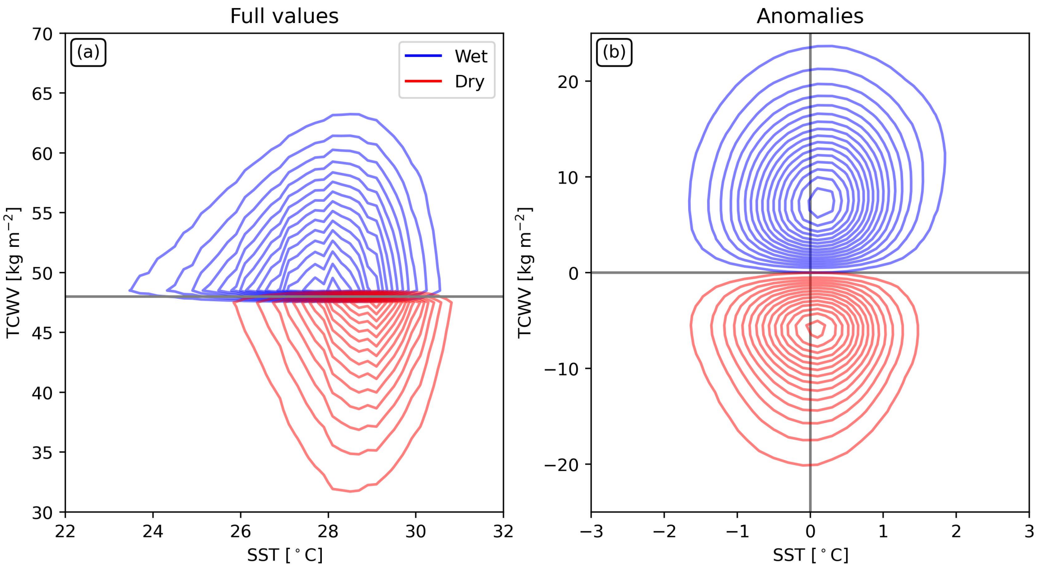

Figure 8. 2D histograms of daily SST and TCWV (a) and their daily anomalies (b), across global tropical oceans (30°N-S). Wet perturbations are in blue and dry perturbations are in red. Each point in the histogram represents one grid point at each time. Histogram spacing is 0.1 K for SST and 1 kg m^{-2} for TCWV, and contours are plotted every 10000 points. Note that by definition, wet perturbations must be above 48 kg m^{-2} and their anomaly above zero, while dry perturbations must be below 48 kg m^{-2} and their anomaly below zero. Therefore, there is no overlap between wet and dry perturbations in the histograms.

Removing the climatological SST may better illustrate any relationship between SST and TCWV, and this is shown in Figure 8b. There is very little difference in the distribution of SST anomalies between wet (mean: +0.14 °C) and dry perturbations (mean: -0.03 °C). This suggests that SST anomalies have little to no relationship with TCWV anomalies and therefore perturbations of the moist margin on daily time scales. This is in agreement with Neelin et al. (2009), who show that SSTs are unimportant for the convective pickup of rainfall over tropical oceans. TCWV variance must therefore be related to internal atmospheric processes.

5.2 Vertical structure of wet and dry perturbations

Figure 9 shows composite profiles of specific humidity, temperature, and vertical motion anomalies for the four categories described in Section 4.2. In general, wet and dry perturbations have the strongest anomalies, while 'wet normal' and 'dry normal' (i.e. areas above/below 48 kg m^{-2} at that timestep as well as the climatology) have weaker anomalies of the same sign. This is because the wet normal category has dry perturbations removed, meaning the average will be wetter than all times. The opposite is also true for the dry normal category.

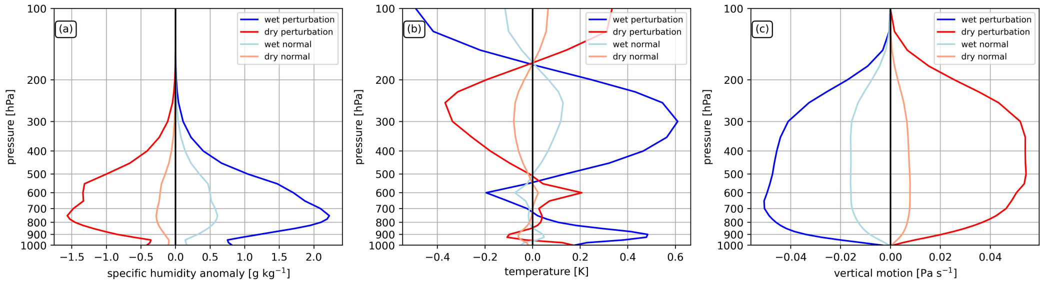

Figure 9. Composite profile of the specific humidity (a), temperature (b), and vertical motion (c) anomalies from the 15-day smoothed seasonal climatology for the four categories described in Section 4.2 within 30°N-S.

Wet perturbations are anomalously moist through the whole troposphere, with the largest anomalies from around 500-900 hPa and a maximum at 750 hPa of 2.2 g kg^{-1}. Anomalies at 1000 hPa are smaller at 0.8 g kg^{-1}, and near-zero above 250 hPa where specific humidity is small in all cases. Dry perturbations follow a very similar profile but with the opposite sign to wet perturbations, having a broader peak of around -1.5 g kg^{-1} from 800-550 hPa. These results show that the largest differences in humidity between wet and dry perturbation exist in the mid-troposphere. This is consistent with a wide body of literature emphasizing the importance of mid-tropospheric moisture for heavy rainfall from the convective and mesoscale (Brown & Zhang, 1997; Sherwood, 1999; Derbyshire et al., 2004; Louf et al., 2019) to synoptic (Smith et al., 2015; Ditchek et al., 2016) and seasonal scales (Parker et al., 2016).

To further investigate the likely predominant source of mid-level humidity, we analyze the vertical motion profiles shown in Figure 9b. These show upward anomalies for wet perturbations and downward anomalies for dry perturbations through the whole troposphere. Wet perturbations peak at lower levels (700 hPa) than dry perturbations (500 hPa), both with values of about 0.05 Pa s^{-1}. Stronger upward motion in the wet perturbations is consistent with enhanced precipitation and a moister mid-troposphere via vertical moisture advection. Similarly, subsidence in the dry perturbations is consistent with reduced precipitation and a drier mid-troposphere. This suggests that vertical advection is a key source of moisture in the mid-troposphere. However, note that vertical advection cannot change the full column-integrated specific humidity (i.e. TCWV), and that changes in TCWV must be due to low-level horizontal convergence and advection.

Insight can also be gained from the temperature profiles shown in Figure 9c. Ther temperature has a more complex structure comprising multiple peaks and sign changes. Wet perturbations are anomalously warm in the lower troposphere (1000-700 hPa), anomalously cool in a shallow layer from 700-550 hPa, warm in a deep layer from 550-150 hPa, and cold above. Dry perturbations again have a very similar profile but in reverse, except for the lower-troposphere which has weak and variable temperature anomalies. These profiles bear a remarkable similarity to a result of Virman et al. (2018) (see their Figure 2), who suggest that the mid-tropospheric cold anomaly in rainy areas is due to strong evaporation below the cloud base, which induces subsidence and creates a warm anomaly at lower levels. This is despite the difference in filtering methods for the composites (we use TCWV anomalies, while Virman et al. (2018) use absolute rainfall thresholds). The temperature profiles are also consistent with the archetypical mesoscale convective system view of Houze (1989, 1997), where subsidence occurs below the cloud base of stratiform regions. Therefore, this appears to be a robust result when comparing wet and dry areas of the oceanic tropics.

6 Discussion

6.1 Evaluating the moist margin in the ERA5 reanalysis

We have analyzed the variability of the moist margin, defined as TCWV = 48 kg m^{-2}, across multiple time scales. We have shown that the ERA5 reanalysis reproduces features of the TCWV distribution observed in satellite-based products by Mapes et al. (2018) and is therefore a suitable dataset to analyze the margin.

The moist margin is strongly associated with heavy rainfall over the tropical oceans, although there are some notable exceptions. Figure 3, along with other snapshots, shows that rainfall often occurs outside the margin, most notably along frontal features in the winter hemisphere subtropics. These discrepancies are likely related to temperature differences across latitudes. For a given TCWV, a colder atmosphere, such as that of the winter hemisphere subtropics, will be closer to saturation and therefore more likely to precipitate. Dynamical effects are also more likely to play an important role in organizing rainfall at higher latitudes, especially along the fronts present in Figure 3.

Considering the above, an alternative to TCWV would be to use a variable which scales with temperature. One example commonly used in the literature is the saturation fraction, defined as the ratio of vertical integrals of specific humidity to saturation specific humidity, as a kind of 'column relative humidity'. Bretherton et al. (2004) found that the relationship between humidity and mean rainfall over tropical oceans collapses onto a single curve when using saturation fraction rather than TCWV as the independent variable. However, Peters and Neelin (2006) and Neelin et al. (2009) find that the critical value for convective pickup still depends on temperature. Therefore, accurately accounting for the temperature dependence on the humidity-precipitation relationship is difficult. Another complication is that adding temperature-dependence makes for more difficult prognostic analysis. For example, while changes to TCWV are simple to understand through the moisture budget, changes to saturation fraction or a similar quantity will also depend on temperature and are not described by one simple equation. Furthermore, snapshots of saturation fraction are noisier and do not depict a clean line in the tropics (not shown), making it difficult to distinguish between the moist tropics and extratropics. For these reasons, we choose TCWV as being the most suitable measure for defining the tropical margin.

Our analysis has also shown that the moist margin covers land regions, most prominently over the Amazon in South America, but also over regions such as northern Australia, the Maritime Continent, and Southeast Asia. However, the margin is conspicuously absent over Africa. The role of moisture on convection is more complicated over land due to additional forcings such as topography (Smith et al., 2009; Kirshbaum & Smith, 2009), strong diurnal heating (Nesbitt & Zipser, 2003), and coastal features such as land-sea breezes (Bergemann & Jakob, 2016). Topography also reduces the depth of the moist layer, resulting in lower TCWV. However, research has suggested that both the Maritime Continent and Amazon display 'oceanic-like' behavior, and that the convective pickup first noted over oceans (Peters & Neelin, 2006; Neelin et al., 2009) also applies over these areas (Schiro et al., 2016; Ahmed & Schumacher, 2017). On the other hand, Africa has more topography which can interfere with the predominantly easterly synoptic flow and its associated rainfall (Jackson, 1947). Despite this, sharp humidity gradients such as the Congo Air Boundary (Howard & Washington, 2019) and Sahel inter-tropical front (Vizy & Cook, 2017) are features over Africa that control areas of heavy rainfall, acting in a very similar way to the moist margin. Caution is therefore needed when analyzing the moist margin over land, though we suggest it is still of value.

Other differences with Mapes et al. (2018) and similar studies which use high-resolution observational datasets is the coarser resolution used in our analysis (1° daily means), which may be expected to alter the relationship of the moist margin with precipitation. Schiro et al. (2016) find that the convective pickup relationship is robust when averaging to 3-hourly data at 2.5° resolution. Averaging beyond this smooths the relationship and slightly reduces the threshold. This implies that the spatial resolution of 1° in this study is adequate, though the low temporal resolution of 24 hours may suggest a threshold slightly lower than 48 kg m^{-2} may be more suitable for the moist margin, consistent with the slightly lower TCWV values seen in Figure 1 compared to Mapes et al. (2018).

Some limitations of the moist margin method include:

1. The moist margin breaks up over land, most notably Africa, and does not capture all rainfall at higher latitudes, particularly in the winter hemisphere.
2. There is still considerable variability within the moist margin, and 48 kg m^{-2} threshold is not a sufficient condition for heavy rainfall. Dynamical factors leading to uplift are another vital component for rainfall.
3. Climate models are poor at representing the moist margin (and more generally, the relationship between moisture and precipitation), as shown in Mapes et al. (2018). Therefore, caution is needed when analyzing the moist margin in models.

6.2 What creates wet and dry perturbations?

The synoptic variability of the margin has been analyzed with ‘wet and dry perturbation’ objects, defined in Section 4.2. These objects occur in the shoulder regions of the deep tropics, which has a strong seasonal migration towards the summer hemisphere.

Wet perturbations likely encompass a variety of dynamical features, including tropical cyclones and lows, tropical waves, as well as atmospheric rivers (Zhu & Newell, 1998; Gimeno et al., 2014), tropical plumes (Knippertz, 2007), tropical moisture exports (Knippertz & Wernli, 2010; Knippertz et al., 2013), and their related synoptic systems. Some of these features are likely due to strong extratropical interactions with the moist margin. One notable area for this is the SPCZ and SACZ, where research has shown that rainfall variability is influenced by extratropical Rossby waves that refract towards the tropics and cause dynamical uplift leading to rainfall (Matthews, 2012; van der Wiel et al., 2015).

Dry perturbations bear a natural resemblance to the ‘dry intrusions’ commonly described in the literature. Dry intrusions generally form through the descent and advection of dry air from the subtropics to the tropics and are also tightly linked to midlatitude processes (Mapes & Zuidema, 1996; Yoneyama & Parsons, 1999; Casey et al., 2009; Raveh-Rubin, 2017; Aslam et al., 2023). Clearly, extratropical dynamics are an important factor for driving variability in the moist margin and creating both wet and dry perturbations. Further investigation of this will be the subject of future research.

Are variations in humidity at the moist margin purely driven by synoptic dynamics, or does moisture itself play a role in producing variability? Theories of ‘moisture modes’ suggest that moisture, rather than temperature, is the key factor controlling large-scale wave dynamics (Raymond & Fuchs, 2007; Adames et al., 2019). Wave-like structures in the moist margin are common, for example in the Southwest Pacific in Figure 3, suggesting a natural link with moisture mode theory. These structures may also include convectively coupled equatorial waves (Wheeler & Kiladis, 1999; Kiladis et al., 2009). However, we leave detailed analysis of this to future work.

7 Conclusion

This study has analyzed the synoptic variability of the moist margin and related it to rainfall and other large-scale conditions in the tropics. The moist margin is a useful measure that relates tropical precipitation variability to tropical moisture over oceans, since it largely bounds heavy rainfall. This defines the 'moist tropics' where heavy rainfall is most likely to occur.

The moist margin exhibits a strong seasonal cycle, particularly in monsoonal regions. Wet and dry perturbations, defined through the movement of the margin relative to its seasonal climatology, are strongly linked to rainfall variability along the shoulder regions of the moist tropics. These perturbations are most related to mid-tropospheric humidity and have little to no correlation with SSTs.

The objects analyzed here may be linked to a variety of processes, such as tropical waves, the Madden-Julian Oscillation, synoptic weather systems such as tropical lows and cyclones, and midlatitude influences. Future work in this topic will explore the dynamical causes, evolution, and decay of synoptic disturbances of the moist tropical margin. This likely requires tracking the objects through time and space, and the use of prognostic analysis such as the moisture and circulation budgets.

Open Research Section

Data from the ERA5 reanalysis is obtainable from the ECMWF Copernicus Climate Data Store (`https://cds.climate.copernicus.eu/cdsapp#!/home`). GPCP rainfall data was received from NCAR at `https://rda.ucar.edu/datasets/ds728.7/`. Data from OISST is available at `https://www.ncei.noaa.gov/products/optimum-interpolation-sst`. The code used to generate all plots is in Python.

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