Geophysical Research Letters

RESEARCH LETTER
10.1029/2020GL088515

A Relationship Between ITCZ Organization and Subtropical Humidity

Cathy Hohenegger[1] **and Christian Jakob**[2,3]

[1]Max Planck Institute for Meteorology, Hamburg, Germany, [2]ARC Centre of Excellence for Climate Extremes, Monash University, Melbourne, Victoria, Australia, [3]School of Earth, Atmosphere and Environment, Monash University, Melbourne, Victoria, Australia

Key Points:
- The large-scale organization of the Atlantic ITCZ is quantified using a 35-year data set of convergence lines
- Relationships derived from reanalysis data between convective organization and humidity are consistent with results from idealized studies
- Years with a more organized ITCZ structure are associated with drier conditions in the subtropics

Supporting Information:
- Supporting Information S1

Correspondence to:
C. Hohenegger,
cathy.hohenegger@mpimet.mpg.de

Citation:
Hohenegger, C., & Jakob, C. (2020). A relationship between ITCZ organization and subtropical humidity. *Geophysical Research Letters*, *47*, e2020GL088515. https://doi.org/10.1029/2020GL088515

Received 23 APR 2020
Accepted 3 AUG 2020
Accepted article online 10 AUG 2020

Abstract Motivated by the results of idealized studies on the self-aggregation of convection, we investigate a potential relationship between the degree of organization of the Intertropical Convergence Zone (ITCZ) and humidity based on reanalysis data. We focus on the Atlantic ITCZ and use the number of long convergence lines occurring per month to define the degree of organization. The latter shows a weak enhancement during June to August (JJA) and a large interannual variability. On an interannual time scale and particularly during JJA, a relationship exists between organization and humidity: Years with more organized ITCZs are associated with a moister ITCZ region and drier subtropics. Even though we cannot demonstrate any causality and cannot rule out the presence of another agent, we show that these moisture anomalies are not incompatible with an effect of organization. We also note that the annual cycle in sea surface temperature (SST) gradient may contribute to the intra-annual variability in organization.

Plain Language Summary The large-scale organization of individual convective cells into a coherent structure over the tropics, the Intertropical Convergence Zone (ITCZ), is an easily recognizable feature of satellite imagery. At times, the ITCZ appears well organized, forming a long line, whereas at other times, it appears much more scattered and made of disconnected convective clusters. We investigate the hypothesis, derived from previous idealized studies, that a relationship exists between organization and atmospheric humidity. We quantify organization by counting the number of times per month the ITCZ is organized in a long line. The study shows for the first time that, indeed, a relationship exists between the large-scale degree of convective organization and humidity in the real world: Years with a more organized ITCZ are associated with drier subtropics and a moister ITCZ region. Given the importance of subtropical humidity for the energy budget of the climate system, our results ask for more studies investigating this relationship and its causality.

1. Introduction

The propensity of convection to organize is undisputable. A prominent example is the large-scale organization of convection in the tropics in the form of the Intertropical Convergence Zone (ITCZ). Even in the absence of large-scale forcing and in purely homogeneous boundary conditions, convection is able to organize on its own and to clump into one large band or cluster (e.g., Held et al., 1993; Tompkins & Craig, 1998), a process referred to as convective self-aggregation. The occurrence of self-aggregation is of utmost importance in such idealized experiments as it drastically affects the atmospheric state and the resulting climate (e.g., Bretherton et al., 2005; Hohenegger & Stevens, 2016; Wing & Cronin, 2016). Whether self-aggregation processes remain important for the real world is an open question (e.g., Bony et al., 2015; Holloway et al., 2017; Jakob et al., 2019).

In this study, we test one prediction from idealized self-aggregation studies using reanalysis data and focusing on the tropical Atlantic. Such studies have shown that the transition from a state with randomly distributed convection to a state made of one convective cluster is accompanied by a strong drying of the subsidence region (e.g., Bretherton et al., 2005). This drying overcompensates an observed moistening of the convecting region. Although the enhanced drying has not been formally explained, it is generally assumed that one convective cluster, which tends to remain stationary, is less efficient at moistening the subsidence region given the longer distances that moisture has to travel, as noted in Tompkins and Semie (2017). Changes in precipitation efficiency, with organized convection being associated with a higher precipitation efficiency, as suggested by Tobin et al. (2012) and Stein et al. (2017), could further explain the strong drying of the subsidence region.

The observational study of Tobin et al. (2012) confirmed that mesoscale regions of enhanced organization, where mesoscale regions are defined as $10° \times 10°$ boxes, are indeed drier than their less organized counterparts for given sea surface temperature (SST), precipitation, and vertical velocity. Here, we interpret the results of self-aggregation studies more in the sense of Hohenegger and Stevens (2016). In their idealized simulation using homogeneous insolation, no rotation, and a slab ocean, they noted that the self-aggregation of convection generated the dry subtropics that allowed their simulation to stabilize at an SST close to the observed mean tropical SST. We thus probe in the reminder of this paper whether a relationship exists between the large-scale organization of the ITCZ and humidity in the real world, where more organized ITCZs are expected to be associated with drier subtropics and a moister ITCZ region. We do so without compositing on similar large-scale conditions as we aim to assess the potential existence of such a relationship in the midst of other factors and in a system that is not as constrained as in idealized studies. That a relationship between the organization of the ITCZ and subtropical humidity may exist appears plausible. Past studies (e.g., Pierrehumbert, 1998; Sherwood, 1996) have shown that horizontal advection of moisture from the ITCZ is an important source of moisture for the subtropics. Changes in organization could alter this source, through changes in precipitation efficiency or in source proximity, as noted above.

2. Methodology

2.1. Quantification of Organization

Quantifying organization is not straightforward (see, e.g., Figure 1 in Brueck et al., 2020), as evidenced by the various organization indices that have been proposed recently (Brune et al., 2018; Kadoya & Masunaga, 2018; Retsch et al., 2020; Tobin et al., 2012; Tompkins & Semie, 2017; White et al., 2018). Different indices emphasize distinct aspects of organization and do not necessarily agree (Pscheidt et al., 2019; Xu et al., 2019). Most organization indices have been developed to quantify convective organization at the mesoscale and not at the scale of the ITCZ. One issue is the large distances that can exist between clusters in the latter case; a few small clusters that lie far apart will dominate and distort the statistics when using organization indices based on distances. Moreover, past organization indices were not designed for a particular convective phenomenon, like the ITCZ, but to quantify organization in a certain geographical area.

Given these considerations, we develop a new approach to quantify the organization of the ITCZ. The idea is that an ITCZ organized in a continuous line that spans the tropical Atlantic, as in Figure 1a, should be recognized as highly organized. In contrast, an ITCZ split into individual clusters without a well-defined continuous line of convection, as in Figure 1b, should be viewed as unorganized. With this in mind, we employ a data set of convergence lines compiled by Weller et al. (2017) to quantify the degree of organization of the ITCZ. This data set is based on an objective convergence line detection algorithm developed by Berry and Reeder (2014). The algorithm is applied on instantaneous values of wind divergence calculated every 6 hr at 950 hPa from ERA-Interim. Weller et al. (2017) showed that the frequency of occurrence of the detected convergence lines matches well with the ITCZ location. Over the tropical Atlantic, 60% to 80% of the annual mean precipitation is associated with the detected convergence lines (see Figure 6a in Weller et al., 2017).

Starting with all detected convergence lines, we identify those lines longer than a threshold. We choose 3,000 km as threshold, a choice discussed further below. We then simply count the number of these long lines occurring per month over the Atlantic ITCZ region, denoted $\mathcal{N}_{\text{long}}$: The larger $\mathcal{N}_{\text{long}}$, the more often highly organized ITCZs occurred and the more likely a relationship between organization and humidity may be detected. We conduct the analysis on a monthly basis as it takes time for moisture to travel (Cau et al., 2007; Pierrehumbert, 1998). The resulting interannual and intra-annual variability in $\mathcal{N}_{\text{long}}$ is used to investigate relationships between organization and humidity.

For our analysis, we only consider oceanic points. We focus on the Atlantic ITCZ region as the presence of South America and Africa naturally confines the extent of the ITCZ, without disturbances arising from the presence of islands. The Atlantic ITCZ region is bounded by the two longitudes 70°W and 30°E. We define its meridional extent by the latitude of the maximum of the zonal mean of the monthly tropical Atlantic oceanic precipitation $\pm 7.5°$. The latter was found to match well the inflection point of the precipitation distribution

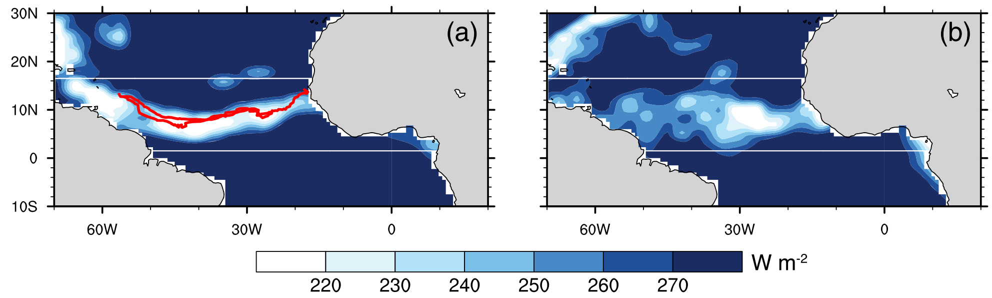

Figure 1. Snapshots of outgoing longwave radiation on a day (a) with and (b) without long lines (in red). The horizontal white lines enclose the ITCZ region for that month. Days are (a) 20 and (b) 13 July 1983. The long line was detected at 0 UTC and then again at 6 UTC. The outgoing longwave radiation corresponds to the mean from 0 to 6 UTC. In this example, only one long line was detected at a particular instant, but times exist where more than one long line is detected.

and, by using a fixed width, avoids potential individual misidentifications of the inflection point. It also ensures that changes in $\mathcal{N}_{\text{long}}$ do not occur because of changes in the width of the ITCZ region.

Various considerations led to choosing a threshold of 3,000 km. First, it is a compromise between having significant temporal variability in $\mathcal{N}_{\text{long}}$ but retaining a large enough sample. The normalized interannual variability in the number of lines increases with line length, but the frequency of occurrence of line length rapidly decreases (see Figures S1a and S1b in the supporting information [SI]). Second, our metric has to be able to clearly isolate those events with a continuous ITCZ spanning a significant portion of the Atlantic. Lines longer than 3,000 km correspond to the 99th percentile of the distribution (see Figure S1c). With an east-west extent of the tropical Atlantic of about 5,500 km, a threshold of 3,000 km implies that a line has to extend over more than half the basin. Lastly, a correlation between the strength of the convergence and line length may be expected, which could lead to a false attribution of the results. Line strength indeed increases with line length (see Figure S2 in the SI) but only for lines smaller than 3,000 km.

From visual inspections, our metric is able to capture the organization of the ITCZ. Lines longer than 3,000 km are zonally oriented and are thus reminiscent of a very well organized ITCZ spanning the tropical Atlantic. Instead of using $\mathcal{N}_{\text{long}}$, we tried alternate metrics such as the total length of long lines per month, the normalized number of long lines per month, or the mean length of lines per month. They all lead to similar overall conclusions (see Figures S3 and S4 in the SI, to be compared to Figures 2 and 3). We choose $\mathcal{N}_{\text{long}}$ in the following as it carries a clear and simple meaning. Compared to the mean length of lines per month, it has the disadvantage that a threshold has to be specified. However, the mean length of lines itself has the disadvantage that 2 months could have the same number of long lines but distinct mean line length, a situation that should not be associated with organization.

2.2. Data

For consistency with the convergence line data set, derived based on ERA-Interim, all the employed atmospheric variables are taken from ERA-Interim. Spatial and temporal resolutions are 0.75° and 6 hr, respectively, and the considered time period is from 1979 to 2013. To quantify humidity, we use the water vapor path, defined as the mass-weighted vertical integral of specific humidity (see Equation (2) in Berrisford et al., 2011).

3. Results

3.1. How Variable is the ITCZ Organization?

Figure 2a shows an overview of the intra-annual and interannual variability in $\mathcal{N}_{\text{long}}$; see also Table S1 in the SI for the actual numbers. A distinct annual cycle is visible with enhanced organization during the months June to August (JJA) and a weak variability during the remaining months, when looking at the 35-year mean. The mean values are 26.4 for JJA and 18.7 otherwise. A similar annual cycle is visible when focusing on the 5 years with the largest or smallest $\mathcal{N}_{\text{long}}$. The increase in $\mathcal{N}_{\text{long}}$ during JJA could be the result of an increase in the number of long lines detected per day and/or of a more frequent occurrence of days with long lines. The number of long lines detected per day, considering only those days with long lines, is slightly

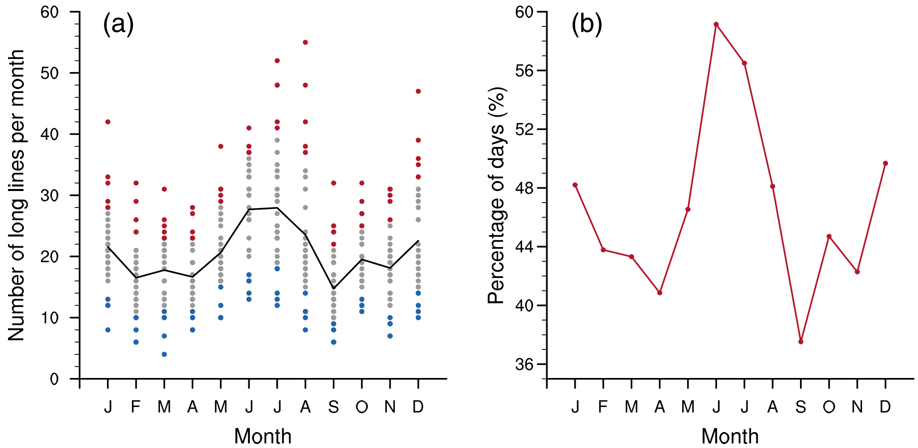

Figure 2. (a) $\mathcal{N}_{\text{long}}$ with 35-year mean in black and dots for individual years and (b) percentage of days with long lines for a given month, computed over the 35 years. In (a) the blue (red) dots indicate the 5 years with the smallest (largest) $\mathcal{N}_{\text{long}}$. Those years are used to compute composites in Figure 3. As distinct years can have the same $\mathcal{N}_{\text{long}}$, not all the symbols are visible in (a).

larger in JJA, with a mean value of 1.6 versus 1.4 in the remaining months. More importantly, the number of days with long lines is increased; see Figure 2b. Notably, during June and July, the days with long lines dominate the statistics.

Figure 2a also indicates that the interannual variability in $\mathcal{N}_{\text{long}}$, with a maximum difference of 47, is larger than its mean (20.6) and much larger than its intra-annual variability (maximum difference of 13.2 for the black curve in Figure 2a). The interannual variability is larger in JJA than in the remaining months.

3.2. Years With a More Organized ITCZ Associated With Drier Subtropics

Given the larger variations in organization on an interannual than on an intra-annual time scale, we start by investigating whether years with a more organized ITCZ are associated with drier subtropics and a moister ITCZ region. To that aim, Figure 3 shows differences in water vapor path based on the 5 years with the largest and smallest $\mathcal{N}_{\text{long}}$. In agreement with our initial hypothesis, a red-blue-red pattern is clearly visible in JJA, with differences statistically significant at the 90% level. Moreover, the complementary relationship is true as well: Years when the ITCZ is particularly unorganized, as quantified by the number of small lines, are associated with a drier ITCZ region and moister subtropics (see Figure S5 in the SI). During the remaining months, the picture is less robust. All the months tend to associate an increase of water vapor path in the ITCZ region with a more organized ITCZ. They also tend to depict a decrease in water vapor path at least in one of the two subtropical regions; in general, the one the ITCZ is moving away from.

The detected clearer signal in JJA is consistent with the larger $\mathcal{N}_{\text{long}}$ and the larger interannual variability detected in JJA (see Figure 2). It is difficult to isolate a relationship between organization and humidity if strongly organized events rarely occur. To partly alleviate this sampling issue, Figure 4 applies an alternative way of compositing, by distinguishing between days with and days without long lines in a given month. As there is persistence in the correlation (see below for further discussion on temporal evolution), using the concurrent correlation between organization and humidity, as done in Figure 4 for simplicity, is adequate. JJA again stands out with anomalous dry subtropics and a moist ITCZ region when composited on the presence of long lines. The signal cannot be explained by chance. The signal can now also be more clearly recognized in the other months; see especially September to December. Figure 4 also confirms the other two findings of Figure 3, i.e. that the ITCZ region is anomalously moist in every month when the ITCZ is strongly organized and that the subtropical drying is generally more prominent in the subtropics the ITCZ is moving away from.

Another factor contributes to the clearer relationship obtained between organization and humidity in JJA. Interannual latitudinal shifts in the ITCZ position can blur the humidity signal in the subtropics and distort it if there is a systematic shift between more and less organized years. Looking at the interannual variability in the ITCZ position indeed reveals a more robust position of the ITCZ during JJA (see Table S2 in the SI). Comparing Table S2 and Figure 3 or especially Figure 4, there seems even to be an anticorrelation between

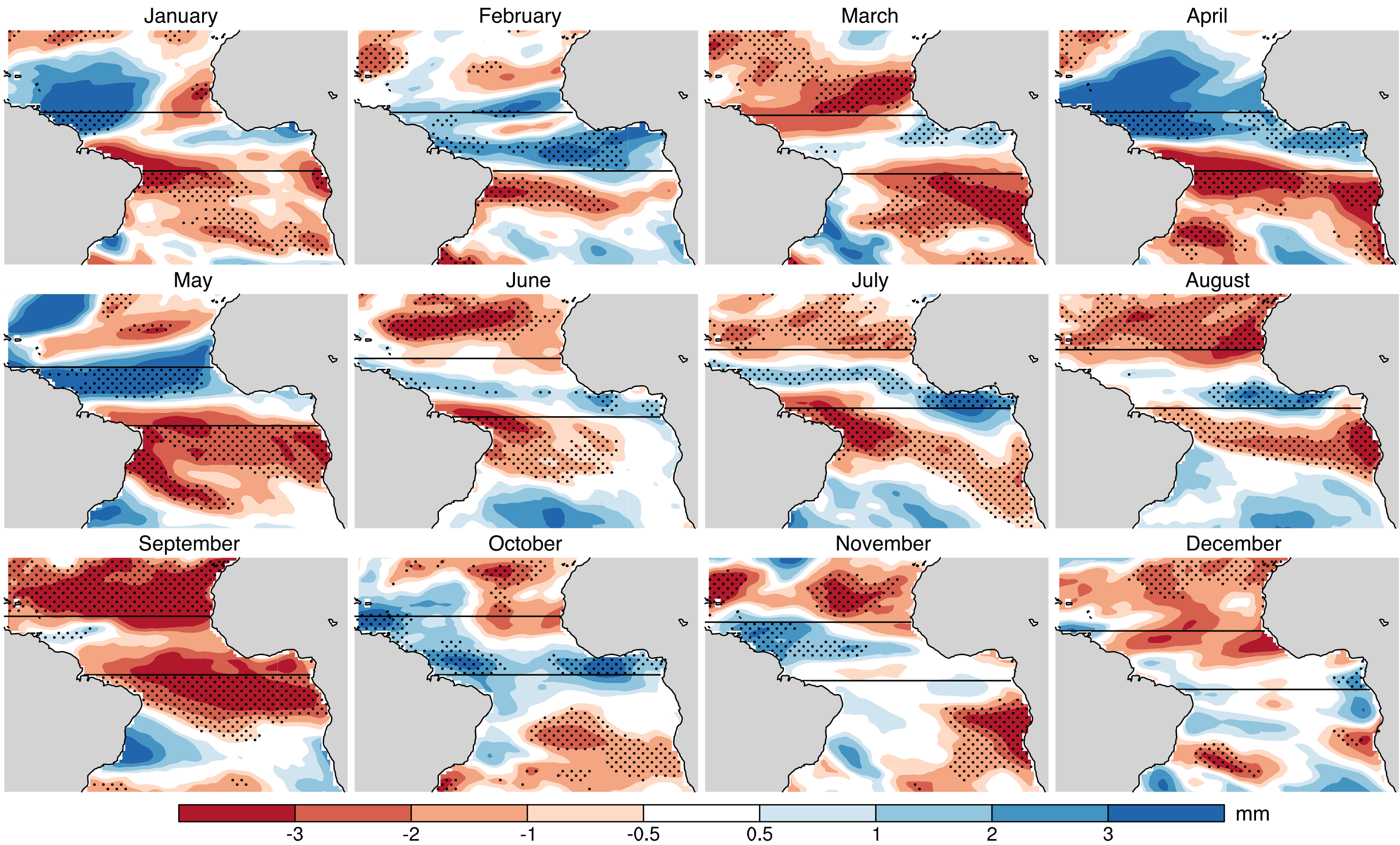

Figure 3. Monthly mean composite difference in water vapor path (shading) between the 5 years with the largest and the 5 years with the smallest $\mathcal{N}_{\mathrm{long}}$. The black horizontal lines enclose the ITCZ region, as averaged over the 10 considered years. Stippling indicates significance at the 90% level, computed by randomly drawing two sets of 5 years each, computing the difference between the two sets, repeating this 30 times, and stippling the points where, in the subtropics (ITCZ region), the composite difference shows a stronger drying (moistening) at the 90% level.

the magnitude of the interannual variability in the ITCZ position and the strength of the subtropical drying. The interannual variability in the ITCZ position also helps explain the peculiar behavior of April, characterized by a strong positive humidity anomaly in the northern subtropics in more organized years (see Figure 3). Those more organized years have an ITCZ displaced by 2.25° northward. Besides interannual variability in the ITCZ position, extratropical influences could also blur the subtropical humidity signal. Extratropical influences are expected to be weaker in JJA and in the summer hemisphere, consistent with our findings.

Our previous analysis does not say anything about causality and cannot exclude the presence of a fortuitous correlation. To investigate this, we focus on JJA when the relationship between organization and humidity is strongest. There is persistence in the correlation between the number of long lines and the water vapor path at various time lags (see Figure S6 in the SI). From this we cannot conclude whether more organized years are just anomalously dry in the subtropics and moist in the ITCZ region or whether the organization contributes to this anomaly. Backward trajectories could help decipher a causality relationship, and are left for further study. Note that in idealized self-aggregation studies, the interactions between humidity and organization are also two-way: the drying and expansion of the subsidence region forces the organization of convection and the latter prevents a moistening of the subsidence region (see, e.g., Figure 1 in Hohenegger & Stevens, 2016 and Tompkins & Semie, 2017).

To get further insight, in particular with respect to the subtropical drying, we composite other atmospheric variables as a function of the degree of organization (see Table S3 in the SI). The more organized years exhibit a statistically significant reduction in precipitation and increase in subsidence over the subtropics, a consequence of the noted drying. Notably, the vertically integrated moisture flux divergence exhibits the largest difference as compared to the other terms of the moisture budget. It is enhanced in the subtropics, whereas convergence is increased inside the ITCZ region (see Figure S7 in the SI). The pattern is reminiscent of the

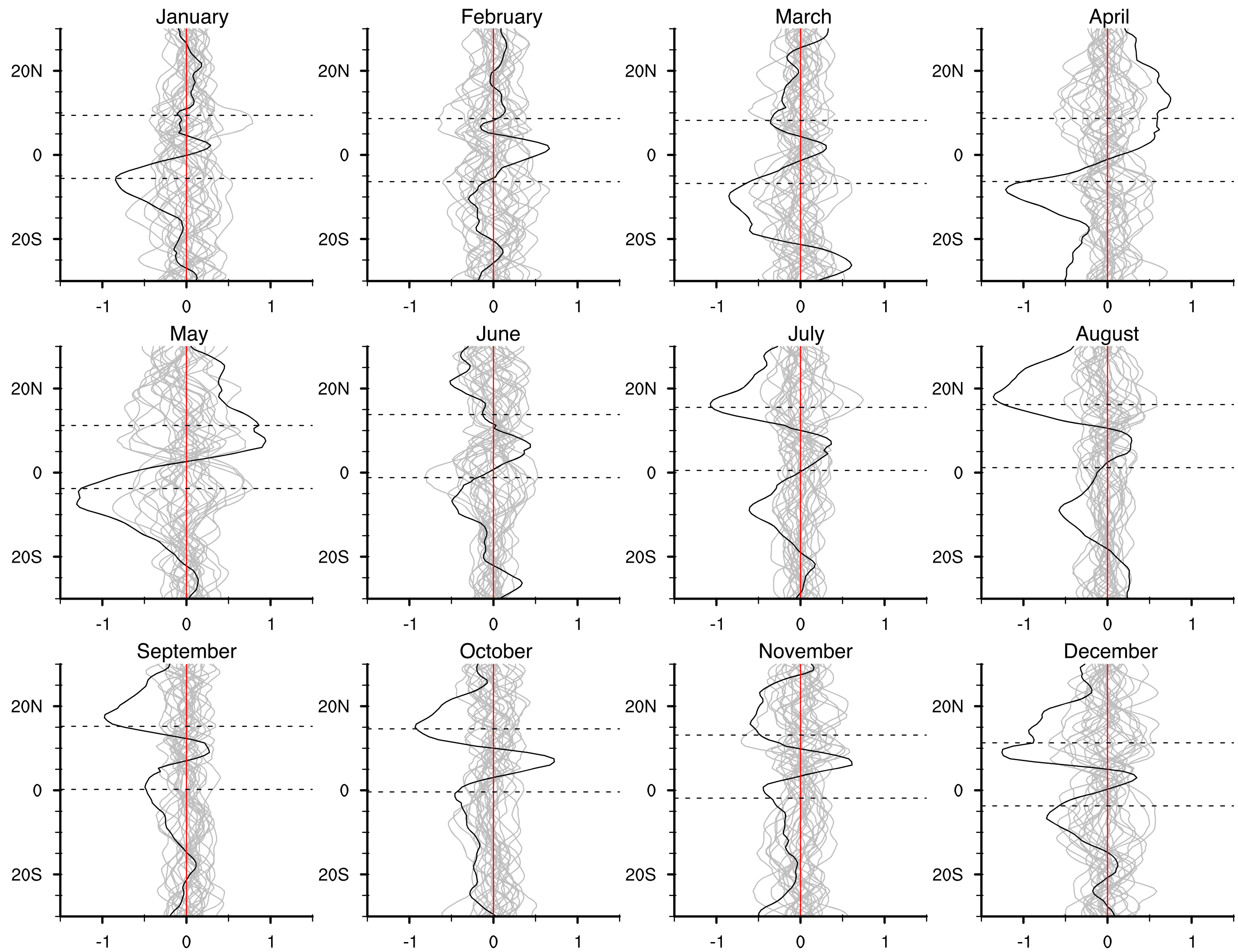

Figure 4. Zonal monthly mean difference in water vapor path (black, mm) between composites of days with and without long lines (see Figure 2b). Gray lines show 25 random computations of this difference. Each of this random realization is obtained by pooling all days of the 35 years together for a given month and building two composites of equal size by randomly picking days, independently of the number of long lines. The horizontal dashed black lines enclose the ITCZ region, as averaged over the 35 years.

difference pattern obtained for the water vapor path in Figure 3. This does not prove any direct relationship between organization and humidity but at least is consistent with the fact that, if the organization of the ITCZ affects subtropical humidity, it has to be by reducing the moisture transport into the subtropics. In fact, a closer look at Figure 3 suggests that, in the more organized years, the subtropics extend farther into the ITCZ region, consistent with an increase contraction and in line organization of the ITCZ, as seen in idealized self-aggregation studies. As a result, the moisture has to travel a longer distance to reach back a given subtropical latitude. The width of the core ITCZ, as measured by the 4-mm contour in the zonal mean precipitation, is reduced by 1.2° in more organized years. Assuming a typical large-scale horizontal velocity of 5 m s $^{-1}$, this 1.2° narrowing gives an extra travel time of 26,600 s in more subtropical-like conditions, during which free tropospheric moisture I_q^{FT} would have time to dry by 4.6 mm. This subsidence drying S is computed as in Equations 5 and 6 of Craig and Mack (2013) assuming an exponential water vapor distribution with a scale height H of 2 km and a free troposphere starting at 500 m, in which case $S = -w/H \cdot I_{\mathrm{q}}^{\mathrm{FT}}$, $I_{\mathrm{q}}^{\mathrm{FT}} = 0.78 \cdot I_{\mathrm{q}}$ with $w = -0.01$ m s $^{-1}$ and I_{q} water vapor path (45 mm in ERA-Interim over the ITCZ region). As the more organized years start from a higher moisture content in the center of the ITCZ region (see Figure 3), by about 1 mm, the extra traveling distance could cause an additional drying of 3.6 mm. This is a rough estimate as neither changes in precipitation nor in surface evaporation were considered. Also, other large-scale processes, such as waves, could cause both a contraction of the ITCZ and a drying of the subtropics. Nonetheless, this simple computation serves as a sanity check. It indicates that, in principle, the subtropical differences in water vapor path between organized and unorganized years could be caused by the longer distance that moisture has to travel when the ITCZ is more organized.

We also checked the potential influence of variations in the strength of the SST gradient, motivated by the results of Müller and Hohenegger (2020). They investigated the interactions between the self-aggregation of convection and an existing SST gradient in an idealized setup and found that stronger SST gradients favor longer convergence lines. Differences in SST gradient during JJA are not statistically significant, and, if anything, the more organized years exhibit a weaker SST gradient (see Figure S8 in the SI). In contrast to this small interannual variability, the intra-annual variability is about 4 times bigger and actually displays an annual cycle broadly consistent with the annual cycle in the organization of the ITCZ.

The relationship between organization and humidity was isolated on an interannual time scale. Given the smaller intra-annual variability in organization, which is even smaller than the interannual variability in the non-JJA months, we refrain from trying to identify any relationship. Moreover, at least the strength of the SST gradient could potentially explain the intra-annual variability in organization.

4. Conclusions

The goal of this study was to test the applicability of relationships derived from idealized studies on the self-aggregation of convection to the tropical Atlantic. To that aim, we used 35 years of reanalysis data and focused on the potential relationship between the degree of organization of the ITCZ and humidity. We quantified organization based on a data set of convergence lines by counting the number of long lines occurring per month. A long line is interpreted as the signature of a highly organized ITCZ and is defined as a line longer than 3,000 km. The number of long lines per month shows a weak annual cycle with, on average, around 26 long line detections per month during JJA and 19 long lines per month otherwise. The interannual variability in the number of long lines per month is much more pronounced, about 4 times its intra-annual variability.

We found a relationship between organization and moisture during JJA on an interannual time scale: Years with more organized ITCZs are associated with a moister ITCZ region and drier subtropics. During the remaining months, the relationship is less robust, but there is a tendency for the ITCZ region to be moister and for at least one subtropical hemisphere to be drier. The larger interannual variability in the number of long lines per month, the smaller interannual variability in the ITCZ position and weaker extratropical influences during JJA contribute to the clearer signal obtained during JJA.

We could not demonstrate any temporal causality between organization and humidity as there is persistence in the correlation. However, we noted that years with a more organized ITCZ are associated with an enhanced moisture flux divergence in the subtropics and a narrower ITCZ. The latter implies a longer traveling distance for moisture, which, we showed, could cause a drying in the order of the noted subtropical differences in water vapor path between more and less organized years. This does not rule out the presence of a third agent that could cause both a narrowing of the ITCZ and a drying of the subtropics but serves as a sanity check. The idea that organization could affect humidity is not per se incompatible with the obtained moisture anomalies. Given our results, there is a need to better understand the physical mechanisms that underpin the relationship between the ITCZ structure and subtropical humidity. Uncovering these mechanisms will require a combination of further observational studies with modeling studies that can bridge the highly idealized assumption of past self-aggregation studies with the real world.

Acknowledgments
C. H. acknowledges funding by the Max Planck Society for the advancement of science; C. J. acknowledges funding through the ARC Centre of Excellence for Climate Extremes (CE170100023). ERA-Interim data can be downloaded from the ECMWF website (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim), and the convergence line data set is documented in Weller et al. (2017). Comments by the reviewers that helped improve the manuscript are acknowledged.

References

Berrisford, P., Kallberg, P., Kobayashi, S., Dee, D., Uppala, S., Simmons, A. J., et al. (2011). Atmospheric conservation properties in ERA-Interim. *Quarterly Journal of the Royal Meteorological Society*, *137*, 1381–1399.

Berry, G., & Reeder, M. J. (2014). Objective identification of the Intertropical Convergence Zone: Climatology and trends from the ERA-Interim. *Journal of Climate*, *27*, 1894–1909. https://doi.org/10.11175/jcli-d-13-00339.1

Bony, S., Stevens, B., Frierson, D. M. W., Jakob, C., Kageyama, M., Pincus, R., et al. (2015). Clouds, circulation and climate sensitivity. *Nature Geoscience*, *8*, 261–268.

Bretherton, C. S., Blossey, P. N., & Khairoutdinov, M. (2005). An energy-balance analysis of deep convective self-aggregation above uniform SST. *Journal of the Atmospheric Sciences*, *62*, 4273–4292. https://doi.org/10.1175/JAS3614.1

Brueck, M., Hohenegger, C., & Stevens, B. (2020). Mesoscale marine tropical precipitation varies independently from the spatial arrangement of its convective cells. *Quarterly Journal of the Royal Meteorological Society*, *146*, 1391–1402. https://doi.org/10.1002/qj.3742

Brune, S., Kapp, F., & Friederichs, P. (2018). A wavelet based analysis of convective organization in ICON large-eddy simulations. *Quarterly Journal of the Royal Meteorological Society*, *144*, 2812–2829.

Cau, P., Methven, J., & Hoskins, B. (2007). Origins of dry air in the tropics and subtropics. *Journal of Climate*, *20*, 2745–2759.

Craig, G. C., & Mack, J. M. (2013). A coarsening model for self-organization of tropical convection. *Journal of Geophysical Research: Atmospheres*, *118*, 8761–8769. https://doi.org/10.1002/jgrd.50674

Held, I. M., Hemler, R. S., & Ramaswamy, V. (1993). Radiative-convective equilibrium with explicit two-dimensional moist convection. *Journal of the Atmospheric Sciences*, *50*, 3909–3927.

Hohenegger, C., & Stevens, B. (2016). Coupled radiative convective equilibrium simulations with explicit and parameterized convection. *Journal of Advances in Modeling Earth Systems*, *8*, 1468–1482. https://doi.org/10.1002/2016MS000666

Holloway, C. E., Wing, A. A., Bony, S., Muller, C., Masunaga, H., L'Ecuyer, T. S., et al. (2017). Observing convective aggregation. *Surveys in Geophysics*, *38*, 1199–1236.

Jakob, C., Singh, M., & Jungandreas, L. (2019). Radiative convective equilibrium and organized convection: An observational perspective. *Journal of Geophysical Research: Atmospheres*, *124*, 5418–5430. https://doi.org/10.1029/2018JD030092

Kadoya, T., & Masunaga, H. (2018). New observational metrics of convective self-aggregation: Methodology and a case study. *Journal of the Meteorological Society of Japan*, *96*, 535–548.

Müller, S. K., & Hohenegger, C. (2020). Self-aggregation of convection in spatially varying sea surface temperatures. *Journal of Advances in Modeling Earth Systems*, *12*, e2019MS001698. https://doi.org/10.1029/2019MS001698

Pierrehumbert, R. T. (1998). Lateral mixing as a source of subtropical water vapor. *Geophysical Research Letters*, *25*, 151–154.

Pscheidt, I., Senf, F., Heinze, R., Deneke, H., Trömel, S., & Hohenegger, C. (2019). How organized is deep convection over Germany? *Quarterly Journal of the Royal Meteorological Society*, *145*, 2366–2384.

Retsch, M. H., Jakob, C., & Singh, M. (2020). Assessing convective organisation in tropical radar observations. *Journal of Geophysical Research: Atmospheres*, *125*, e2019JD031801. https://doi.org/10.1029/2019JD031801

Sherwood, S. C. (1996). Maintenance of the free-tropospheric tropical water vapor distribution. Part I: Clear regime budget. *Journal of Climate*, *9*, 2903–2918.

Stein, T. H. M., Holloway, C. E., Tobin, I., & Bony, S. (2017). Observed relationships between cloud vertical structure and convective aggregation over tropical ocean. *Journal of Climate*, *30*, 2187–2207. https://doi.org/10.1029/2018JD0300092

Tobin, I., Bony, S., & Roca, R. (2012). Observational evidence for relationships between the degree of aggregation of deep convection, water vapor, surface fluxes and radiation. *Journal of Climate*, *25*, 6885–6904.

Tompkins, A. M., & Craig, G. C. (1998). Radiative-convective equilibrium in a three-dimensional cloud-ensemble model. *Quarterly Journal of the Royal Meteorological Society*, *124*, 2073–2097.

Tompkins, A. M., & Semie, A. G. (2017). Organization of tropical convection in low vertical wind shears: Role of updraft entrainment. *Journal of Advances in Modeling Earth Systems*, *9*, 1046–1068. https://doi.org/10.1002/2016MS000802

Weller, E., Shelton, K., Reeder, M. J., & Jakob, C. (2017). Precipitation associated with convergence lines. *Journal of Climates*, *30*, 3169–3183.

White, B. A., Buchanan, A., Birch, C. E., Stier, P., & Pearson, K. J. (2018). Quantifying the effects of horizontal grid length and parameterized convection on the degree of convective organization using a metric of potential for convective interaction. *Journal of the Atmospheric Sciences*, *75*, 425–450.

Wing, A., & Cronin, T. W. (2016). Self-aggregation of convection in long channel geometry. *Quarterly Journal of the Royal Meteorological Society*, *142*, 1–15.

Xu, K.-M., Hu, Y., & Wong, T. (2019). Convective aggregation and indices examined from CERES cloud object data. *Journal of Geophysical Research: Atmospheres*, *124*, 13,604–13,624. https://doi.org/10.1029/2019JD030816