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To cite this article: Sharon E Nicholson *et al* 2022 *Environ. Res. Lett.* **17** 054052

IOP Publishing Environ. Res. Lett. 17 (2022) 054052 https://doi.org/10.1088/1748-9326/ac61c4

ENVIRONMENTAL RESEARCH
LETTERS

RECEIVED
26 August 2021

REVISED
6 January 2022

ACCEPTED FOR PUBLICATION
28 March 2022

PUBLISHED
16 May 2022

LETTER

Recent rainfall conditions in the Congo Basin

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Keywords: Congo Basin, drought, rainfall variability, Congo rainfall

Abstract

In the Congo Basin, a drying trend in the April–May–June rains prevailed between 1979 and 2014, accompanied by a decline in forest productivity. This article examines the subsequent years, in order to determine whether rainfall conditions have improved and to examine meteorological factors governing conditions in those years. It is shown that a wetter period, comparable to that of 1979–1993, spanned the years 2016–2020. However, the meteorological factors responsible for the wetter conditions appear to be significantly different from those related to the earlier wet period. The wetter conditions of 1979–1993 were associated with changes in the tropical Walker circulation, in moisture flux and flux divergence, and in Pacific sea-surface temperatures (SST), namely a warmer central and eastern Pacific and a cooler western Pacific, compared to the dry phase in 2000–2014. This resulted in a lower-than-average trans-Pacific SST gradient. In contrast, SSTs were almost ubiquitously higher in the 2016–2020 period than in either prior period. However, there was some reduction in the trans-Pacific gradient. The Walker circulation and moisture flux/flux divergence were not factors in this episode. The major factors provoking the return to wetter years appear to be an increase in convective available potential energy and in total column water vapor. This could be related to the general warming of the oceans and land.

1. Introduction

Tropical rainforests are a critical resource of our planet. They feed the carbon cycle and provide atmospheric oxygen and moisture. They are bastions of biological diversity, by some estimates containing over 8000 species. The future of the forests is uncertain in the face of extensive deforestation (Barbier *et al* 1991) and global climate change (Fearnside and Laurance 2004).

Equatorial Africa is home to the second largest tropical rainforest in the world. Deforestation is an ongoing problem (Laporte *et al* 2007, Turbanova *et al* 2018), but reports of a recent, long drying trend in the Congo Basin region of the forest (Malhi and Wright 2004, Yin and Gruber 2010, Samba and Nganga 2011, Dezfuli 2017, Bush *et al* 2020, Cook *et al* 2020, Nicholson 2021) have heightened concern about the forest. The drying was evident throughout the boreal spring (Nicholson *et al* 2018a) and was strongest during the months of April, May and June (AMJ, Diem *et al* 2014, Zhou *et al* 2014). Hua *et al* (2016) showed that the trend over the period 1979–2014 was statistically significant during that season and that the trend was strongest in the eastern sector of the Congo Basin. This coincided with a widespread decline in forest photosynthetic capacity over the Congo Basin and a decline in total water storage in the ground plus vegetation (Malhi and Wright 2004, Zhou *et al* 2014), changes which Zhou *et al* (2014) attributed to this drying trend.

The factors associated with the drying were evaluated by Hua *et al* (2016), (2018) and by Dyer *et al* (2017). Hua *et al* (2016) contrasted the wet period, 1979–1993, with the dry period, 2000–2014, and Hua *et al* (2018) performed AMIP-type model simulations forced by observed sea-surface temperatures (SSTs). Both studies concluded that the principal factors associated with the long-term drying trend were an enhanced and westward extended tropical Walker circulation, an anomalous anticyclonic circulation in the lower troposphere over southern Africa, weakened ascent over Central Africa, and reduced low-level moisture transport. These appear to have been triggered by changes in SSTs in the Indo-Pacific sector and over the tropical Atlantic. In particular, SSTs decreased in the equatorial Pacific but increased over the tropical Atlantic and Indian Oceans and in the western Pacific. Dyer *et al* (2017) likewise concluded that the drying was associated with changes in advective moisture sources, especially those over the Indian Ocean. Cook *et al* (2020) suggested the drying trend was associated with surface warming, but indicated that the warming was not strong over the Congo Basin. Several modeling studies examined wet versus dry conditions in the region, although not the drying trend itself. These also identified the important role of moisture flux and moisture flux convergence (Washington *et al* 2013, Creese and Washington 2016, Sori *et al* 2017, Tamoffo *et al* 2019).

Cook *et al* (2020) suggested that the drying trend noted above for the Congo Basin might not be continuing. In this article, we test that by examining rainfall trends in the years subsequent to the analysis of Hua *et al* (2016). The goal is to determine whether the drying trend has continued and whether the same factors appear to govern rainfall variations over the last five years. The data sets utilized and the approach taken are described in section 2. Section 3 presents the results: the links to large-scale atmospheric ocean characteristics, moisture divergence and moisture flux, convective available potential energy (CAPE) and convective inhibition (CIN), and atmospheric moisture content. A discussion is presented in section 4, along with conclusions in section 5.

2. Study region, data and methods

The study area, shown in figure 1, is that evaluated by Hua *et al* (2016). It roughly approximates the Congo River drainage basin (Nicholson 2021). Here, a comparison will be made between several wet and dry periods in this region. Mean rainfall for AMJ is shown in figure 1 for the period 1979–2014. This period will be considered to define the long-term mean (LTM), as it is the base period used by Hua *et al* (2016) in calculating anomalies.

Because of the paucity of rain data in this region in recent years, rainfall variability is examined using both a gauge data set and two satellite data sets. The Global Precipitation Climatology Centre (GPCC, Schneider *et al* 2014) has 1° × 1° resolution and covers the period 1950–2020. The Global Precipitation Climatology Project (GPCP, Adler *et al* 2003) has 2.5° × 2.5° resolution and covers the period 1979–2020. To add confidence in the estimates, the Tropical Rainfall Measuring Mission (TRMM) satellite product (version 3B43) is also used. It has a resolution of 0.25° × 0.25° and runs from 1998 to 2019. Several studies have demonstrated the excellent performance of both TRMM 3B43 and GPCP in this region (e.g. Munzimi *et al* 2015, Nicholson *et al* 2019).

Time series of AMJ rainfall are shown in figure 2 for all three data sets, with rainfall expressed as a standardized departure from the 1979–2014 mean. These confirm a wet period continuing to roughly 1993, then comparatively low rainfall until 2014, and once again higher rainfall in 2016–2020. The average standardized anomalies over these periods are +0.63 for 1979–1993, −0.48 for 2000–2014, and +0.55 for 2016–2020, based on GPCP. The approach will be to examine for each variable the LTM, the differences of the 2000–2014 dry period means from the means for the wet periods, and the differences between the two wet periods.

Ideally, one would compare periods of the same length. In this case, the length of period was dictated by the need for comparison with Hua *et al* (2016). To determine if the diverse period length affected the results, all analyses were repeated using the last five years of the first wet period and the last five years of the dry period. There was little difference in the results. The exception was that the contrast noted in CAPE, CIN and total column water vapor (see section 3.3) were more extreme.

Atmospheric variables are assessed using reanalysis data sets. For direct comparison with the prior results of Hua *et al* (2016), the European Centre for Medium-Range Weather Forecast ERA Interim reanalysis is used (Dee *et al* 2011), although it is being phased out. It runs from 1979 to 2019 and its spatial resolution is roughly 80 km. ERA Interim is used to derive vertical velocity (i.e. omega), geopotential height, moisture flux and moisture flux divergence. Values for 2020 were obtained from its successor, ERA 5, after a comparison of common years confirmed that both reanalysis products provided similar results. ERA5 is also used to examine total column water vapor, CAPE, and CIN, variables not examined in Hua *et al* (2016). It also commences in 1979 and provides hourly coverage at roughly 31 km global resolution on 137 vertical levels (Hersbach and Dee 2016). To examine global SST variations, the updated monthly SST dataset is obtained from the UK Met Office Hadley Centre's Global Sea Ice and SST data set (HadISST; Rayner *et al* 2003).

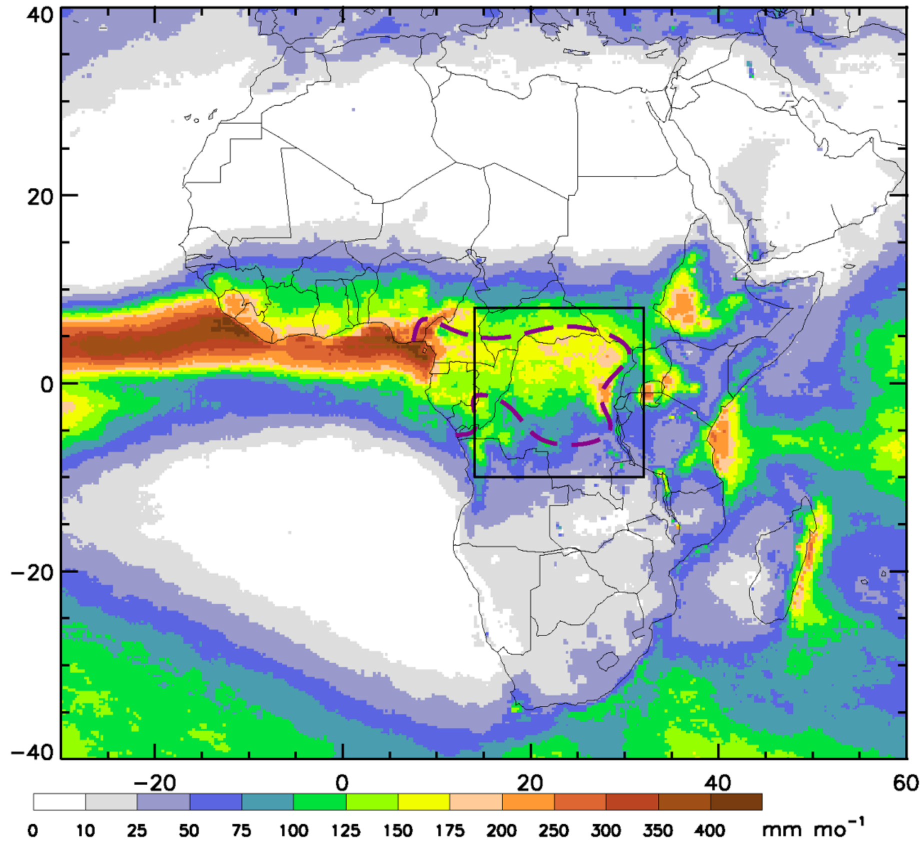

Figure 1. Map of mean AMJ rainfall (mm/mo). The black line indicates the analysis sector over which rainfall is averaged. The magenta line indicates the area of the Congo Basin.

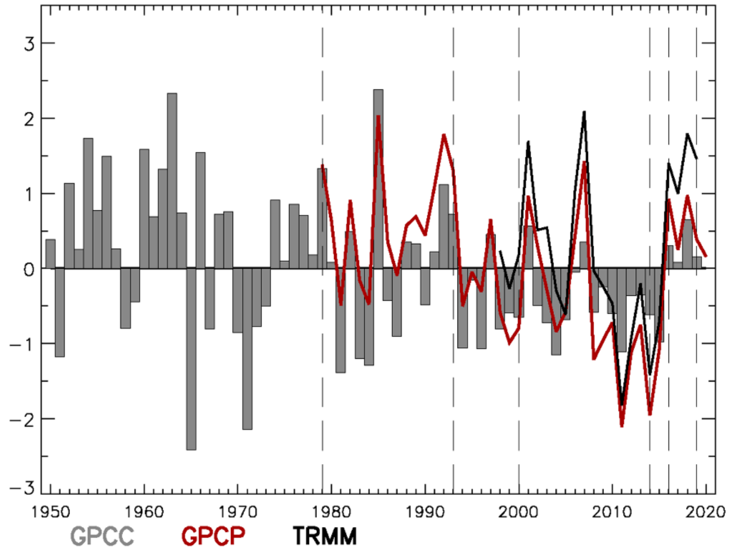

Figure 2. Time series of AMJ rainfall 1950–2019 based on GPCC (bars), GPCP (red dashed line) and TRMM 3B43 (black dashed line). Rainfall is expressed as a standardized departure, with the standard deviation calculated for the base period 1979–2014. Vertical lines delineate the wet and dry periods considered in Hua *et al* (2016) and the recent wet period.

3. Results

3.1. Links to large-scale processes: atmospheric circulation, vertical motion and SSTs

Figure 3 shows the difference in AMJ geopotential height at 850 hPa for 2000–2014 minus 1979–1993. Wind vector differences are also shown. The geopotential height difference is negative nearly ubiquitously over Africa, with two areas of anti-cyclonic circulation indicated over southern and western equatorial Africa. The impact on rainfall would be related to the divergence of the

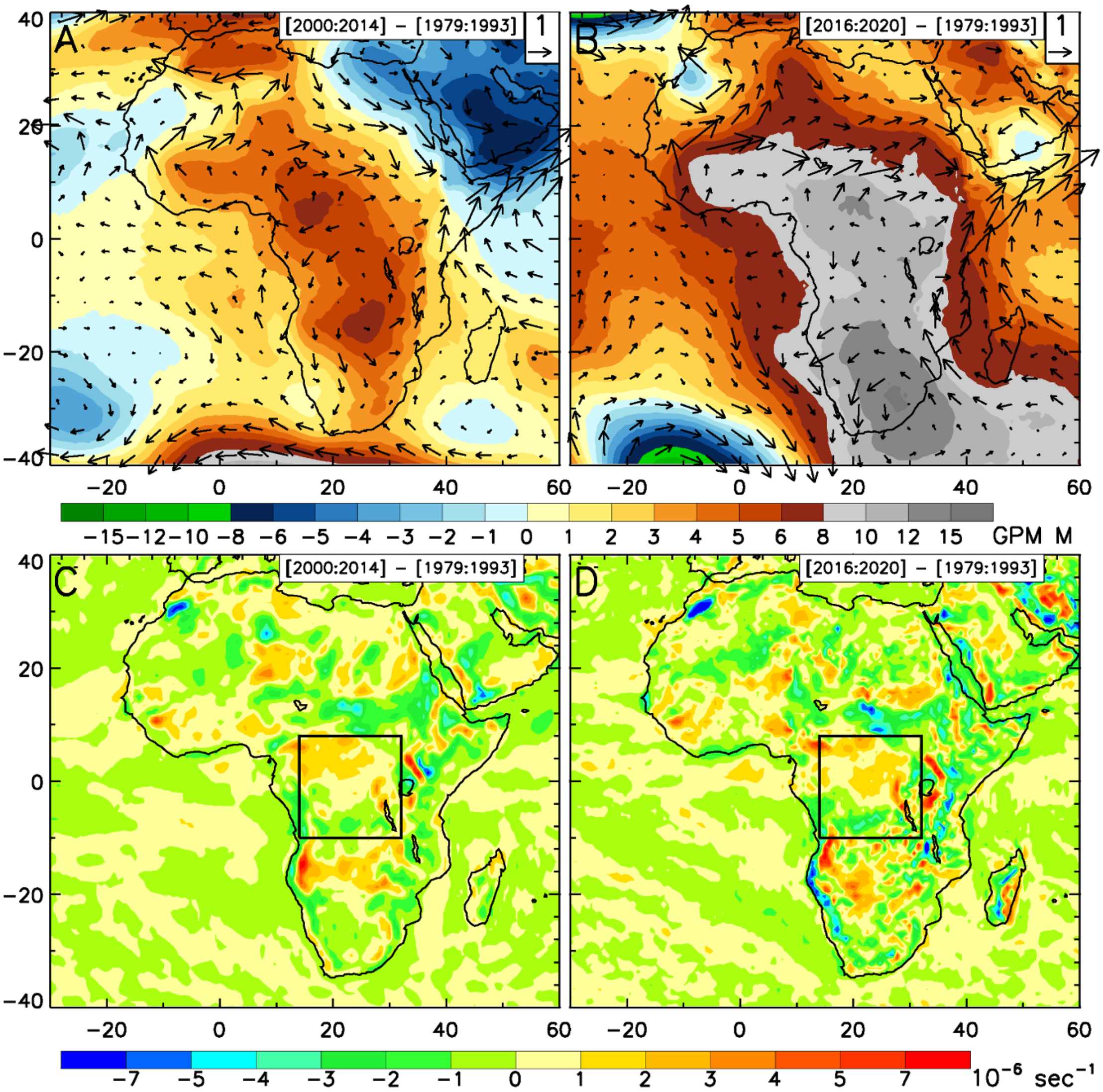

Figure 3. 850 hPa geopotential height and wind vectors in AMJ (A) differences between 2000–2014 and 1979–1993, (B) differences between 2000–2014 and 2016–2020. Divergence at 850 hPa (C) differences between 2000–2014 and 1979–1993, (D) differences between 2000–2014 and 2016–2020.

winds. Both anticyclonic areas are associated with increased divergence in the drier period (2000–2014). The divergence anomaly is even stronger at 925 hPa (not shown).

If this is a factor in the drier conditions, a decrease in divergence during the recent wetter period 2016–2020 would be anticipated. However, that is not the case. The geopotential height difference between that period and 1979–1993 is markedly greater than between 2000–2014 and 1979–1993 (figure 3). However, within the analysis sector there are areas of weak increase and decrease. This suggests that anomalies in the mean geopotential height and wind are not factors in the recent increase in rainfall.

Hua *et al* (2016) suggested that changes in the Walker circulation were a major factor in the long-term drying trend. Figure 4 shows omega differences between the dry period and the two wet periods. During the dry period 2000–2014 there was reduced ascent over most of the Congo compared to 1979–1993, and reduced subsidence over eastern Africa. There was also reduced ascent over the central Pacific from roughly 175° E to 90° W but increased ascent over the western Pacific. This is consistent with an enhanced Pacific Walker cell. Changes are minimal over the Indian Ocean. The contrast with the recent wet period 2016–2020 is similar over the Pacific, but the differences are less extreme, particularly in the central Pacific, where they are minimal. Only minor contrasts are evident over the Congo and eastern Africa but reduced ascent is evident over the eastern Indian Ocean.

Figure 5 shows SST differences between 2000–2014 and 1979–1993. The differences are strongly negative in the central and eastern Pacific, but positive and relatively weak almost everywhere else in the tropics. The negative Pacific anomaly runs from about 175° E to 80° W, consistent with the

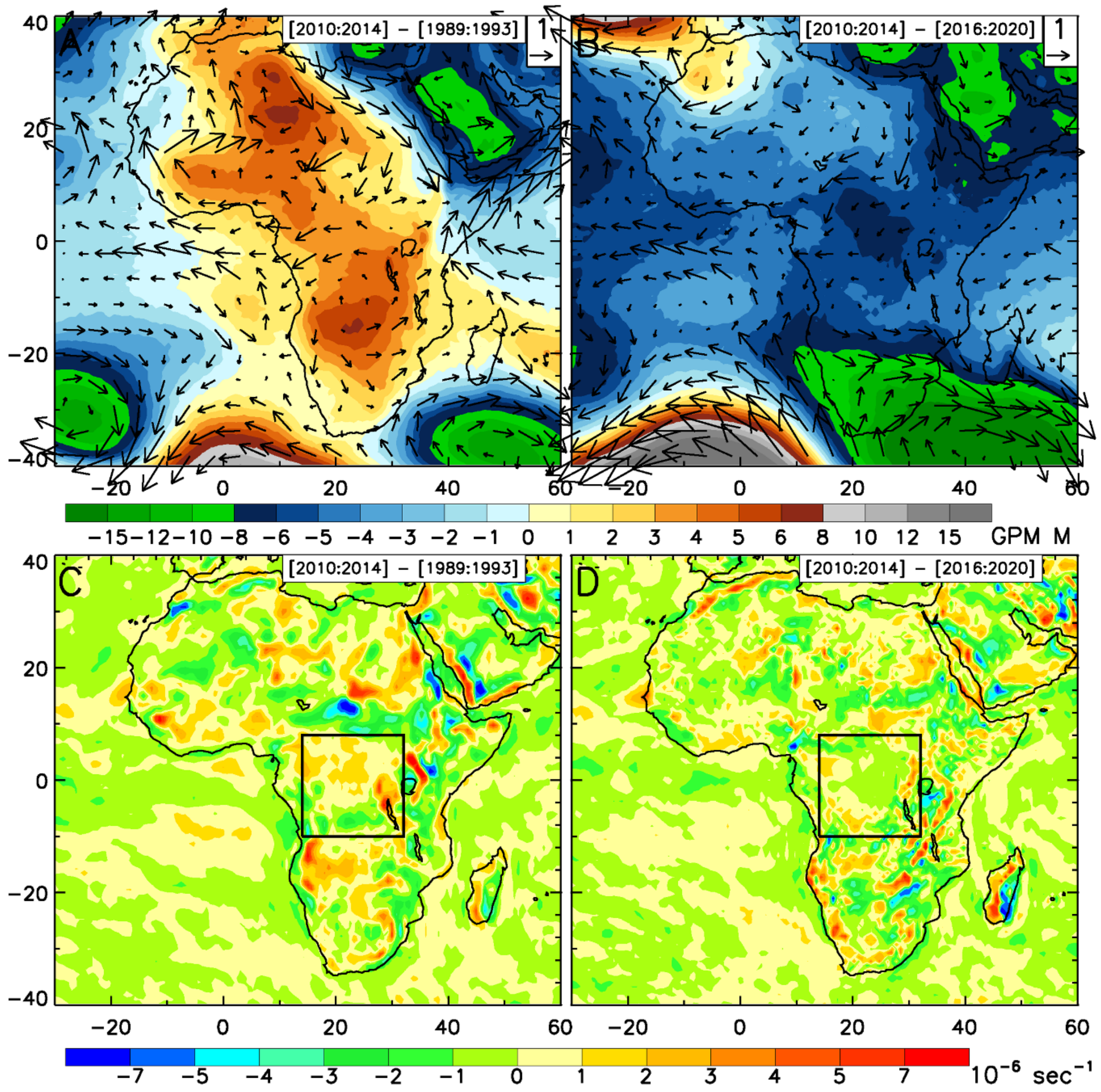

Figure 4. Vertical motion (i.e. omega) in AMJ: (top) differences between 2000–2014 and 1979–1993, (middle) differences between 2000–2014 and 2016–2020, (bottom) differences between 2016–2020 and 1979–1993. Data are averaged between 10° N and 10° S.

location of the positive omega differences. The weak SST differences elsewhere are also consistent with a lack of strong omega differences.

Examining the contrasts with the wet period 2016–2019 is problematic because of the general ocean warming that has taken place since the 1970s. Thus, the SST differences between 2000–2014 and 2016–2020 are negative nearly everywhere. However, they are much larger over the central and eastern Pacific than elsewhere. This is consistent with the contrasts noted between 2000–2014 and 1979–1993 and with the much weaker omega contrasts between 2000–2014 and 2016–2020.

3.2. Moisture flux

Figure 6 shows contrasts in vertically-integrated moisture flux and moisture flux divergence between wet and dry periods, as well as the means for 1979–2014. The mean pattern shows strong moisture convergence over most of the Congo, but divergence south of roughly 5° S. Flux is from the east and is strongest between 5° S and 10° S. During the period 2000–2014 moisture flux and flux convergence over the Congo are markedly weaker than during the 1979–1993 wet period. However, there is comparably little contrast between 2000–2014 and the recent wet period of 2016–2020. In some areas the convergence is actually greater during the drier period. Moreover, the moisture contrast between the two wet periods, 2016–2020 and 1973–1993, is similar to the contrast between the 2000–2014 dry period and 1979–1993. This suggests that atmospheric moisture flux and flux convergence are not factors in the recent wet period.

3.3. Moisture and stability

Figure 7 shows mean CAPE and CIN, and the differences among the three periods 2016–2020, 2000–2014 and 1979–1993. The first and last are 'wet' periods and 2000–2024 is the dry period. CAPE is a measure of the energy available for convection; positive CAPE

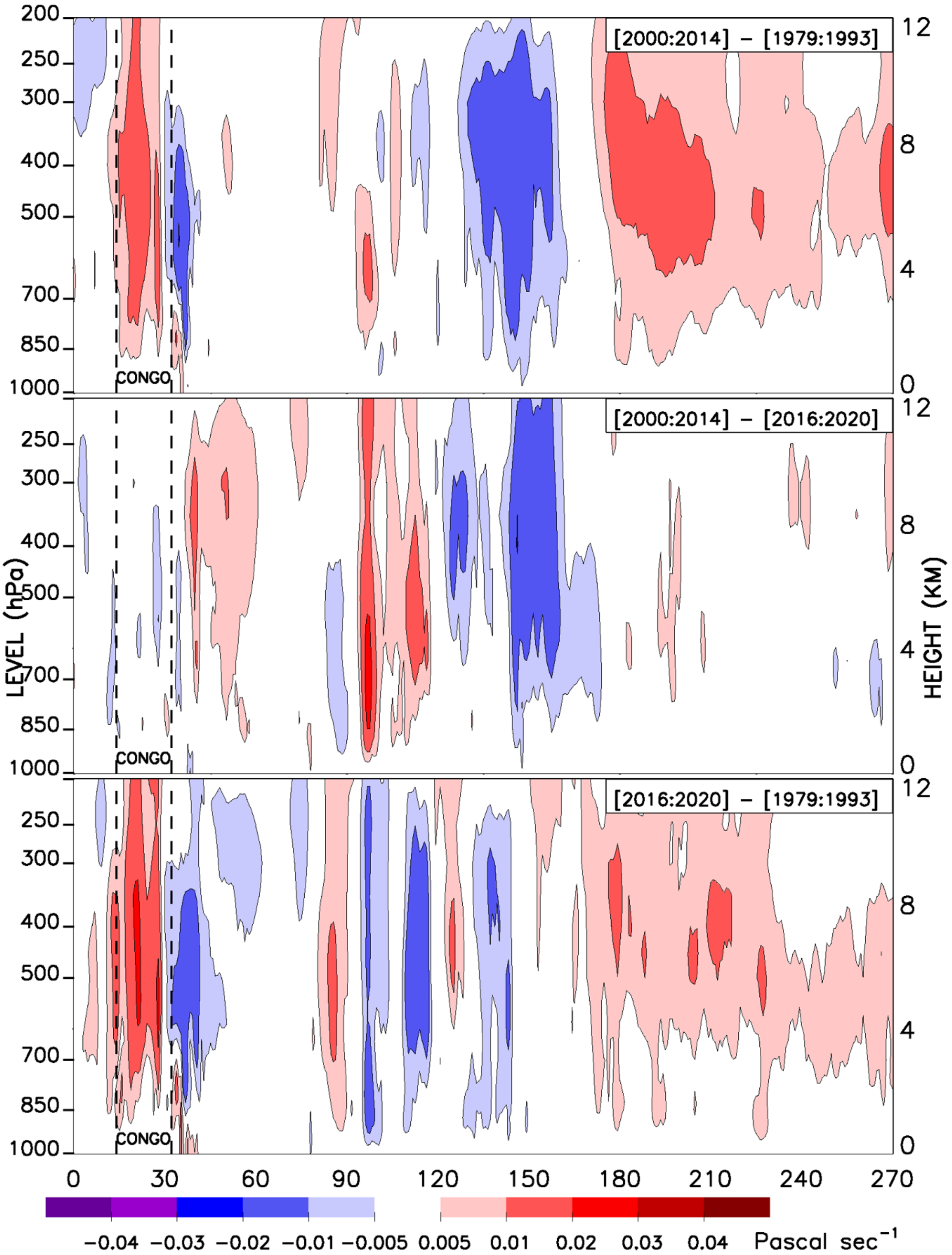

Figure 5. SST differences (°C) in AMJ: (A) 2000–2014 minus 1979–1993, (B) 2000–2014 minus 2016–2020 (C) 2016–2020 minus 1979–1993.

will cause an air parcel to rise, negative will cause it to sink. It is measured from the level of free convection to the height above at which the stability is neutral. CIN is the opposite: it is the ability of the atmosphere to inhibit convection. It covers the layer from the ground to the level of free convection. Both are calculated from virtual temperatures and hence are strongly affected by atmospheric moisture content.

In the mean, CAPE has a strong positive value throughout the analysis sector. It increases towards the center of the Congo Basin. An interesting feature is an area of high CAPE (1800–2200 Jkg^{-1}) that corresponds closely to the Congo River and the edaphic forest area along its banks. This also corresponds to the western rainfall maximum, suggesting that the river basin may play a role in the

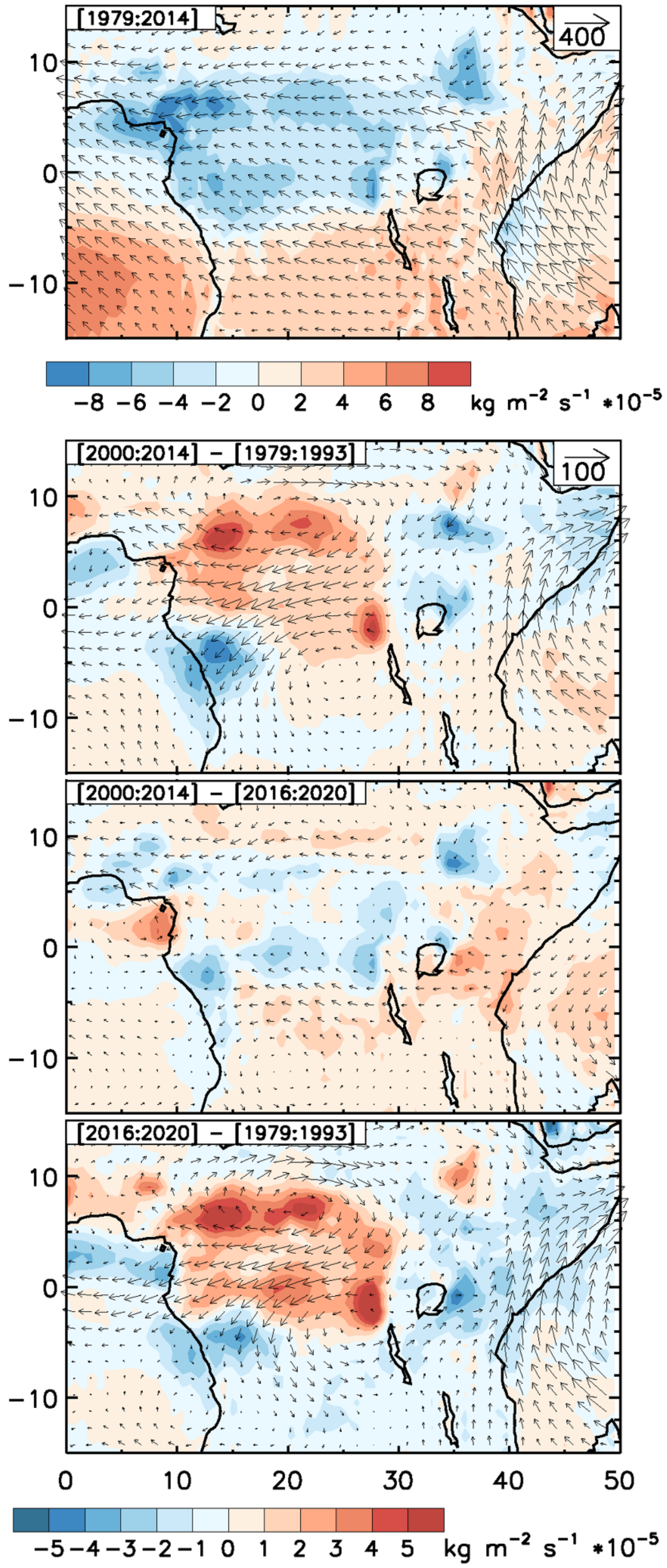

Figure 6. Vertically integrated moisture flux (kg m^{-2} s^{-1}) and moisture flux divergence (kg m^{-1} s^{-1} × 10^{-5}) in AMJ. Top diagram: 1979–2014 mean. Bottom diagram: (top) 2000–14 minus 1979–93, (middle) 2000–2014 minus 2016–2020, (bottom) 2016–2020 minus 1979–1993. Integration is from the surface to the top of the atmosphere.

development of that maximum. During the periods 2016–2020 and the very dry years from 2008 to 2014, the river's signature is also apparent as a reduction in CIN (not shown).

During the dry period 2000–2014, CAPE is anomalously low throughout the region and CIN is weakly above normal (not shown). CAPE is low compared to both wet periods. However, CIN is slightly lower

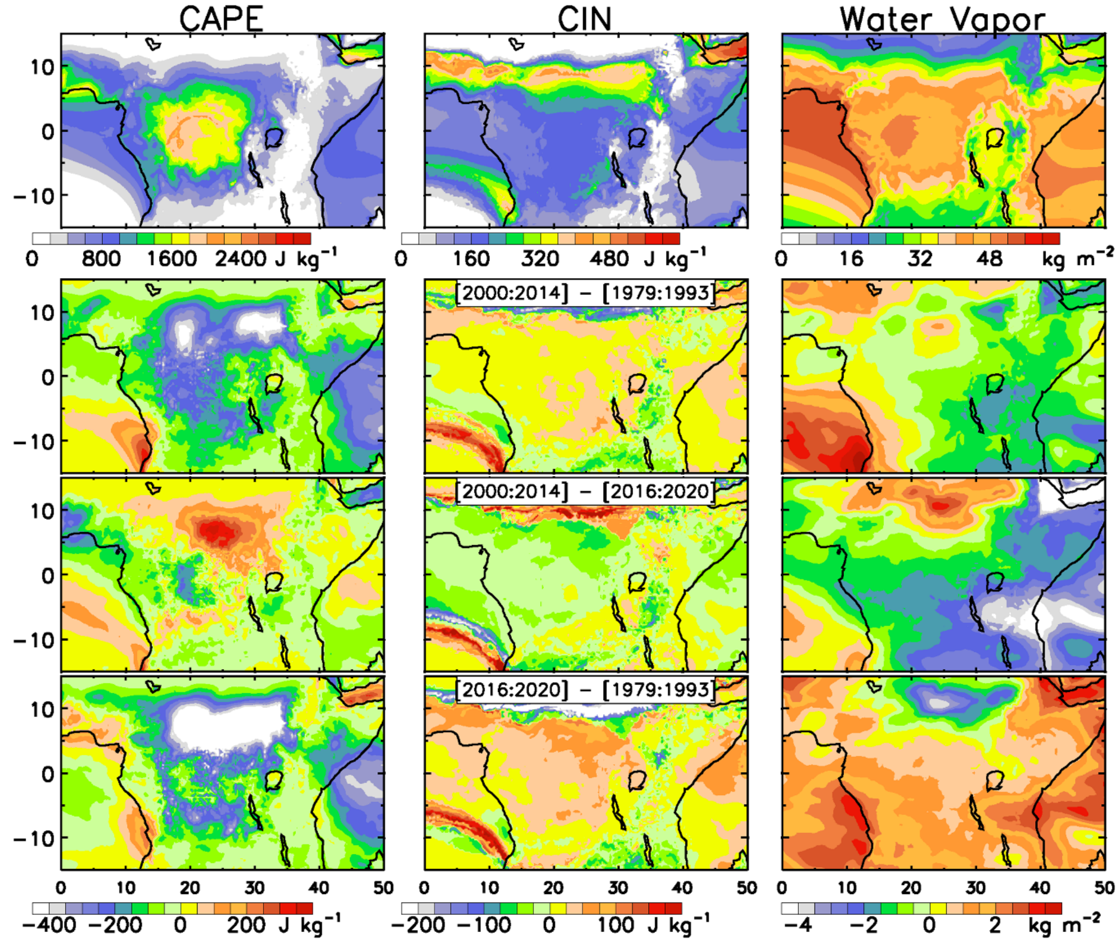

Figure 7. CAPE, CIN and total column water vapor in AMJ: top diagram: 1979–2014 mean. Bottom diagram: (top) 2000–2014 minus 1979–1993, (middle) 2000–2014 minus 2016–20, (bottom) 2016–2020 minus 1979–1993. Total column water vapor is the integral from the surface to the top of the atmosphere.

than in the 2016–2020 wet period but higher than in the 1979–1993 wet period. Both CAPE and CIN are lower in 2016–2020 than in 1979–1993.

The total column water vapor is greater in both wet periods than in the 2000–2014 dry period, consistent with the higher CAPE in the wet periods. Total column water vapor is markedly higher in the recent wet period than in the 1979–1993 wet period. Notably, CAPE and atmospheric moisture are the main determinants of the seasonal cycle over Lake Victoria, just to the east of the Congo Basin (Nicholson *et al* 2021).

4. Discussion

4.1. The drying trend and the walker circulation

Hua *et al* (2016) compared vertical motion fields in the tropics in a wet period (1979–1993) and a dry period (2000–2014) in the AMJ rains over the Congo basin. They concluded that the drying trend between 1979 and 2014 was associated with SST variations over the Indo-Pacific, which resulted in an enhanced and westward extended Walker circulation. The mechanism of the association was not clear. However, vertical motion over the Congo was reduced in the dry period compared to the wet. Contrasts in the omega field over the Indo-Pacific region were similar to, but weaker than, those for 1979–1993. However, vertical motion over the Congo in 2016–2020 was similar to that during the dry period. Hence changes in the Walker circulation were probably not responsible for the increase in rainfall in 2016–2020.

Coincident with the drying trend over the Congo, a drying trend in the March-to-May rainfall occurred over eastern Africa (Liebmann *et al* 2014, 2017). Consistent with Hua *et al* (2016), Williams and Funk (2011) similarly concluded that the trend was associated with a westward extension of the Walker circulation over the Pacific and SST changes in the Indo-Pacific region. Specifically, SSTs had increased more over the Indian Ocean and western Pacific than over the central Pacific, leading to an increase in the zonal SST gradient between Indonesia and the central Pacific (Williams and Funk 2011, Hoell and Funk 2013).

The SSTs in figure 5 are consistent with the suggested increase in the zonal gradient during the dry period, compared to 1979–1993. Determining whether or not the configuration of SSTs has contributed to the development of wetter conditions during 2016–2020 is difficult because an overall warming trend has continued throughout the tropical oceans. However, the warming that occurred during 2016–2020 was greater in the central and eastern Pacific than in the western, reducing the SST gradient.

4.2. Upper-level winds

It is not clear, however, whether or not these changes in SSTs may have contributed to the wetter conditions over the Congo. The mechanism suggested by Williams and Funk (2011) for the drying trend over eastern Africa involves increased precipitation in the upward branch of the Pacific Walker cell in the dry period. They suggested that this resulted in increased mid-tropospheric water vapor condensation but drier air in the upper troposphere. They hypothesized that the anomalous easterly winds in the upper troposphere brought this drier air towards Africa. Liebmann *et al* (2017) concluded that there was no change in specific humidity, so that it was merely the presence of the upper-level easterlies that contributed to the drying trend.

Over the Congo there was anomalous easterly wind in the upper troposphere during 2000–2014, compared to 1979–1993 (figure 8). However, the mean upper-level winds in 2000–2014 were actually more westerly than in the recent wet period of 2016–2020. Hence, changes in upper-level winds cannot explain the return to wetter conditions.

4.3. Moisture flux and stability

Another factor that distinguished the 1979–1993 wet period from the subsequent dry period was vertically integrated moisture flux and flux divergence. The flux out of the region was greater in the dry period, as was the flux divergence (figure 6(b)). This was probably an important factor in the drier conditions. However, changes in flux and flux divergence cannot explain the return to wetter conditions, as there is little contrast between 2000–2014 and 2016–2020. This result is surprising because several earlier studies have equated wetter conditions over the Congo Basin to increased vertically integrated moisture flux convergence (Washington *et al* 2013, Creese and Washington 2016, Tamoffo *et al* 2019).

The analysis showed that CAPE was higher in both wet periods than during the dry period but that little contrast was evident in CIN between the dry period and the wet periods. This suggests that CAPE was a factor in producing the dry conditions while CIN was not. Notably, CAPE was higher and CIN lower in 2016–2020 compared to 1979–1993. This is consistent with the higher rainfall in the earlier period.

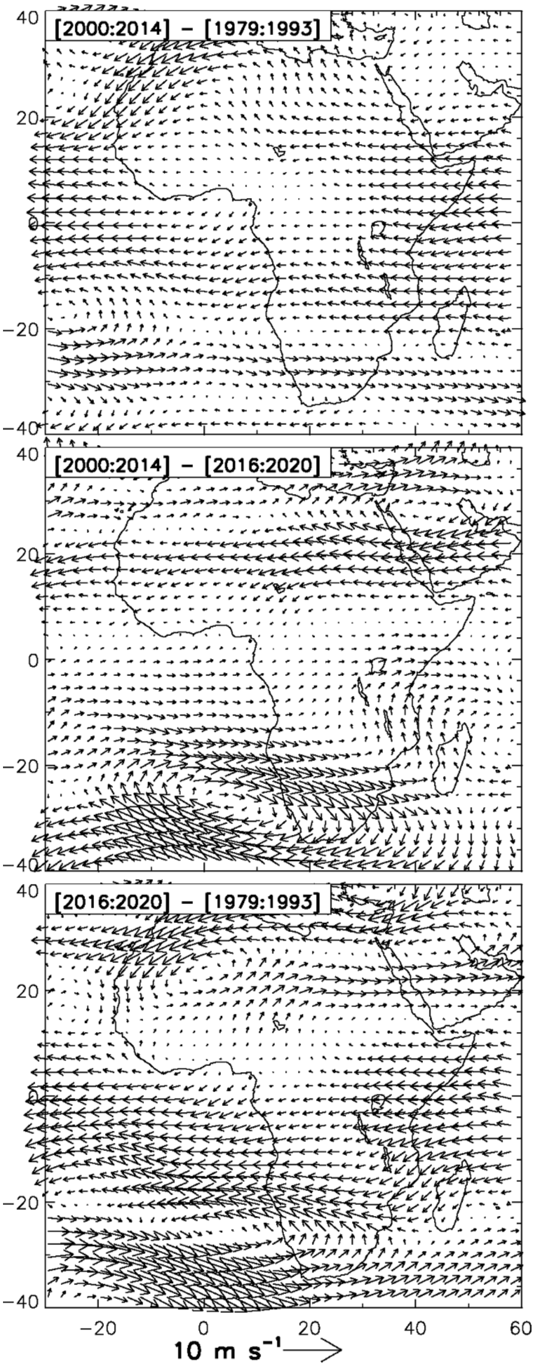

Figure 8. Differences in mean 200 hPa AMJ 00/14 wind between the wet and dry periods. (Top) 2000–2014 minus 1979–1993 (middle) 2000–2014 minus 2016–2020 (bottom) 2016–2020 minus 1979–1993.

4.4. Atmospheric moisture

The total column water vapor was greater in both wet periods than in the dry period. This suggests that atmospheric moisture content might be an important factor determining precipitation in AMJ. The increase requires either an increase in moisture flux into the region or moisture flux convergence, or an increase in local evaporation. Figure 6 indicated that increased moisture flux from the region and flux divergence could have contributed to the dry conditions but a reversal of that condition could not explain the return to wetter conditions during 2016–2020. Thus, presumably, increased evaporation led to the increase in atmospheric moisture. Evaporation has been shown to be an important source of moisture over the Congo Basin (Worden *et al* 2021).

Consistent with increased evaporation, several studies demonstrated rising temperatures. Collins (2011) noted rising temperatures over the Congo Basin and concluded this was due to anthropogenic climatic change. Bush *et al* (2020), using direct surface-based measurements in the forest region of Gabon, observed a significant warming trend over the prior 34 years, coincident with a drying rate of −75 mm per decade. Mahli and Wright (2004) found a warming trend throughout the tropical rain forests since the 1970s. The warming trend could result in an increase in evaporation in the Congo Basin.

An increase in evaporation would be consistent with the increased CAPE that we observed during 2016–2020. Whether an increase in evaporation occurred is inconclusive. Ndehedehe *et al* (2018) found that MODIS indicated widespread negative trends in evaporation over the Congo Basin between 2000 and 2014, i.e. coincident with the dry period evaluated here. They concluded that this was probably associated with observed changes in soil moisture. Burnett *et al* (2020) determined that net radiation, photosynthetically active radiation (PAR), and vapor pressure deficit all increased significantly within the Congo Basin from 2002 to 2016. This might imply an increase in evaporation. However, using a very sophisticated water balance model that included measurements of ground water storage, they found that evaporation remained stable over the observation period, despite sunnier and drier conditions. They hypothesized that the stability of evaporation might be due to increasing atmosphere carbon dioxide concentrations, which would offset the impact of increased dryness and radiation on stomatal water use efficiency.

This leaves the possibility that the increase in CAPE is associated with a general increase in atmospheric water vapor forced by the global rise in SSTs and land temperatures. The warming is also consistent with the large continual increase in geopotential height over the Congo region (figure 3). An increase in atmospheric water vapor requires either increased moisture advection or increased evaporation within the region. Since the former was ruled out by our analysis, an increase in evaporation is implied. Unfortunately, studies that have examined that issue are inconclusive. Likewise, it is not a given that rising temperatures would lead to increased evaporation in the region.

Much of the problem is related to the lack of observational data over the Congo Basin during the last few decades (Nicholson *et al* 2018b, Burnett *et al* 2020, Tshimanga *et al* 2021). At least partially a consequence of this, rainfall estimates for the Congo Basin vary widely among satellite and reanalysis products, sometimes by an order of magnitude (Washington *et al* 2013, Hua *et al* 2019, Nicholson *et al* 2019, 2021, Tamoffo *et al* 2019). For the same reason, evaporation estimates in the Congo Basin are poorly constrained (Burnett *et al* 2020) and there is a huge spread in the estimates from reanalysis products and global climate models (Crowhurst *et al* 2020, 2021). Currently, process-based assessments of model performance are providing a strong degree of optimism in model improvement (e.g. Creese and Washington 2016, 2018, Crowhurst *et al* 2020). However, improved ground-based observations are also critical, particularly in the performance of satellite estimates of hydrologic variables (Nicholson *et al* 2019, Burnett *et al* 2020). The importance of these is underscored by the concern about the future of the Congo rain forest (Akkermans *et al* 2014).

Two enigmatic aspects of the Congo Basin's rainfall regime are the extremely low spatial coherence and the lack of teleconnections to other African regions (Nicholson 2021). If, as our study suggests, CAPE plays a major role in the interannual variability of Congo rainfall, it stands to reason that, in a high CAPE environment, small local perturbations can produce a storm, in the absence of external, largescale forcing. This could potentially explain the very local rainfall signal within the Congo Basin.

5. Conclusions

The results of this study suggest that the main factors in the recent wetter conditions are CAPE and total column water vapor, which influences CAPE. Over the central basin the mean total column water vapor in 2016–2020 was anomalously high compared to the mean for 1979–2014 and was much higher than during the period 2000–2014. CAPE was also higher in the earlier wet period than in the 2000–2014 dry period. CAPE was markedly below the LTM during 2000–2014. This is consistent with total column water vapor, which was greater in both wet periods than in the dry period, when it was markedly below the mean for 1979–2014. The increase in CAPE occurred without attendant changes in SSTs or atmospheric circulation that could account for the increase.

Data availability statement

No new data were created or analysed in this study.

Acknowledgments

This project is supported by a grant from the National Science Foundation, Number GEO/ATM 1854511. We also thank the two reviewers for their suggestions for improvement of the manuscript.

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