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Key Points:
- Longitudinally resolved trends for the Hadley cell edge (HCE) and the subtropical jet (STJ) core are provided
- The observed zonal-mean poleward shift consists of pronounced regional differences in both magnitude and sign of the trends
- The increased year-to-year variability of the HCE in the Mediterranean can explain most of the increased variability in precipitation here

Supporting Information:
- Supporting Information S1

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Regional Changes in the Mean Position and Variability of the Tropical Edge

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Abstract Recent studies indicate that the tropical belt has been expanding during recent decades, which can significantly influence precipitation in subtropical climates. Often the location of the tropical border is identified using the Hadley cell edge (HCE) or the subtropical jet stream (STJ), but most studies concentrated on the zonal-mean state, thereby missing regional impacts. Here we detect longitudinal-resolved trends in STJ cores and HCEs over 1979–2016 in both hemispheres at a higher spatial and temporal resolution than previous studies. Besides pronounced regional trend differences in both sign and magnitude, we show that winter HCE and STJ variability increased in the Mediterranean region and decreased over the American and Asian continents. Rainfall variability in these regions changed likewise, and most of those changes can be explained by changes in HCE/STJ variability. This highlights the importance of understanding future tropical belt changes both regionally and in terms of variability.

Plain Language Summary We applied a new network-based method to detect motion of the tropical climate border with longitudinal resolution. Depending on the longitudinal position, there are differences in both direction and magnitude of the border motion. In addition, we demonstrate that the rainfall variability is increasing in the Mediterranean region and decreasing over the American and Asian continents, which can be explained by the variability of the tropical belt location.

1. Introduction

Tropical broadening is a robust feature in climate simulations with strong future greenhouse gas forcing scenarios, leading to reduced rainfall in subtropical regions like the Mediterranean (IPCC, 2013).

Observations indicate that the hydroclimate in many regions and especially in the tropics has been changing over the last decades (Dayan et al., 2015; Seager & Vecchi, 2010). Especially over land, these changes are crucial, since land-based precipitation serves as freshwater resource (Lucas et al., 2015). Land-based drying underlies completely different mechanisms than precipitation reduction over ocean. While the precipitation decline over the oceans results mainly from higher CO_2 emissions, the land-based drying is significantly influenced by planetary warming and the Hadley circulation as for example shown in studies about the South American rainfall anomalies, the Sahel summer rainfall, or the north China summer rainfall (Scheff & Frierson, 2012; Zhao & Moore, 2008). Therefore, it is important to analyze characteristics of and changes in the Hadley cell edge (HCE) in order to explain precipitation variability.

Most studies so far concentrated on the zonal-mean state of the HCE (Allen et al., 2012; Lu et al., 2007; Lucas et al., 2014; Seidel et al., 2008), which represents in the first place its behavior over the oceans, and this metric is thus not of direct relevance for society (Grise et al., 2018).

Choi et al. (2014) were among the first to develop a method which identified the HCE in the Southern Hemisphere (SH) not only for the zonal-mean state but at each longitude using monthly surface pressures. They detected a significant poleward trend of the HCE during the austral summer, primarily from the South Atlantic Ocean eastward to Australia. Choi et al. focused on the SH, because in the Northern Hemisphere (NH) continents play a larger role in modifying the atmospheric circulation, making HCE detection more challenging.

A first attempt to detect the longitudinally resolved HCE trends in the NH was done by Chen et al. (2014), who separated the zonal belt into six regions: South America, Africa, Indian Ocean, western and eastern Pacific, and Atlantic. According to their study the trends of the HCEs in five regions (Africa, Indian Ocean, western and eastern Pacific, and Atlantic) were not significantly different from 0 in the SH. Only the HCE in South America has a significant poleward trend. This is different for the NH, where all six regions except western Pacific show a strong poleward trend. Chen et al. (2014) used only annual data, making it difficult to study possible direct influences of the regional HCE on climate extremes on smaller time ranges.

Models also simulate a tropical belt widening under greenhouse gas forcing but not as pronounced as observed (Allen et al., 2014; Frierson et al., 2007).

Also, the subtropical jet stream (STJ) has a crucial impact on weather throughout the NH midlatitudes. Changes of the jet stream can influence midlatitude storms, the exchange between troposphere and stratosphere, and circulation regimes (Strong & Davis, 2007). In addition, the regional position of the jet stream can impact weather extremes locally (e.g., extreme rainfall after the storm Harvey 2017, Rosen, 2017; the 2010 Russian heatwave and the flood in Pakistan, Dole et al., 2011; Houze et al., 2011; Lau & Kim, 2012; Otto et al., 2012). The detection of the STJ is difficult, because jet streams can alter very quickly, both spatially and temporally. Jet properties can change over time as jets sometimes merge and break, making jet detection based on objective criteria complicated (Pena-Ortiz et al., 2013).

Nevertheless, Molnos et al. (2017) developed a network-based method to longitudinally track the subtropical jet and polar front jet separately. Using European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA)-Interim data (Dee et al., 2011), they detected a poleward trend in winter for the subtropical jet. Other studies did not explicitly distinguish between the subtropical and polar jet stream, but the STJ is stronger and more persistent and thus, they likely detected the path of the subtropical jet. Studies as Archer and Caldeira (2008) as well as Rikus (2015) and Pena-Ortiz et al. (2013) found also a poleward trend for the winter jet.

Pena-Ortiz et al. (2013) also studied the longitudinal resolved trends of the STJ. For the time period 1979–2008 the subtropical jet moved significantly poleward, whereas in the period 1958–2008 over the North Atlantic a negative trend was found.

While the aforementioned studies affirm the poleward trend in the zonal-mean HCE and STJ dynamic positions, the regional changes and (sub)seasonal variations of the HCE in the NH remain unclear.

Here we use the network-based method developed by Molnos et al. (2017) to study changes in the tropics regionally, in particular the STJ and the HCE. We calculate the trends for all seasons and present HCE changes in the NH at a higher level of detail.

In addition, we show that the interannual variability in the HCE has changed in several regions leading to changes in year-to-year rainfall variability. We compare our results with the literature and discuss potential implications for extreme weather events.

2. Data and Methods

In this study, ERA-Interim data (Dee et al., 2011) as well as National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis data (Kalnay et al., 1996) are used to analyze longitudinally resolved trends in the STJ and the HCE.

We calculate 15-day running mean using four 6-hourly time steps per day for the years 1979–2016 and vertically averaged (mass-weighted) wind velocity on a 0.75° latitude-longitude grid resolution for ERA-Interim data and 2.5° latitude-longitude grid for NCEP/NCAR data. For the mass weighting, we choose 11 vertical layers for ERA-Interim data and 6 vertical layers for NCEP/NCAR data of the upper troposphere stretching from 500 to 150 mbar. Moreover, we use the mean sea level pressure (MSLP), which is the average atmospheric pressure at sea level, from ERA-Interim data and NCEP data to detect the HCE.

For comparison of our method with the results from Choi et al. (2014), we also use the MSLP from the Hadley Centre Sea Level Pressure data set (Allan & Ansell, 2006) for calculating the HCE from observational data.

Motivated by the analysis of Choi et al., we applied a 30° longitudinal moving average for both data sets to eliminate the effects of local circulations and topography.

In addition, we include a gridded data set of precipitation anomalies provided by the Earth System Research Laboratory (Schneider et al., 2011; Wang & Fan, 2008) for the Mediterranean region between 20° and 40°

latitude and −10° and 40° longitude and for the American region between 20° and 40° latitude and 230° and 300° longitude for the winter season (December–January–February [DJF]) 1979 to 2016. The rainfall data set is used to determine the regional impacts on changes in the tropical edge.

The detection of the STJ and the HCE is based on Dijkstra's shortest path algorithm (Dijkstra, 1959). It is presented in detail in Molnos et al. (2017) and therefore explained only briefly for the HCE in the supporting information (SI) (section S1.1).

An example of the STJ core and the HCE is shown in the SI (Figure S1).

3. Results

The validation of the method based on Dijkstra's algorithm as well as the tuning parameters are presented in the SI (section S1).

3.1. Trends of the STJ and HCE

We calculated the latitudinal trends of STJ and HCE along longitudinally resolved positions for all seasons in the NH and SH using ERA-Interim data (Figure 1) and using NCEP/NCAR data (SI, Figure S3). The zonal-mean trends using ERA-Interim data are displayed in Table 1, and trends using NCEP/NCAR data are displayed in the SI (Table S3) showing significant trends in asterisks according to the student t test ($p = 0.1$). We used Monte Carlo analysis with 10,000 surrogate time series of shuffled data to determine significance (Kretschmer et al., 2018). Positive trends represent poleward movement, whereas negative trends indicate equatorward shifts of the HCE/STJ. In general, we observe a poleward movement of the STJ and HCE for both data sets, with the exception in spring for the SH STJ. However, the trends differ greatly between seasons and longitude. Also, for some seasons in some regions there are differences between the two data sets. Those differences are most probably caused by the lower resolution of the NCEP/NCAR data. Since the Dijkstra algorithm acts on a grid field, a finer resolution also results in more accurate path ways.

The NH STJ and NH HCE have a positive mean trend in winter season (DJF), which is only significant for the HCE for both data sets (Table 1 and SI Table S3). In the longitudinal trend analysis it can be seen that the positive trend is mostly due to the Pacific and Asia regions (Figure 1g and SI Figure S3g). The trend is negative but nonsignificant for the American region for the STJ in both data sets. In September-October-November (SON) we also observe in both data sets a significant positive zonal-mean trend in the NH HCE which is not observable for the NH STJ. In this season the widening is more or less homogeneous, with the American sector contributing most to the positive trend (Figure 1e and SI Figure S3e). In spring a significant northward trend over America in both NH STJ and NH HCE is visible in the ERA-Interim data. In the NCEP/NCAR data set there is a nonsignificant poleward trend over America for both NH STJ and NH HCE (SI Figure S3a). In addition, the NH STJ in Asia exhibits a significant poleward trend in both data sets (Figure 1a and SI Figure S3a).

In the SH, we observe in ERA-Interim data a significant zonal-mean equatorward trend in spring (March-April-May) for the SH STJ, which is probably due to the strong equatorward trend over South America (Figure 1b). We observe the opposite trend for the NCEP/NCAR data set indicating the challenge to detect the STJ core in the seasons of spring and autumn due to weaker winds and MSLP.

In addition, there is a significant zonal-mean poleward movement in boreal autumn and winter for both SH STJ and SH HCE for both data sets. In these seasons there is an almost homogenous poleward movement except for the Indian Ocean.

For the NCEP/NCAR data, a significant zonal-mean poleward trend in boreal summer for the Hadley cell in the SH is found due to the strong poleward trends over South America.

3.2. Variability of the STJ/HCE and Regional Precipitation Using ERA-Interim Data Set

Additionally, we analyzed the change in NH STJ and NH HCE probability density from 1979 to 1999 and 2000 to 2016 for SON and DJF using ERA-Interim data (Figure 2). We subtracted the probability density of the STJ (HCE) for the time range 1979–1998 from the density of the STJ (HCE) for 2000–2016: Red shaded areas indicate that the probability to locate the STJ or HCE in this domain is higher for the time range from 2000 to 2016 than in the time range from 1979 to1999. By contrast, blue shaded areas mean that it is more likely that the STJ and HCE were detected in this area from 1979 to1999 than from 2000 to 2016.

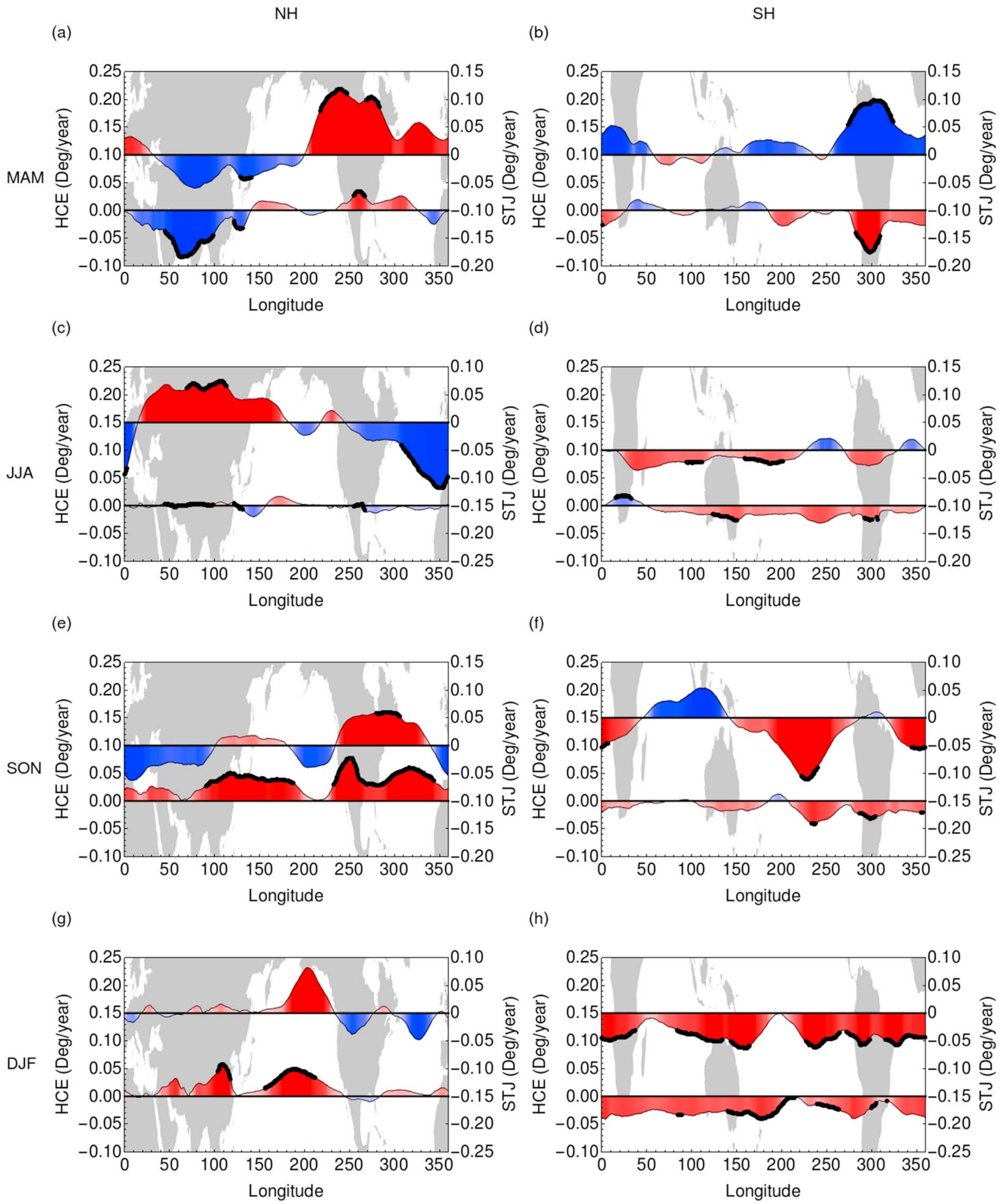

Figure 1. Longitudinal resolved trends of HCE and STJ, for all seasons and the (a, c, e, g) Northern and (b, d, f, h) Southern Hemispheres. Black dots represent significance at the *p* value of 0.1. HCE = Hadley cell edge; STJ = subtropical jet stream; NH = Northern Hemisphere; SH = Southern Hemisphere; MAM = March-April-May; JJA = June-July-August; SON = September-October-November; DJF = December-January-February.

In all plots we see again a poleward trend for most longitudes, which, however, differs with longitude. The variability of the STJ density is generally larger than in the HCE, showing the spiral behavior as observed by Koch et al. (2006; Figures 2a and 2c).

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Table 1
Jet Stream and Hadley Cell Zonal-Mean Trends for the Northern and Southern Hemispheres

Season	STJ NH (deg/year)	HCE NH (deg/year)	STJ SH (deg/year)	HCE SH (deg/year)	HCE SH HADSLP (deg/year)
Winter (DJF)	0.0037	0.015*	−0.039*	−0.027*	−0.005*
Spring (MAM)	0.000	−0.011	0.026*	−0.010	0.025
Summer (JJA)	0.0032	−0.001	−0.012	−0.013*	−0.004
Autumn (SON)	−0.017	0.032*	−0.018	−0.014	−0.001

Note. Stars indicate statistically significant values according to the *t* test. Positive (negative) values indicate northward (southward) shift. STJ = subtropical jet stream; HCE = Hadley cell edge; NH = Northern Hemisphere; SH = Southern Hemisphere; HADSLP = Hadley Centre Sea Level Pressure; DJF = December-January-February; MAM = March-April-May; JJA = June-July-August; SON = September-October-November.

Changes in the variability of the STJ and HCE may also influence the regional precipitation which we exemplary investigated using three regions in winter: the Mediterranean, North American subtropics, and the Asian subtropics (Figure 3). We analyze the Mediterranean region since it is a hot spot of climate change (Giorgi, 2006). Also, California had experienced several droughts and therefore motivated us to include also the American region (AghaKouchak et al., 2014). In addition, we also chose the western Asian region since climate impacts threaten societal stability and peace. It is especially observable in low-development countries, where almost no industry exists (von Uexkull et al., 2016). The year-to-year variability in the precipitation anomalies

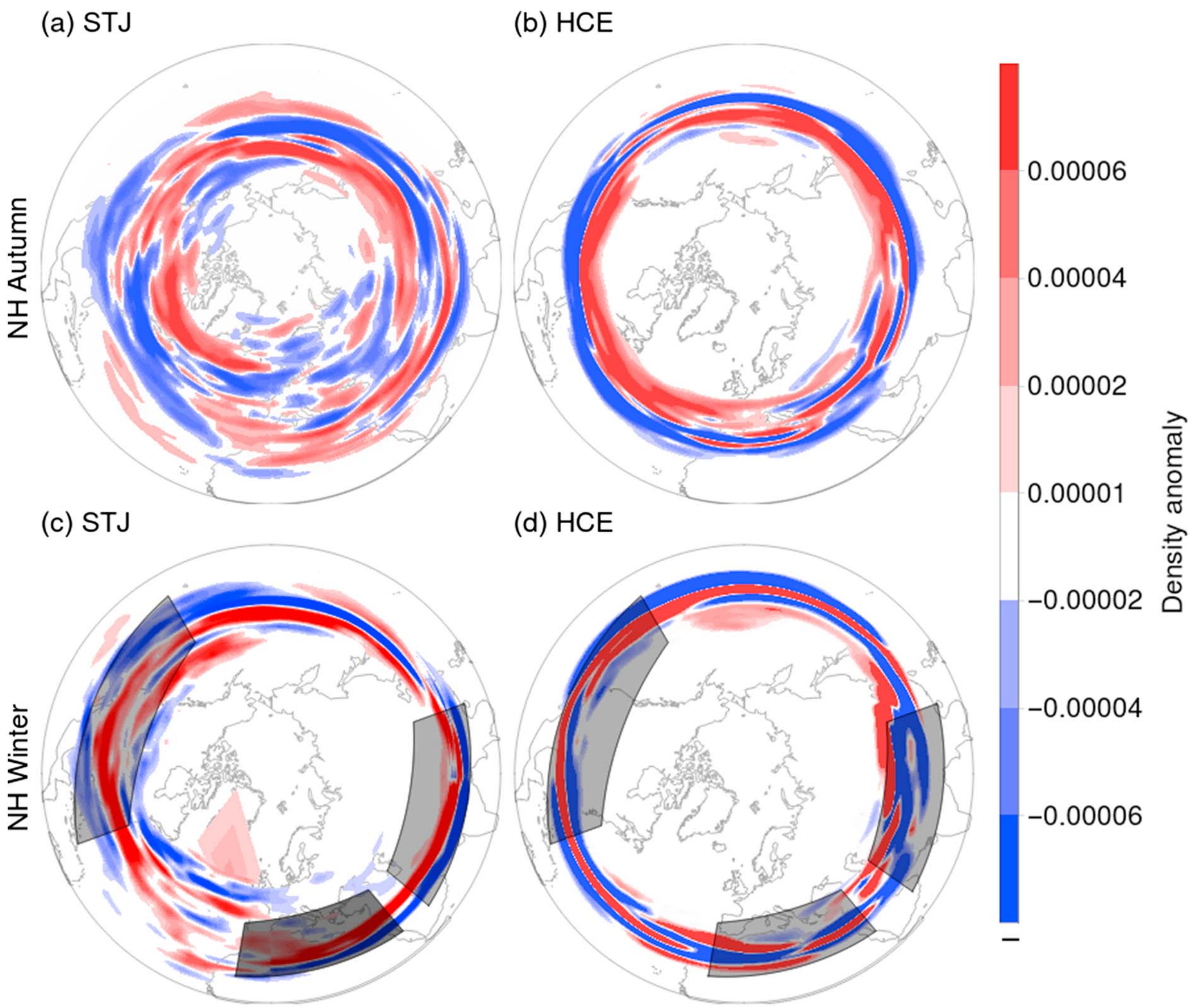

Figure 2. Hadley cell and subtropical jet stream density differences for the period 1979–1999 versus 1999–2016. (a) STJ in autumn, (b) HCE in autumn, (c) STJ in winter, and (d) HCE in winter. The gray shaded regions are the chosen areas for calculating the correlation between HCE/STJ core and precipitation (prcp) in autumn. HCE = Hadley cell edge; STJ = subtropical jet stream.

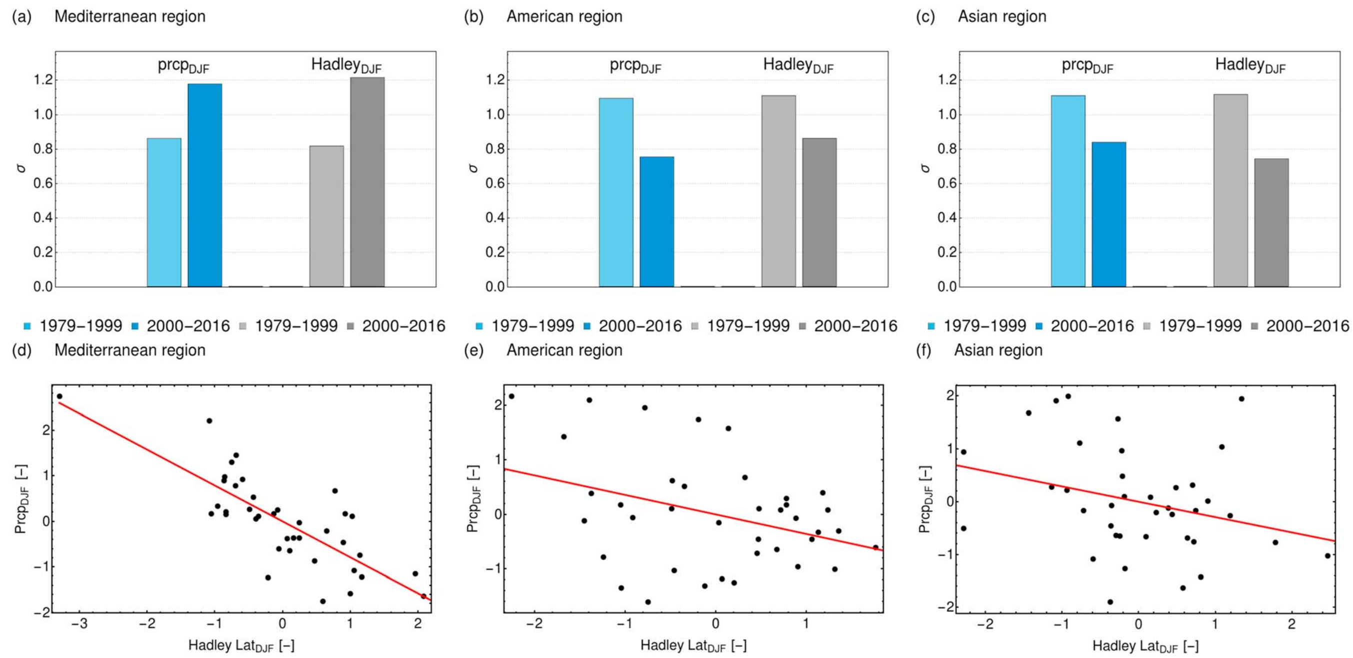

Figure 3. Standard deviation of winter precipitation for 1979–1999 (lighter cyan) and for 2000–2016 (dark cyan) for the Mediterranean region (a), American region (b), and Asian region (c). Likewise, the standard deviation for the HCE is shown for 1979–1999 (gray) and 2000–2016 (dark gray). The change of the standard deviations is significant for all variables (p value = 0.1). The regression models for the standardized HCE and precipitation data are shown in (d) for the Mediterranean region, in (e) for the American region, and (f) for the Asian region. HCE = Hadley cell edge; DJF = December-January-February.

in the time range 1979–1999 is significantly smaller than the variability in the time range 2000–2016 in the Mediterranean region. The opposite behavior is observed for the American sector (Figures 3a and 3b). Year-to-year variability in the HCE shows similar changes (with a significant increase in the Mediterranean), and we can show that most of the rainfall changes can be explained by HCE changes. The significances of variability change were calculated by the bootstrap method: 10,000 times randomly 38 data points were selected and the change of the two standard deviations from the new time series calculated. From the 10,000 variability changes we computed the Gaussian distribution and could show that the change of the standard deviations is significant for all variables (p value = 0.1).

We compared the HCE and STJ variability with precipitation variability changes using a linear regression model (Figures 3d–3f and S2d–S2f in the SI). All linear regression models are significant by a p value of 0.1. Projecting the precipitation variabilities on the linear regression model, we can show that the HCE deviation can explain up to 83% of the precipitation deviation in the Mediterranean region, up to 46% in the American region, and up to 30% of the Asian region. The STJ can explain up to 58% of the precipitation standard deviation in the Mediterranean region, up to 86% in the American region, and up to 26% of the Asian region. In addition, there exists a significant correlation of -0.78 between the time series of the HCE and precipitation in the Mediterranean region. Extreme drought years 1989, 2007, and 2008 in the Mediterranean region are also associated with extreme HCE (p value = 0.05).

4. Discussion

In this paper we show that the detected latitudinal shifts of the STJ and the HCE in the SH and NH strongly depend on season and longitudinal position.

The longitudinal positions of the HCE in the NH move uniformly poleward in boreal autumn and boreal winter with significant positive trends in western Asia and Pacific in both data sets (Figure 1 and SI Figure S3). There is an additional poleward significant trend over the Atlantic in SON (Figure 1 and SI Figure S3). These results indicate that the annual significant movement in the five regions (Africa, Indian Ocean, eastern Pacific, Atlantic, and America) found by Chen et al. (2014) may be attributed mainly to the significant poleward expansion in SON and DJF. In addition, our results indicate that the trends over the six chosen regions used by Chen et al. have similar amplitude justifying the zonal averages taken over these areas. Only the African and Atlantic region reveal different trends, making a longitudinally resolved HCE necessary.

In the SH, we observe a significant southward trend in the Pacific and South America for winter in both data sets. Trends at other longitudinal in the SH are weak as in Chen et al. (2014).

The trends for the STJ are mostly similar to those for HCE, but there are differences, probably because both analyses depended on different input data and disturbances had different effects on the variables. Another reason is that the STJ also interacts with the polar jet stream depending on the region and season. Sometimes there is only one jet stream, when the STJ's position is more poleward than usual. This the case when the STJ is very strong and the baroclinicity is very high (Lee and Kim, 2003).

In spring, we observe a significant poleward trend in America for the STJ in both hemispheres in spring for the ERA-Interim data and mixed trends for the NCEP/NCAR data set. This trend using ERA-Interim data is consistent with the study from Pena-Ortiz et al. (2013). In addition, we detect significant poleward trends in Eurasia (June-July-August) and North America (SON) for the STJ using ERA-Interim data, which were not identified by Pena-Ortiz et al. (2013). Whereas we observe in DJF a poleward nonsignificant strong movement in the Atlantic region, Pena-Ortiz et al. (2013) obtained a statistically significant poleward trends along Eurasia, Pacific, and the Atlantic Ocean. A reason for the different trend besides different time periods or different data sets is that Pena-Ortiz et al. (2013) calculated the trend of the frequency of jet core occurrence, whereas we calculate the trends of the STJ location.

4.1. Variability of the STJ/HCE and Regional Precipitation

The probability density anomaly maps (Figure 2) show the variability of the HCE and STJ in the NH as explained in section 3.2.

While the HCE and Jet stream density differences in SON reveal a clear poleward trend and confirm the longitudinal trend results, the probability density maps for DJF reveal changes in the variability. We observe in some areas a narrowing of the variability of the HCE and STJ and in some regions a widening of the variability. In the American and Asian sectors the HCE shows less year-to-year variability since 2000. The opposite behavior can be observed in the Mediterranean region (Figure 3). Our analyses show that the observed interannual variability of changes in STJ and HCE can explain most of the increased variability of precipitation in the Mediterranean region and decreased variability in the American sector (Figure 3). This result appears consistent with one modeling study showing an increase in annual rainfall variability in the Mediterranean area in Coupled Model Intercomparison Project Phase 5 (CMIP5) models (Polade et al., 2014). Moreover, our results confirm the crucial link between HCE dynamics and precipitation variabilities as suggested by He and Soden (2016), Scheff and Frierson (2012) and Zhao and Moore (2008).

4.2. Potential Implications for Extreme Weather Events

The longitudinally resolved trends and variability analysis of the HCE and STJ clearly indicates the expansion of the tropics in some regions. It is consistent with Kossin et al. (2014), who investigated the movement of hurricanes by tracking the latitude at which the maximum intensities of tropical cyclones occur. They found a significant poleward migration of the hurricanes with largest contribution to the NH trend from the western North Pacific Ocean. Similarly, we also observe a significant poleward trend of the HCE in SON over the Pacific Ocean. The poleward migration of tropical cyclones associated with tropical expansion may lead to higher risk of torrential rains triggering floods and/or landslides (Kossin et al., 2016). On the other hand, tropical broadening might increase the probability of heat waves and droughts and can contribute to drying trends as observed in California or the Mediterranean region (AghaKouchak et al., 2014; Diffenbaugh & Giorgi, 2012; Giorgi & Lionello, 2008). Therefore, it is important to further study the expansion of the tropics and the potential connection to changes of temperature and precipitation pattern as well as extreme events. We demonstrated that our detection of the STJ and HCE locations is a useful tool for that purpose.

5. Summary

This study presents regional changes in mean and variability of the tropical edge for different seasons in the SH and NH for the time period 1979–2016. The tropical edge is described by the HCE and STJ core using a novel technique based on Dijkstra's shortest path algorithm. We show that trends of the HCE and STJ depend not only on season but also on the longitudinal position.

In addition, we identify changes in HCE year-to-year variability in the second half of the data set and show that these changes likely influenced rainfall variability over land. This highlights the importance of not only understanding mean changes in dynamics due to climate change but also changes in the variability.

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