NOTES AND CORRESPONDENCE

The Impact of Tropical Tropopause Cooling on Sahelian Extreme Deep Convection

Kunihiko KODERA

Meteorological Research Institute, Tsukuba, Japan

Nawo EGUCHI

Research Institute for Applied Mechanics, Kyushu University, Kasuga, Japan

Rei UEYAMA

NASA Ames Research Center, California, USA

Beatriz M. FUNATSU

CNRS, Université de Nantes, France

Marco GAETANI

Universitaria Superiore IUSS, Italy

and

Christopher M. TAYLOR

UK Centre for Ecology and Hydrology, UK
National Centre for Earth Observation, UK

(Manuscript received 6 January 2021, in final form 28 April 2021)

Abstract

Previous studies have suggested that the recent increase in tropical extreme deep convection, in particular over Asia and Africa during the boreal summer, has occurred in association with cooling in the tropical lower stratosphere. The present study is focused on the Sahel region of West Africa, where an increased occurrence of extreme precipitation events has been reported over recent decades. The results indicate that the changes over West Africa since the 1980s involve a cooling trend in the tropical lower stratosphere and tropopause layer, combined with warming in the troposphere. This feature is similar to that which might result from increased greenhouse-gas levels but is distinct from the interannual variation of precipitation associated with the transport of water vapor from the Atlantic Ocean. It is suggested that the decrease in the vertical temperature gradient in the tropical tropopause region enhances extreme deep convection over the Sahel, where penetrating convection is frequent, whereas tropospheric warming suppresses the shallower convection over the Guinea Coast. Therefore, the essen-

Corresponding author: Kunihiko Kodera, Meteorological Research Institute, 1-1 Nagamine, Tsukuba, Ibaraki 305-0052, Japan
E-mail: kodera.kk@gmail.com
J-stage Advance Published Date: 14 May 2021

tial feature of the recent changes over West Africa is the depth of convection rather than the total amount of surface precipitation.

Keywords Sahel; recent trend; tropical tropopause layer; deep convection; land precipitation

Citation Kodera, K., N. Eguchi, R. Ueyama, B. Funatsu, M. Gaetani, and C. M. Taylor, 2021: The impact of tropical tropopause cooling on Sahelian extreme deep convection. *J. Meteor. Soc. Japan*, **99**, 1127–1139, doi:10.2151/jmsj.2021-055.

1. Introduction

West Africa is particularly susceptible to the impacts of climate change, with rising temperatures already threatening human health (Russo et al. 2016), and significant changes in the precipitation regime are likely to occur over the next few decades (Gaetani et al. 2020). Assessing the role of the tropical tropopause layer (TTL; around 140–70 hPa) in driving precipitation trends is a valuable step forward that will improve our understanding of the present and future evolution of the rainfall regime in West Africa.

Kodera et al. (2019) have indicated that extreme deep convection in the ascending branch of the boreal summer Hadley circulation became more active over recent decades, particularly over the African and Asian sectors. In West Africa, this increase in convective activity was associated with the recent recovery of rainfall over the Sahel following the long and severe drought conditions of the 1970s and 1980s (Fontaine et al. 2011; Nicholson 2013; Maidment et al. 2015). Such a recovery was associated with accelerating global warming, which increased the moist static energy in the troposphere over West Africa by enhancing local evaporation (Giannini 2010) and also strengthened moisture transport from the subtropical North Atlantic (Giannini et al. 2013; Dong and Sutton 2015). The present increase in precipitation over the Sahel is, however, not a simple recovery to the former wet state: the characteristics of rainfall have also changed, becoming more intense and intermittent. According to Panthou et al. (2014, 2018) the number of rainy days per year is still below average, implying that there has been an increase in severe rainfall events. It should be noted that the increase in rainfall has not occurred uniformly over West Africa; for example, rainfall decreased somewhat over the Guinea coastal region (Odoulami and Akinsanola 2018).

As hydrological changes have a major impact on human activity in West Africa (Sultan and Gaetani 2016), a number of studies have investigated precipitation at the surface, as documented in review papers (Rodríguez-Fonseca et al. 2011; Biasutti 2019). These studies have demonstrated the important role of sea surface temperatures (SSTs) with respect to the last drought over the Sahel (Folland et al. 1986; Mohino et al. 2011; Rodríguez-Fonseca et al. 2015). The interannual variation of rainfall is also related to the phase of El Niño–Southern Oscillation (ENSO; Janicot et al. 2001; Diakhaté et al. 2019; Hart et al. 2019). However, state-of-the-art climate models still struggle to reproduce precipitation variability and trends in West Africa through the historical period, which is mainly due to their low skill in simulating the observed SST teleconnections (Rowell 2013).

Taylor et al. (2017; hereafter referred to as T17) demonstrated that the occurrence frequency of mesoscale convective systems (MCSs) with a cloud top temperature (CTT) of less than −70°C has tripled since the mid-1980s, whereas more common MCSs with CCT up to −40°C have increased only moderately in frequency. They investigated the role of recent Saharan warming, enhanced wind shear, and changes in the properties of the Saharan Air Layer as drivers of MCS intensification. Further evidence supporting the important role of enhanced meridional temperature gradients in deepening MCSs has subsequently been presented for the wider tropical North African region (Taylor et al. 2018; Klein and Taylor 2020; Klein et al. 2020). The increase in the number of cold cloud top MCSs can be related to the increase in extreme rainfall events over the Sahel (Klein et al. 2018). It should be noted that an air temperature of −70°C roughly corresponds to the 140-hPa level at the bottom of the TTL. This suggests the possible role of TTL processes in the recent precipitation increase over the Sahel. In the present study, we demonstrate the importance of TTL processes for explaining this rainfall recovery and show that the atmospheric circulation associated with the precipitation increase is somewhat different from the accepted paradigm based on the transport of water vapor from the ocean (Druyan and Koster 1989; Pu and Cook 2012; Giannini et al. 2013).

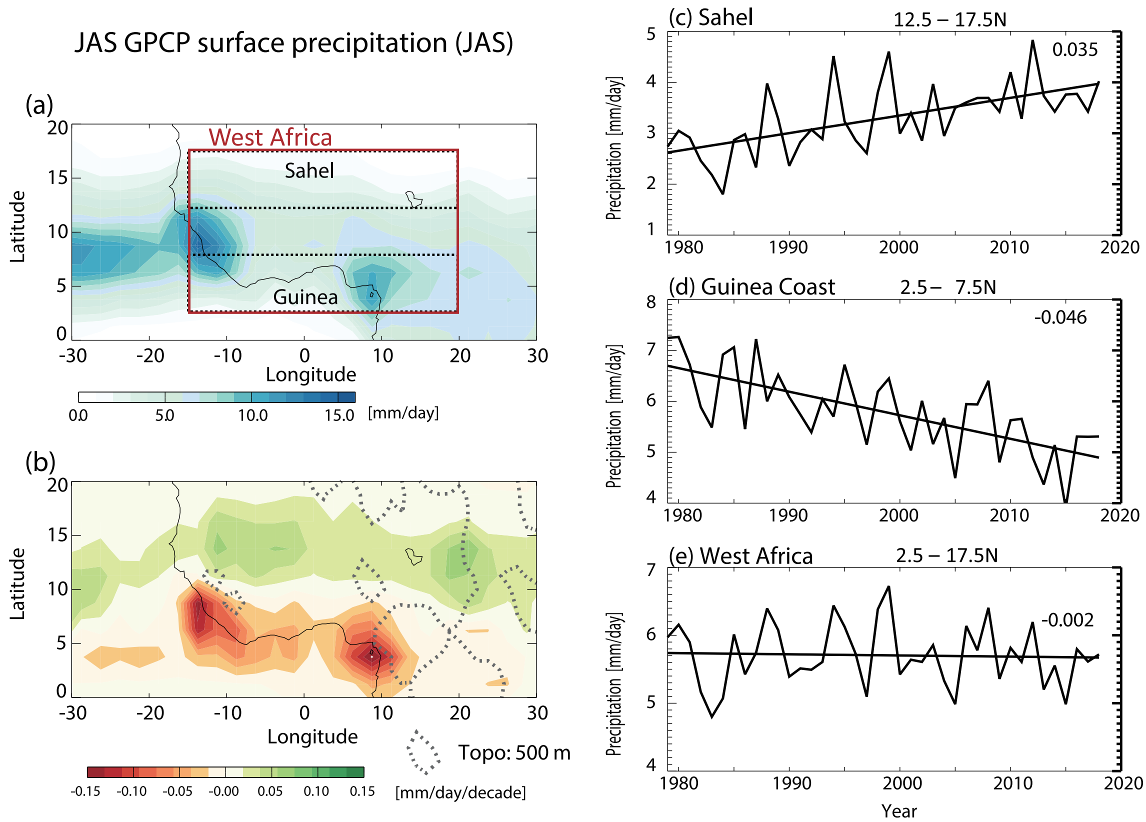

Fig. 1. (a) Climatological mean surface precipitation over West Africa during JAS and (b) its linear trend over the period 1979–2018. (c, d, and e) Time series of JAS mean precipitation averaged over (c) the Sahel, (d) the Guinea Coast, and (e) West Africa. Straight lines and numbers indicate linear trend (mm/day/decade). Regions within West Africa are indicated by dotted lines within the brown box in (a). Contours with dotted lines indicate topography of 500 m.

2. Data

We make use of monthly mean meteorological reanalysis data by the Japan Meteorological Agency, JRA-55 (Kobayashi et al. 2015), during the period of satellite observation era after 1979. For this study, we defined climatology as the 40-year mean for the period of 1979–2018 (unless stated otherwise), and the standard deviation was also calculated over this period.

Analysis of the surface precipitation was conducted using the Global Precipitation Climatology Project (GPCP) monthly mean data version 2.3 (Adler et al. 2003). Extreme deep convection, such as tropical overshooting clouds (COV) that penetrate beyond the level of neutral buoyancy and overshoot into the TTL, was identified using the diagnostics developed by Hong et al. (2005). These diagnostics are based on the differences in brightness temperature measured by three high-frequency channels of the advanced microwave sounding unit (AMSU) or the microwave humidity sensor (MHS) for the period of 2001–2018 (Funatsu et al. 2016). This is similar to the approach used by Kodera et al. (2019). We compared our results with the occurrence frequency of MCSs over the Sahel obtained by T17.

3. Results

The changes in precipitation during the summer monsoon season [July, August, and September (JAS)] from the 1980s to the present have not occurred homogeneously over West Africa (Fig. 1). Precipitation increased over the Sahel (15°W–20°E, 12.5–17.5°N; Fig. 1c), but decreased over the Guinea Coast (15°W–20°E, 2.5–7.5°N; Fig. 1d), as also reported by Odoulami and Akinsanola (2018). In fact, surface precipitation does not show a clear trend when averaged over the whole of West Africa (15°W–20°E, 2.5–17.5°N;

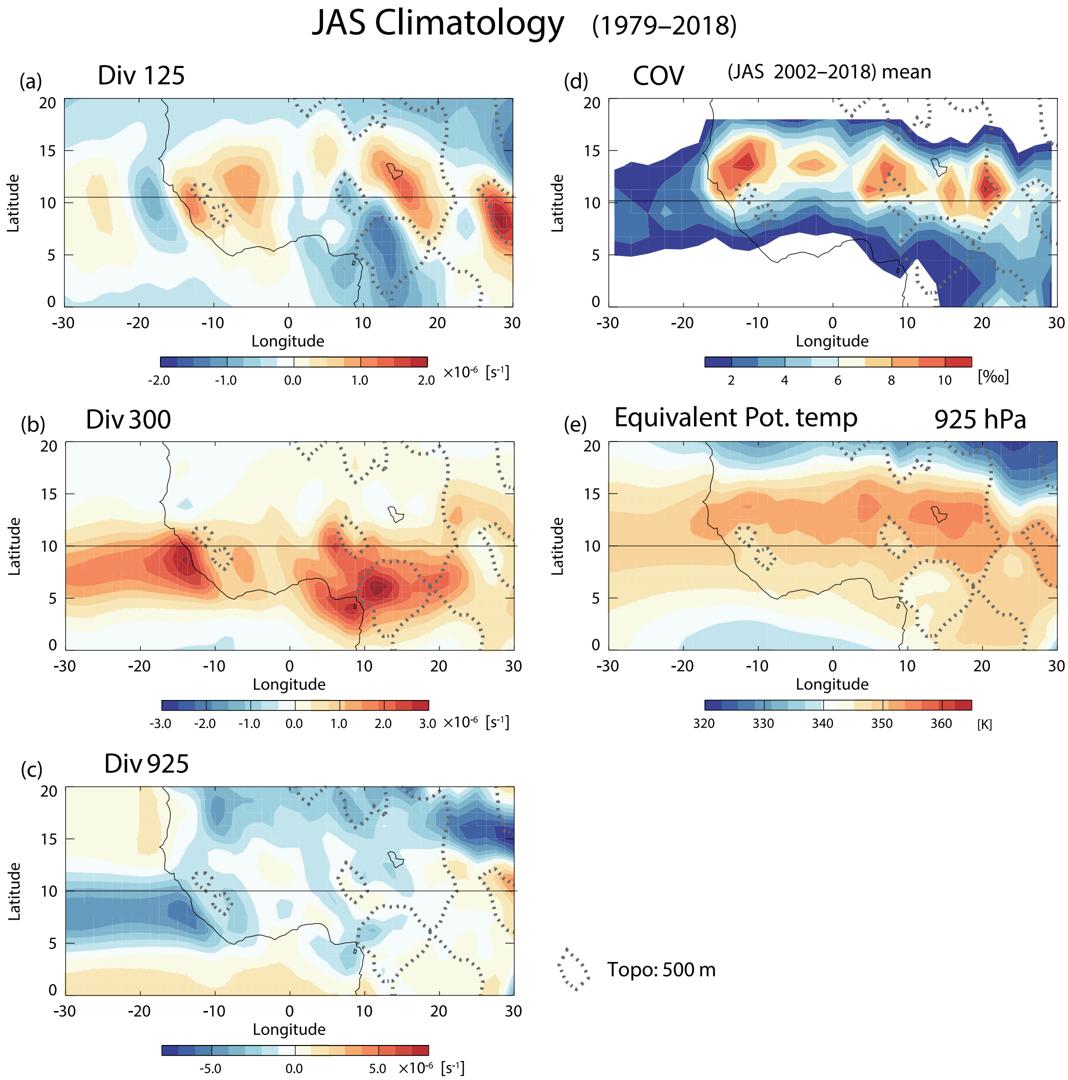

Fig. 2. Climatology for JAS. Horizontal divergence at (a) 125, (b) 300, and (c) 925 hPa. (d) Frequency of convective overshooting. (e) Equivalent potential temperature at 925 hPa. Contours with dotted lines indicate topography of 500 m.

Fig. 1e).

In fact, convective activity strongly varies within West Africa during the monsoon season; e.g., broad stratiform clouds frequently occur over the coastal region, whereas extreme deep convection is common further inland (Zuluaga and Houze 2015). A decreasing precipitation trend is particularly pronounced over the coastal regions west of the Guinea Highlands and South Cameroon Plateau (Fig. 1b). Over these elevated terrains, convergence of the air from the ocean (Fig. 2c) results in heavy precipitation (Fig. 1a). As the convection over the coastal region is generally not deep enough to penetrate into the TTL, uplifted air diverges in the upper troposphere (Fig. 2b). An increasing precipitation trend is observed in regions of high equivalent potential temperature near the surface (Fig. 2e), where extreme deep convective clouds with overshooting tops occur (Fig. 2d). This extreme deep convection is also evident in the large horizontal divergence at higher levels in the TTL (Fig. 2a).

These results suggest that the regional differences in recent precipitation trends (Fig. 1b) may arise from the difference in the structure of convection. In particular, precipitation increased where extreme deep convection frequently occurs but decreased where convection is relatively shallow. This implies the important role of the depth of convection in precipitation changes over the last few decades.

We now focus on the Sahelian region. The time series shown in Fig. 1c is also shown in Fig. 3a. Large interannual variations are superimposed over the increasing precipitation trend. The red dots and black crosses indicate the maxima and minima, respectively, in the interannual variations. The first thing to elucidate is whether the decadal trend is produced by the same processes causing the year-to-year variability. To investigate this, we conducted composite analysis of the standardized anomalies, i.e., anomalies normalized using the standard deviation of the interannual variation. For the composite means of the year-to-year variation, the 8 largest positive deviations in precipitation above the linear trend line (wet years: 1980, 1986, 1988, 1994, 1999, 2003, 2010, and 2012) and the same number of precipitation minima below the linear trend line (dry years: 1984, 1987, 1990, 1997, 2002, 2004, 2011, and 2014) were selected.

The composite differences between the dry and wet years are indicated in the left-hand panels of Fig. 3, and the composite differences between two 19-year periods, 2000–2018 and 1979–1997, are shown in the right-hand panels. Naturally, we can see an increase in the precipitation over the Sahel in both cases, although the contrast between increased precipitation in the Sahel and decreased precipitation over the Guinea Coast is more pronounced in the decadal changes (Fig. 3c). The relationship between moisture flux and precipitation over Africa has been studied. Significant differences in environmental conditions are observed from the zonal moisture flux in the lower troposphere (Fig. 3c). The anomalous zonal moisture flux at 850 hPa extends from the Atlantic Ocean over the African continent during the wet years. This feature is consistent with the feedback process proposed by Rowell (2003), whereby precipitation increases over the Sahel due to a teleconnection from remote oceans, which induces stronger westerlies over the Atlantic Ocean, thus transporting more water vapor over the continent and further increasing precipitation over the Sahel. However, the decadal changes indicate a weaker connection between the moisture flux from the oceanic sector (Fig. 3f). The occurrence of wet and dry years corresponds well to years of large and small eastward moisture flux, respectively, driven by zonal wind over the Atlantic Ocean (Fig. 7c). The decadal change in water vapor flux rather shows a meridional seesaw between the Sahel and Guinea Coast. Thus, the overall change in Western Africa is small, consistent with the insignificant trend in precipitation averaged over Western Africa (Fig. 1b). We note that some of the wet years (1988, 1999, and 2010) correspond to La Niña years, whereas some of the dry years (1987, 1997, and 2002) correspond to El Niño years. This suggests the possible role of ENSO variability in influencing the decadal trend. However, Pomposi et al. (2020) found minor influence of ENSO variability in the recent precipitation trend in West Africa.

Increased precipitation induces upwelling in the atmosphere. The year-to-year variability suggests that this response is limited mainly in the troposphere (Fig. 3d). However, the decadal changes indicate that upwelling generally increases in the TTL, except for a region of suppressed tropospheric upwelling over the West African coast. In the following, we investigate why the decadal changes in vertical velocity differ between the Sahel and the Guinea Coast.

The evolution of the JAS mean anomalous temperature and pressure vertical velocity (ω) over West Africa is illustrated in Fig. 4. The amplitude of vertical velocity is shown relative to the climatological value, ω_{clim}, as $(\omega/\omega_{\mathrm{clim}}) \times 100$. The black and red contours indicate ratios greater and less than 100 %, respectively. Although there is no clear trend in the surface precipitation averaged over West Africa (Fig. 1e), trends are evident in the temperature and vertical velocity in the TTL. In particular, the temperature decreased by more than 2 K over this time period, while the vertical velocity increased fourfold from 50 % to 200 % around 150–100 hPa. A decreasing trend in the upwelling in the troposphere is also seen in association with the tropospheric warming trend.

The evolution of the temperature and horizontal divergence are presented in Figs. 5a and 5b for the Sahel and Guinea Coast, respectively. The vertical velocity in both regions is shown in Figs. 5c and 5d. Cooling trends in the lower stratosphere and TTL are observed in both regions. The divergence field indicates that convection over the Sahel reaches the TTL. It should be noted that cooling in the TTL can enhance deep convective activity, consistent with that found in a study on a sudden stratospheric warming (SSW) in January (Eguchi et al. 2015). Contrarily, because convection over the Guinea Coast is not very deep, there is a clear separation between the upwelling above and below the 150-hPa level. Accordingly, although cooling and upwelling trends are observed in both the lower stratosphere and TTL, tropospheric vertical velocity does not show an increasing trend over the Guinea Coast.

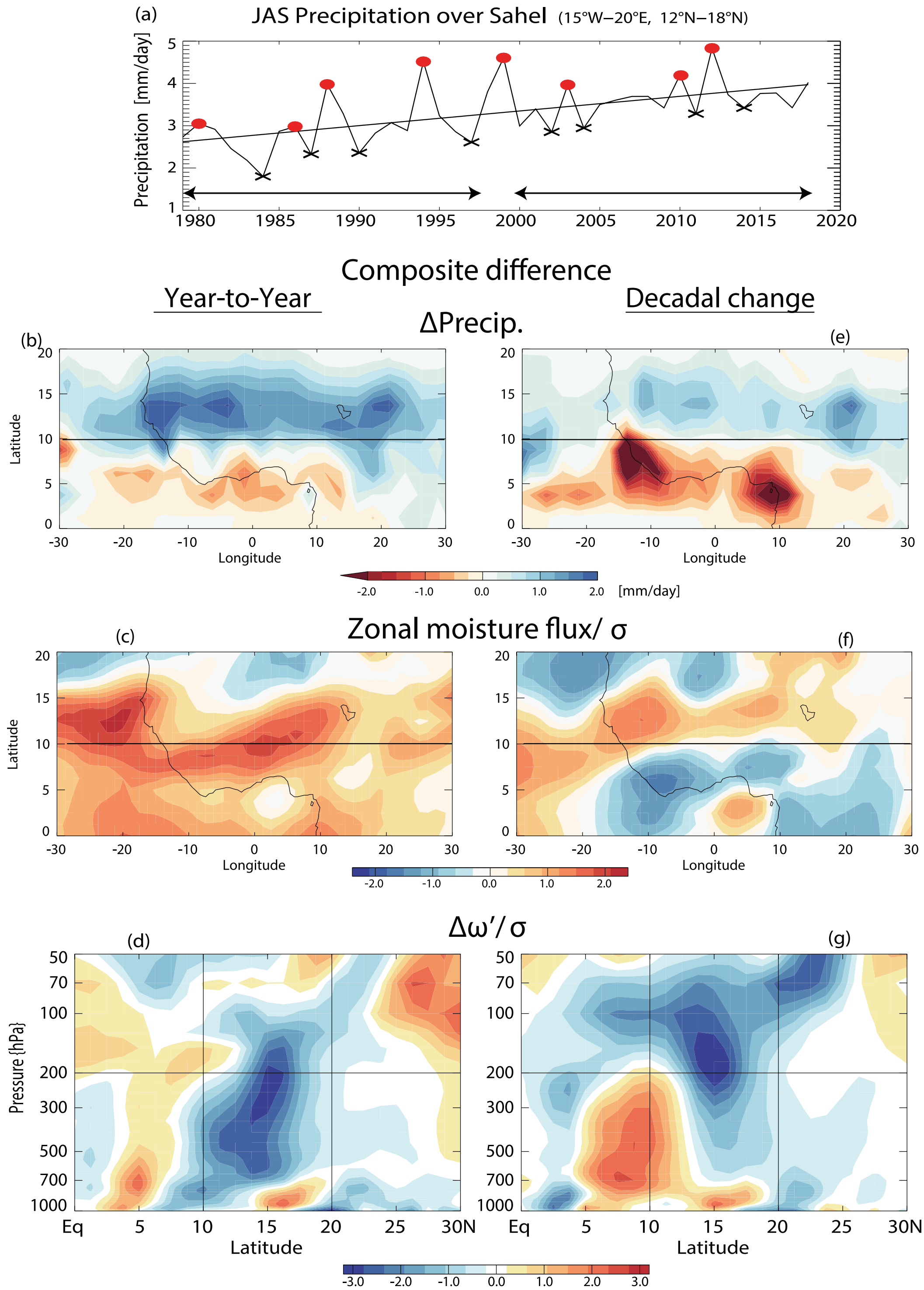

Fig. 3. (a) Time series of JAS mean surface precipitation over the Sahel from GPCP. Red dots and black crosses indicate wet and dry summers, respectively. (b–d) Composite mean differences between wet and dry summers: (b) surface precipitation, (c) standardized anomalous zonal moisture flux at 850 hPa, and (d) standardized anomalous pressure vertical velocity over the West African sector (15°W–20°E). (e, f, g) As (b, c, d) except the differences were calculated between two 19-year periods; 2000–2018 and 1979–1997 indicated by two arrows in (a).

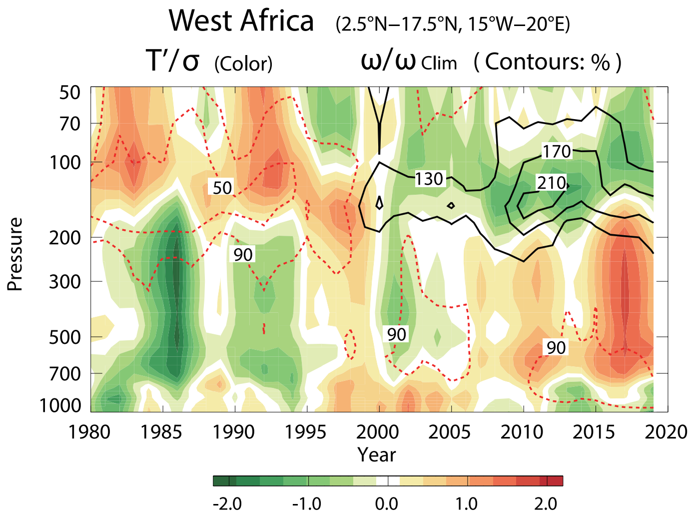

Fig. 4. Height–time cross-section over West Africa of JAS mean standardized anomalous temperature (color shading) and amplitude (%) of pressure vertical velocity relative to its climatological value (contours: 100 % > by black lines, and < 100 % by red dashed lines). A 3-year running mean has been applied to the data.

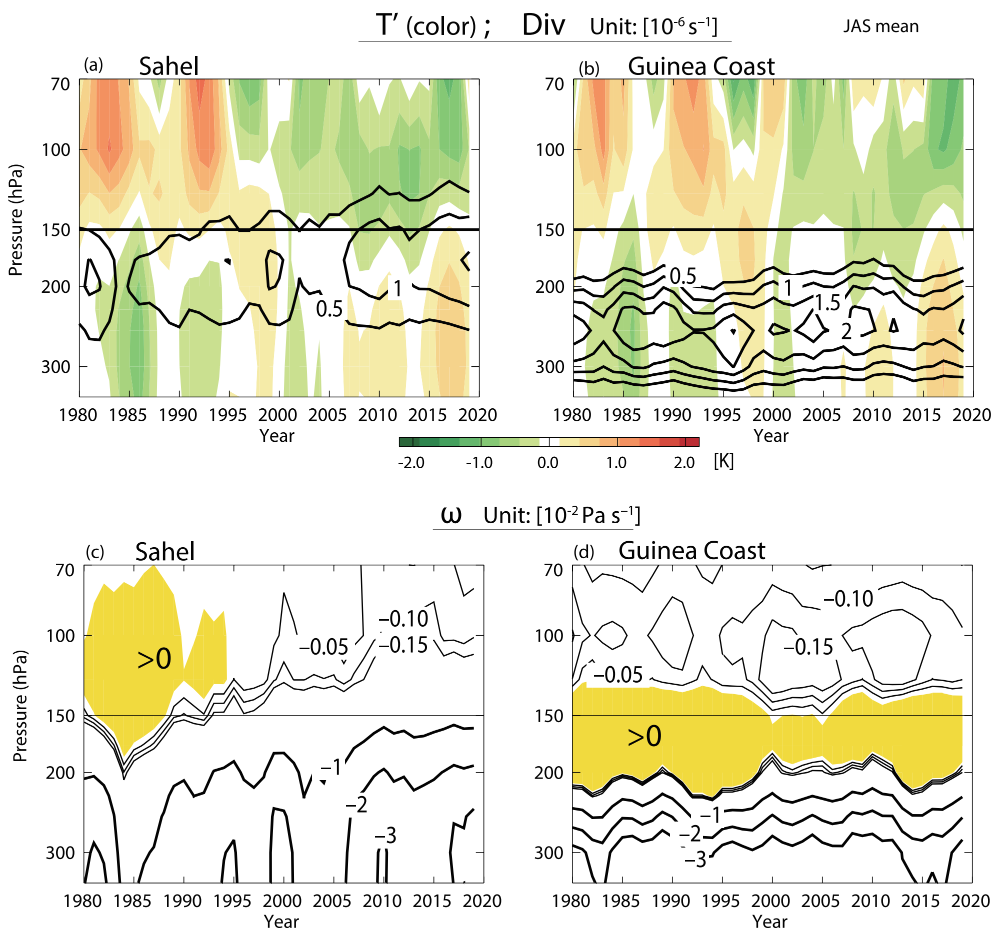

Fig. 5. JAS mean (a, b) horizontal divergence (contours) and anomalous temperature (color shading) and (c, d) pressure vertical velocity (ω) (contours). Yellow shading indicates the region of downward velocity. Left- and right-hand panels are for the Sahel (12.5–17.5°N) and Guinea Coast (2.5–7.5°N), respectively. A 3-year running mean has been applied to the data.

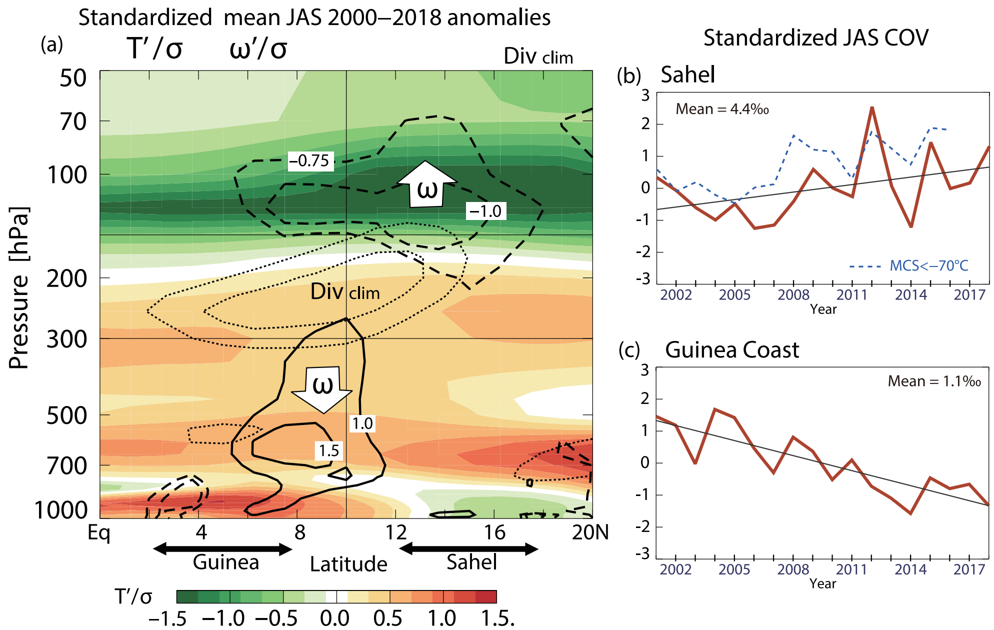

Fig. 6. (a) Meridional cross-section of standardized mean JAS 2000–2018 anomalies over the West African sector (15°W–20°E). Temperature is shown by color shading, and pressure vertical velocity are shown by contour lines (positive by solid lines, and negative by dashed lines). Climatology of the horizontal divergence is shown by dotted lines. Contours are for 1, and 2 × 10^{-6} s^{-1}. (b, c) Standardized JAS mean COV occurrence frequency from 2001 to 2018 over (b) the Sahel and (c) the Guinea Coast. These two regions are indicated by the arrows along the x-axis of (a). Blue dashed lines in (b) indicate the standardized JAS mean MCSs with a CTT below −70°C from T17 (same as in Fig. 7a).

Latitudinal differences between the two regions can be clearly seen in the meridional cross section of the JAS mean standardized temperature and vertical velocity anomalies shown in Fig. 6. Although cooling in the TTL occurred over a range of latitudes, upwelling in the troposphere was enhanced over the Sahel, but suppressed over the Guinea Coast.

The widespread cooling over the regions of both increasing and decreasing convections suggests that lower stratospheric temperatures are driving changes in convection and are not a simple response to convective activity (Holloway and Neelin 2007). This leads to a working hypothesis that the cooling in the TTL mainly impacts those regions where upwelling extends from the upper troposphere to the TTL (i.e., about 200–140 hPa), as indicated by the climatological divergence field (dotted lines).

Figures 6b and 6c show the evolution of standardized COV frequencies during the period of 2001–2018. The mean occurrence frequency of COV over the Sahel is 4.4 ‰, which is four times as large as that over the Guinea Coast. There is an increasing trend superimposed on the year-to-year variability in the COV occurrence frequency over the Sahel, which matches the evolution of MCSs with a CTT of less than −70°C reported by T17. In fact, the increase in MCSs over the Sahel had already began in the 1980s, as is presented in Fig. 7. Contrarily, the COV occurrence frequency over the Guinea Coast exhibits a decreasing trend.

We also compared the time series of the horizontal divergence at 125 hPa over the Sahel with the occurrence frequency of MCSs with a CTT below −70°C obtained by T17. It should be noted that the climatological air temperature around 125 hPa is about −75°C. As expected, not only is the large increasing trend common to both properties, some in-phase interannual variability is also seen, with the correlation coefficient (r) between the two being 0.87. The correlation coefficient between the detrended time series of divergence and MCS is 0.47 and is still statistically significant for 35-year data (Fig. S1). It is noted, however, that good correlation comes from the late period, when very cold MCSs became more frequent. It should also be noted that the vertical temperature gradient in the TTL (i.e., the temperature difference

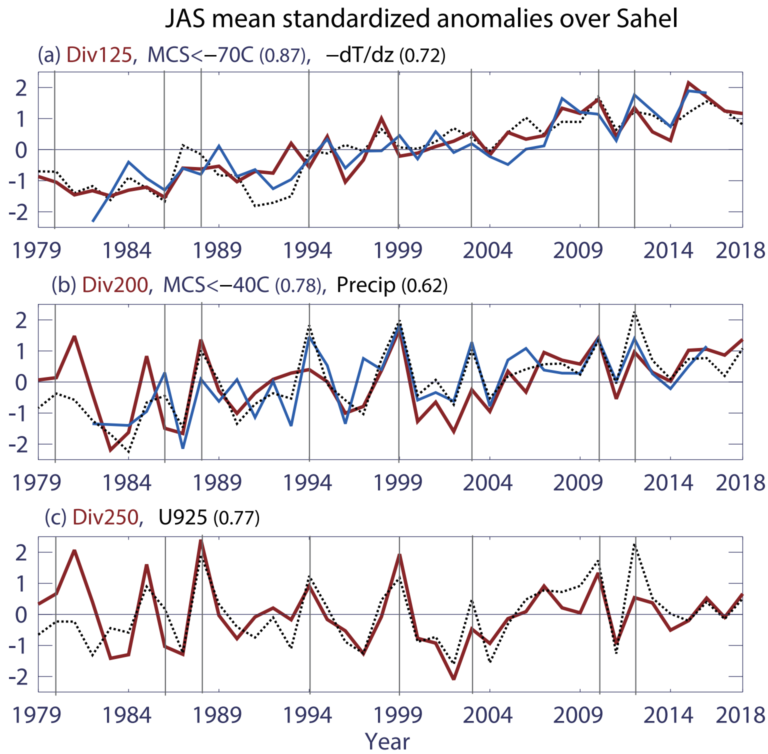

Fig. 7. Time series of JAS mean standardized anomalies. (a) Horizontal divergence at 125 hPa (brown lines), occurrence frequency of MCSs with a CTT below −70°C (blue lines), and anomalous temperature differences between 125 hPa and 175 hPa (black dotted lines). (b) Horizontal divergence at 200 hPa (brown lines), MCSs with a CTT below −40°C (blue lines), and surface precipitation (black dotted lines). (c) Horizontal divergence at 250 hPa (brown lines) and anomalous zonal wind over the Atlantic Ocean (10–15°N, 30–15°W) at 925 hPa (black dotted lines). The correlation coefficients between the divergence and other variables are indicated on the top of each panel. Vertical lines indicate peak years in the year-to-year variability of surface precipitation in Fig. 3a.

between 125 hPa and 175 hPa) shows a decreasing trend, i.e. destabilization.

In the case of the divergence at the top of the troposphere at 200 hPa, we observed a good correlation (r = 0.78) between MCSs with a CTT below −40°C (Fig. 7b). It was noted in T17 that precipitation over the Sahel region is better correlated with the more common MCSs (CTT < −40°C; r = 0.88) than the extremely cold MCSs. Increasing trends at the top of the troposphere are less pronounced than those in the TTL due to the large interannual variability, especially prior to 2000. Peaks in the year-to-year variability of horizontal divergence become more prominent at a lower level. The divergence at 250 hPa correlates well (r = 0.77) with the near-surface zonal wind velocity over the Atlantic Ocean west of Africa (10–15°N, 30–15°W) (Fig. 7c). This is consistent with the analysis in Fig. 3d that the variation of the moisture flux from the ocean produces large year-to-year variability in the upwelling within the troposphere.

Seasonal differences in the spatial structure of temperature and vertical velocity in the West African sector are shown in Fig. 8. West African monsoon evolves during the summer: the landing of the rain belt on the coast occurs in May–June, and the actual Sahelian rain season occurs in July–September. The recent decadal change in the temperature field shows very similar feature throughout the early and late summer with cooling in the stratosphere and warming in the troposphere (Figs. 8a, c), although the active center of the convection shifts northward in mid-summer from the coastal region to over the continent (contours in Figs. 8b, d). This suggests that the change in the temperature in the lower stratosphere does not reflect local convective activity.

Recent decadal changes in the vertical velocity in early summer (May–June) resulted in the suppression of upwelling in the troposphere in association with the

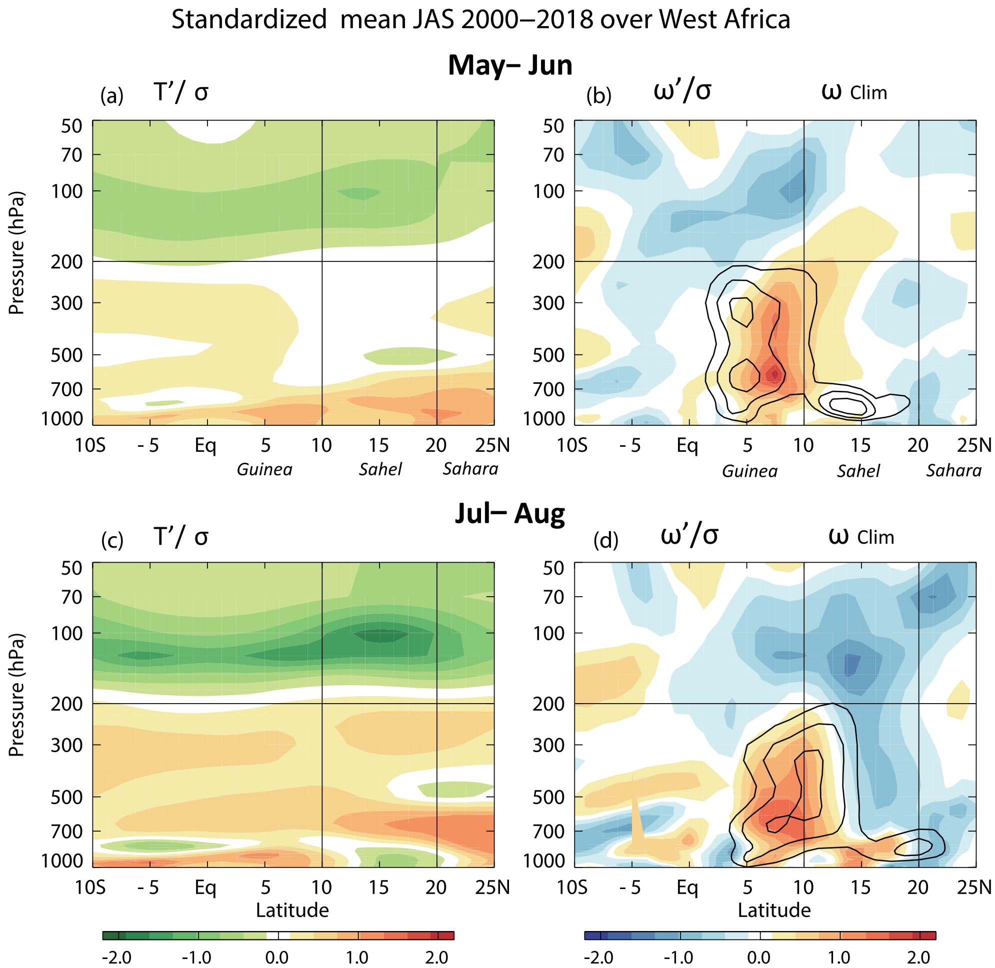

Fig. 8. Meridional cross-sections of standardized seasonal mean anomalies over the West African sector (15°W–20°E) between 2000 and 2018: (Top) May–June and (Bottom) July–August. (a, c) Air temperature, (b, d) pressure vertical velocity. Climatological pressure vertical velocity is shown by contours for −0.01, −0.04, and −0.07 Pa s^{-1} in (c) and (d).

warming there, but upwelling in the TTL enhanced in association with cooling in the TTL and the lower stratosphere. An increasing trend in the upwelling is also evident near the surface around the southern edge of the Sahara Desert, which is associated with a large warming near the surface. The active center of convection shifts northward over land according to the seasonal march in mid-summer (July–August) (Figs. 8c, d). Deep convection in mid-summer becomes deeper and shifts northward in recent decades.

4. Discussion and conclusions

The recent precipitation trends in West Africa during the summer monsoon season differ according to the regional characteristics of convective activity. There is an increasing precipitation trend over the Sahel where extreme deep convection develops, whereas a decreasing precipitation trend is evident over the Guinea Coast where convection is relatively shallow (Figs. 1, 2). These trends support the findings of previous studies (Odoulami and Akinsanola 2018; Biasutti 2019). However, surface precipitation averaged over the entire West African region shows no clear trend (Fig. 1e), suggesting that the change in the total amount of water vapor transported over West Africa may not be essential for the recent decadal changes.

The different precipitation trends observed over the Sahel and Guinea Coast can be interpreted as a result of the differences in the depth of convective clouds in the two regions. Penetrating deep convection over the Sahel is susceptible to temperature changes in the TTL and thus increases in response to TTL cooling. Contrarily, convective activity over the Guinea Coast is not influenced by cooling in the TTL but rather suppressed by warming in the troposphere.

Although an increasing decadal trend in summer precipitation exists over the Sahel, there is also substantial year-to-year variability, which may be driven by the transport of water vapor from the Atlantic Ocean (Fig. 3). Modulation of the upward velocity by this year-to-year variability in precipitation is limited to the troposphere. Contrarily, circulation changes related to the recent decadal trends are observed in the TTL. This suggests that the recent trends in circulation are driven by processes other than those producing the year-to-year variability in the tropospheric circulation.

Variations in the lower stratospheric temperature are similar between the Sahel and Guinea Coast (Fig. 5). However, in the Sahel, upwelling produced by convection is connected to the lower stratospheric circulation, whereas over the Guinea Coast, tropospheric upwelling is decoupled from the stratosphere. In the present analysis, we assumed that the horizontal divergence in the upper troposphere and TTL is related to detrained air around the cloud top in deep convection. This relationship was verified through a comparison of the horizontal divergence with the occurrence frequency of MCSs (Fig. 7).

Panthou et al. (2018) noted that the recent decadal increase in precipitation over the Sahel is by no means a recovery to the former wet period, but rather a shift to more intermittent and extreme rainfall regime. Convective clouds with extremely high tops generally produce extreme precipitation (Zhou et al. 2013; Kim et al. 2018; Klein et al. 2018). Thus, the recent increase in intense precipitation over the Sahel is likely to be related to an increase in the frequency of extreme deep convection. The most notable change in mid-summer is the increased upwelling in the TTL over the Sahel. This enhanced Sahelian upwelling may be connected with that over the Sahara, as discussed in T17, but it could also be caused by the increase in extreme deep convection penetrating to the TTL.

Increases in greenhouse-gas levels have resulted in recent tropospheric warming, but the effects are not limited to the troposphere. The indirect effects generated via the enhanced Brewer–Dobson circulation and resultant ozone decrease have caused the lower tropical stratosphere to cool, which has, in turn, led to a decrease in vertical static stability in the TTL (Lin et al. 2017). The intensification of extreme deep convective activity over the Sahel in July and August in recent decades is associated with cooling in the lower tropical stratosphere and TTL. It has been said that the effect of global warming on precipitation is that "wet gets wetter" (Held and Soden 2006); however, in that analysis, the depth of convection was not considered. What we observe over West Africa is rather that "deep gets deeper".

It is difficult to use statistical methods to demonstrate a causality between two variables exhibiting large trends, such as the vertical temperature gradient and divergence in the TTL ($r = 0.72$) in Fig. 7a. Over intraseasonal timescales, a causal relationship between the tropical stratospheric temperature and deep convection was demonstrated using large ensemble experiments focusing on the September 2009 SSW event (Noguchi et al. 2020). Careful inspection of their Fig. 4b over the African region reveals that precipitation over Sahel increases, while that over the Guinea Coast decreases following a cooling in the TTL, similar to the present study, as shown in Fig. 1b.

This model study supports a physical relationship between the temperature variation in the tropical lower stratosphere and deep convective activity that penetrates the TTL. In this study, we used the vertical velocity and divergence data from the JRA-55 reanalysis. However, vertical velocity is not an observable variable and strongly depends on the model (i.e., the cumulus parameterization) used for the reanalysis. This is especially true in the TTL, where there is little observational data available. The preliminary analysis of the European Centre for Medium-Range Weather Forecasts reanalysis data (ERA5) in Western Africa is shown in the supporting material (Fig. S2). There is good agreement between JRA-55 and ERA5 in terms of air temperature at 100 hPa. Although sufficient agreement in vertical velocity is observed over the Guinea Coast, pressure vertical velocities at 150 hPa disagree over the Sahel: no trend is detected in ERA5. Discrepancies are especially large along a zone in frequent COV. It should be noted that the horizontal divergence of JRA-55 agrees quite well with a number of MCS of TCC < -70°C (Figs. 7a, S1). It should also be noted that the trend in surface precipitation over the Sahel is completely missed in ERA5, whereas that in JRA-55 is exaggerated (Quagraine et al. 2010). This could be due to a problem of a parameterization of the cumulus convection over land in the model used for reanalysis. This is a key aspect for the understanding of the TTL role in driving deep convection in the Sahel and the tropics and should be investigated more in detail in future studies.

Supplements

Figure S1: (a) Time series of JAS mean standardized anomalies for horizontal divergence at 125 hPa (brown lines), occurrence frequency of MCSs with CTT below −70°C (blue lines) same as in Fig. 7a. (b) Same as (a), but for the detrended time series. Correlation coefficients between the two variables are 0.87 for (a) and 0.47 for (b) based on the 35-year data.

Figure S2: Comparison between JRA-55 and ERA5 reanalyses. (a) JAS mean air temperature at 100 hPa over Sahel (10–20°N, 0–20°E) from 1979 to 2020. Red and blue lines are for ERA5 and JRA-55 reanalyses, respectively. (b) Same as in (a), except for pressure vertical velocity at 150 hPa (ω150). (c and d) Same as (a and b) except for over Guinea Coast (0–10°N, 0–20°E). Equatorial temperature variation related with the stratospheric QBO is visible in (c). (e) Difference in spatial structure of seasonal difference in anomalous ω150 from climatology between ERA5 and JRA-55 during recent decades (JAS 2000–2020 mean). Difference is large where extreme deep convection is frequent (c.f. Fig. 2). Climatology is JAS 1981–2010. Images are provided by the NOAA-ESRL Physical Sciences Laboratory, Boulder Colorado from their Web site at https://psl.noaa.gov/.

Acknowledgments

This work was supported in part by Grants-in-Aid for Scientific Research (25340010, 17H01159, JP18K03743) from the Japan Society for the Promotion of Science. Preliminary analysis of this study was carried out using the Interactive Tool for Analysis of the Climate System (ITACS) provided by the Japan Meteorological Agency. AMSU data was accessed through ICARE with support of the IPSL-ESPRI team. CT was supported by UK NERC/DFID African Monsoon Multidisciplinary Analysis-2050 project (Grant NE/M020428/1). RU was supported by NASA Upper Atmospheric Composition Observations Program.

References

Adler, R. F., G. J. Huffman, A. Chang, R. Ferraro, P.-P. Xie, J. Janowiak, B. Rudolf, U. Schneider, S. Curtis, D. Bolvin, A. Gruber, J. Susskind, P. Arkin, and E. Nelkin, 2003: The Version-2 Global Precipitation Climatology Project (GPCP) monthly precipitation analysis (1979–present). *J. Hydrometeor.*, **4**, 1147–1167.

Biasutti, M., 2019: Rainfall trends in the African Sahel: Characteristics, processes, and causes. *WIREs Climate Change*, **10**, e591, doi:10.1002/wcc.591.

Diakhaté, M., B. Rodríguez-Fonseca, I. Gómara, E. Mohino, A. L. Dieng, and A. T. Gaye, 2019: Oceanic forcing on interannual variability of Sahel heavy and moderate daily rainfall. *J. Hydrometeor.*, **20**, 397–410.

Dong, B., and R. Sutton, 2015: Dominant role of greenhouse-gas forcing in the recovery of Sahel rainfall. *Nat. Climate Change*, **5**, 757–760.

Druyan, L. M., and R. D. Koster, 1989: Sources of Sahel precipitation for simulated drought and rainy seasons. *J. Climate*, **2**, 1438–1446.

Eguchi, N., K. Kodera, and T. Nasuno, 2015: A global non-hydrostatic model study of a downward coupling through the tropical tropopause layer during a stratospheric sudden warming. *Atmos. Chem. Phys.*, **15**, 297–304.

Folland, C. K., T. N. Palmer, and D. E. Parker, 1986: Sahel rainfall and worldwide sea temperatures, 1901–85. *Nature*, **320**, 602–607.

Fontaine, B., P. Roucou, M. Gaetani, and R. Marteau, 2011: Recent changes in precipitation, ITCZ convection and northern tropical circulation over North Africa (1979–2007). *Int. J. Climatol.*, **31**, 633–648.

Funatsu, B. M., C. Claud, P. Keckhut, A. Hauchecorne, and T. Leblanc, 2016: Regional and seasonal stratospheric temperature trends in the last decade (2002–2014) from AMSU observations. *J. Geophys. Res.: Atmos.*, **121**, 8172–8185.

Gaetani, M., S. Janicot. M. Vrac, A. M. Famien, and B. Sultan, 2020: Robust assessment of the time of emergence of precipitation change in West Africa. *Sci. Rep.*, **10**, 7670, doi:10.1038/s41598-020-63782-2.

Giannini, A., 2010: Mechanisms of climate change in the semiarid African Sahel: The local view. *J. Climate*, **23**, 743–756.

Giannini, A., S. Salack, T. Lodoun, A. Ali, A. T. Gaye, and O. Ndiaye, 2013: A unifying view of climate change in the Sahel linking intra-seasonal, interannual and longer time scales. *Environ. Res. Lett.*, **8**, 024010, doi:10.1088/1748-9326/8/2/024010.

Hart, N. C. G., R. Washington, and R. I. Maidment, 2019: Deep convection over Africa: Annual cycle, ENSO, and trends in the hotspots. *J. Climate*, **32**, 8791–8811.

Held, I. M., and B. J. Soden, 2006: Robust responses of the hydrological cycle to global warming. *J. Climate*, **19**, 5686–5699.

Holloway, C. E., and J. D. Neelin, 2007: The convective cold top and quasi equilibrium. *J. Atmos. Sci.*, **64**, 1467–1487.

Hong, G., G. Heygster, J. Miao, and K. Kunzi, 2005: Detection of tropical deep convective clouds from AMSU-B water vapor channels measurements. *J. Geophys. Res.*, **110**, D05205, doi:10.1029/2004JD004949.

Janicot, S., S. Trzaska, and I. Poccard, 2001: Summer Sahel-ENSO teleconnection and decadal time scale SST variations. *Climate Dyn.*, **18**, 303–320.

Kim, J., W. J. Randel, and T. Birner, 2018: Convectively driven tropopause-level cooling and its influences on stratospheric moisture. *J. Geophys. Res.: Atmos.*, **123**, 590–606.

Klein, C., and C. M. Taylor, 2020: Dry soils can intensify mesoscale convective systems. *Proc. Natl. Acad. Sci. U.S.A. (PNAS)*, **117**, 21132–21137.

Klein, C., D. Belušić, and C. M. Taylor, 2018: Wavelet scale analysis of mesoscale convective systems for detecting deep convection from infrared imagery. *J. Geophys. Res.: Atmos.*, **123**, 3035–3050.

Klein, C., F. Nkrumah, C. M. Taylor, and E. A. Adefisan, 2020: Seasonality and trends of drivers of mesoscale convective systems in southern West Africa. *J. Climate*, **34**, 71–87.

Kobayashi, S., Y. Ota, Y. Harada, A. Ebita, M. Moriya, H. Onoda, K. Onogi, H. Kamahori, C. Kobayashi, H. Endo, K. Miyaoka, and K. Takahashi, 2015: The JRA-55 reanalysis: General specifications and basic characteristics. *J. Meteor. Soc. Japan*, **93**, 5−48.

Kodera, K., N. Eguchi, R. Ueyama, Y. Kuroda, C. Kobayashi, B. M. Funatsu, and C. Claud, 2019: Implication of tropical lower stratospheric cooling in recent trends in tropical circulation and deep convective activity. *Atmos. Chem. Phys.*, **19**, 2655–2669.

Lin, P., D. Paynter, Y. Ming, and V. Ramaswamy, 2017: Changes of the tropical tropopause layer under global warming. *J. Climate*, **30**, 1245–1258.

Maidment, R. I., R. P. Allan, and E. Black, 2015: Recent observed and simulated changes in precipitation over Africa. *Geophys. Res. Lett.*, **42**, 8155–8164.

Mohino, E., S. Janicot, and J. Bader, 2011: Sahel rainfall and decadal to multi-decadal sea surface temperature variability. *Climate Dyn.*, **37**, 419–440.

Nicholson, S. E., 2013: The West African Sahel: A review of recent studies on the rainfall regime and its interannual variability. *Int. Scholar. Res. Notices*, **2013**, 453521, doi:10.1155/2013/453521.

Noguchi, S., Y. Kuroda, K. Kodera, and S. Watanabe, 2020: Robust enhancement of tropical convective activity by the 2019 Antarctic sudden stratospheric warming. *Geophys. Res. Lett.*, **47**, e2020GL088743, doi:10.1029/2020GL088743.

Odoulami, R. C., and A. A. Akinsanola, 2018: Recent assessment of West African summer monsoon daily rainfall trends. *Weather*, **73**, 283–287.

Panthou, G., T. Vischel, and T. Lebel, 2014: Recent trends in the regime of extreme rainfall in the Central Sahel. *Int. J. Climatol.*, **34**, 3998–4006.

Panthou, G., T. Lebel, T. Vischel, G. Quantin, Y. Sane, A. Ba, O. Ndiaye, A. Diongue-Niang, and M. Diopkane, 2018: Rainfall intensification in tropical semi-arid regions: The Sahelian case. *Environ. Res. Lett.*, **13**, 064013, doi:10.1088/1748-9326/aac334.

Pomposi, C., Y. Kushnir, A. Giannini, and M. Biasutti, 2020: Toward understanding the occurrence of both wet and dry Sahel seasons during El Niño: The modulating role of the global ocean. *J. Climate*, **33**, 1193–207.

Pu, B., and K. H. Cook, 2012: Role of the West African westerly jet in Sahel rainfall variations. *J. Climate*, **25**, 2880–2896.

Quagraine, K. A., F. Nkrumah, C. Klein, N. A. B. Klutse, and K. T. Quagraine, 2020: West African summer monsoon precipitation variability as represented by reanalysis datasets. *Climate*, **8**, 111, doi:10.3390/cli8100111.

Rodríguez-Fonseca, B., S. Janicot, E. Mohino, T. Losada, J. Bader, C. Caminade, F. Chauvin, B. Fontaine, J. García-Serrano, S. Gervois, M. Joly, I. Polo, P. Ruti, P. Roucou, and A. Voldoire, 2011: Interannual and decadal SST-forced responses of the West African monsoon. *Atmos. Sci. Lett.*, **12**, 67–74.

Rodríguez-Fonseca, B., E. Mohino, C. R. Mechoso, C. Caminade, M. Biasutti, M. Gaetani, J. Garcia-Serrano, E. K. Vizy, K. Cook, Y. Xue, I. Polo, T. Losada, L. Druyan, B. Fontaine, J. Bader, F. J. Doblas-Reyes, L. Goddard, S. Janicot, A. Arribas, W. Lau, A. Colman, M. Vellinga, D. P. Rowell, F. Kucharski, and A. Voldoire, 2015: Variability and predictability of West African droughts: A review on the role of sea surface temperature anomalies. *J. Climate*, **28**, 4034–4060.

Rowell, D. P., 2003: The impact of Mediterranean SSTs on the Sahelian rainfall season. *J. Climate*, **16**, 849–862.

Rowell, D. P., 2013: Simulating SST teleconnections to Africa: What is the state of the art? *J. Climate*, **26**, 5397–5418.

Russo, S., A. F. Marchese, J. Sillmann, and G. Immé, 2016: When will unusual heat waves become normal in a warming Africa? *Environ. Res. Lett.*, **11**, 054016, doi:10.1088/1748-9326/11/5/054016.

Sultan, B., and M. Gaetani, 2016: Agriculture in West Africa in the twenty-first century: Climate change and impacts scenarios, and potential for adaptation. *Front. Plant Sci.*, **7**, 1262, doi:10.3389/fpls.2016.01262.

Taylor, C. M., D. Belušić, F. Guichard, D. J. Parker, T. Vischel, O. Bock, P. P. Harris, S. Janicot, C. Klein, and G. Panthou, 2017: Frequency of extreme Sahelian storms tripled since 1982 in satellite observations. *Nature*, **544**, 475–478.

Taylor, C. M., A. H. Fink, C. Klein, D. J. Parker, F. Guichard, P. P. Harris, and K. R. Knapp, 2018: Earlier seasonal onset of intense mesoscale convective systems in the Congo Basin since 1999. *Geophys. Res. Lett.*, **45**, 13458–13467.

Zhou, Y., W. K. M. Lau, and C. Liu, 2013: Rain characteristics and large-scale environments of precipitation objects with extreme rain volumes from TRMM observations. *J. Geophys. Res.: Atmos.*, **118**, 9673–9689.

Zuluaga, M. D., and R. A. Houze, Jr., 2015: Extreme convection of the near-equatorial Americas, Africa, and adjoining oceans as seen by TRMM. *Mon. Wea. Rev.*, **143**, 298–316.