# The impact of tropical tropopause cooling on Sahelian extreme deep convection

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## 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 a 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 show that the changes over West Africa since the 1980s involve a cooling trend in the tropical lower stratosphere and tropopause layer, combined with a 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. The essential feature of the recent changes over West Africa is therefore the depth of convection, rather than the total amount of surface precipitation.

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

## 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 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). This recovery was linked to accelerating global warming, which increased 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 of rainfall has not occurred uniformly over West Africa; for example, rainfall decreased somewhat over the Guinea coastal region (Odoulami and Akinsanola, 2017).

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). Interannual variation of rainfall is also related to the phase of El Niño–Southern Oscillation (ENSO; Janicot et al.,1996; 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) showed 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, while 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). Note 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 will 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, 2011; Giannini et al., 2013).

## 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 the climatology as the 40-year mean for the period 1979–2018 (unless stated otherwise), and the standard deviation was also calculated over this period.

Analysis of the surface precipitation was performed using 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, were identified using the diagnostics developed by Hong et al. (2005). These diagnostics are based on brightness temperature differences measured by three high-frequency channels of the Advanced Microwave Sensing Unit (AMSU) or the Microwave Humidity Sensor (MHS) for the period 2001 to 2018 (Funatsu et al., 2016), and 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 of 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°N–17.5°N; Fig. 1c), but decreased over the Guinea Coast (15°W–20°E, 2.5°N–7.5°N; Fig. 1d), as also reported by Odoulami and Akinsanola (2017). In fact, the surface precipitation does not show a clear trend when averaged over the whole of West Africa (15°W–20°E, 2.5°N–17.5°N; (Fig. 1e).

Fig. 1

In fact, convective activity varies strongly within West Africa during the monsoon season; e.g., broad stratiform clouds occur frequently 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 found 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). Fig. 2

These results suggest that the regional differences in recent precipitation trends (Fig. 1b) may arise from difference in the structure of convection. In particular, precipitation increased where extreme deep convection occurs frequently, 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 will 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 Fig. 3

trend. The red dots and black crosses denote the maxima and minima, respectively, in the interannual variations. The first thing to clarify is whether the decadal trend is produced by the same processes that cause the year-to-year variability. To investigate this, we carried out 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, 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.

Composite differences between 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 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. 3e). The relationship between moisture flux and precipitation over Africa has been investigated. Large differences in environmental conditions are seen 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 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. The decadal changes, however, indicate a weaker connection 1 the moisture flux from the oceanic sector (Fig. 3f). Occurrence of wet and dry years correspond well to years of large and small eastward moisture flux, respectively, driven by zonal wind over the Atlantic Ocean (Fig. 7c). Decadal change of water vapor flux rather shows a meridional seesaw between Sahel and Guinea Coast. Thus, the overall change in Western Africa is small, consistent with the insignificant trend in precipitation averaged over the Western Africa (Fig. 1e). We note that some of the wet years (1988, 1999, 2010) correspond to La Niña years, while some of the dry years (1987, 1997, 2002) correspond to El Niño years. This suggests a 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 increased 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 pressure vertical velocity (ω) differ between the Sahel and the Guinea Coast.

Fig. 4

The evolution of the JAS mean anomalous temperature (T) and pressure vertical velocity over West Africa is illustrated in Fig. 4. The amplitude of vertical velocity is shown relative to the climatological value, $\omega_{clim}$, as $(\omega/\omega_{clim}) \times 100$. Black and red contours indicate ratios greater or 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 four-fold 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.

Fig. 5

The evolution of the temperature and horizontal divergence are shown in Fig. 5a and 5b for the Sahel and Guinea Coast separately. The vertical velocity in both regions is shown in Fig. 5c and 5d. Cooling trends in the lower stratosphere and TTL are found in both regions. The divergence field indicates that convection over the Sahel reaches the TTL. It should be noted that a 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). In contrast, because convection over the Guinea Coast is not very deep, downwelling persists in the upper troposphere between 200-150 hPa. This indicates a clear separation between the upwelling in the stratosphere and troposphere. Accordingly, although cooling and upwelling trends are found in both the lower stratosphere and TTL, tropospheric vertical velocity does not show an increasing trend over the Guinea Coast.

Latitudinal differences between the two regions can clearly be seen in the meridional cross-section of 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 regions of both increasing and decreasing convection suggests that lower stratospheric temperatures are driving the changes in convection and not a simple response to convective activity (Holloway and Neelin 2007). This leads to a working hypothesis that the cooling in the TTL impacts mainly those regions where upwelling extends from the upper troposphere to the TTL (*i.e.*, about 200 to 140 hPa), as indicated by the climatological divergence field (dotted lines).

Fig. 6

Figures 6b and 6c show the evolution of standardized COV frequencies during the period 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 will be shown in Fig.

7. In contrast, 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. Note 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. Correlation coefficient between 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 the 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 between 125 and 175 hPa) shows a decreasing trend, i.e. destabilization.

Fig. 7

In the case of the divergence at the top of the troposphere at 200 hPa, we found a good correlation ($\boldsymbol{r}$ = 0.78) between MCSs with a CTT below −40°C (Fig. 7b). It was noted in T17 that precipitation over the Sahel 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 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°N–15°N, 30°W–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 temperature field shows very similar feature throughout the early and late summer with cooling in the stratosphere and warming in the troposphere (Figs. 8a and 8c), although the active center of the convection shifts northward in mid-summer from coastal region to over the continent (contours in Figs. 8b and 8d). This suggests that the change in the temperature in the lower stratosphere does not reflect local convective activity.

Fig. 8

Recent decadal changes in the vertical velocity in early summer (May–June) resulted in a suppression of upwelling in the troposphere in association with the warming there, but upwelling in the TTL enhanced in association with a cooling in the TTL and lower stratosphere. An increasing trend in the upwelling is also evident near the surface around the southern edge of the Sahara Desert, and this 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) (Fig. 8c and 8d). Deep convection in mid-summer becomes deeper and shifts northward in recent decades.

## 4. **Discussion and Conclusions**

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 and 2). These trends support the findings of previous studies (Odoulami and Akinsanola, 2017; Biasutti, 2019). However, surface precipitation averaged over the entire West African region shows no clear trend (Fig. 1e), which suggests 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 seen 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. In contrast, 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. In contrast, 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 regions (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 the 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 that focused 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 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 made use of the vertical velocity and divergence data from the JRA-55 reanalysis. However, vertical velocity is not an observable variable and depends strongly on the model (i.e., the cumulus parametrization) used for the reanalysis. This is especially true in the TTL, where there is little observational data available. Preliminary analysis of the European Centre for Medium-Range Weather Forecasts reanalysis data (ERA 5) in Western Africa is shown in supporting material (Fig. S2). There is good agreement between JRA-55 and ERA5 for air temperature at 100 hPa. Although sufficient agreement in vertical velocity is found over Guinea Coast, pressure vertical velocities at 150 hPa disagree over Sahel: no trend is detected in ERA5. Discrepancies are especially large along a zone in frequent COV. It should be noted that horizontal divergence of JRA-55 agrees quite well with a number of

MCS of TCC< −70° (Figs. 7a and S1). It should also be noted that the trend in surface precipitation over the Sahel is completely missed in ERA5, while that in JARA-55 is exaggerated (Quagraine et al., 2010). This could be due to a problem of a parametrization 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 detailed in future studies.

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## References

Adler, R.F., G.J. Huffman, A. Chang, R. Ferraro, P. Xie, J.E. Janowiak, B. Rudolf, U. Schneider, S. Curtis, D.T. Bolvin, A. Gruber, J. Susskind, P.A. Arkin, and E.J. 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** (4), DOI: 10.1002/wcc.591.

Diakhaté, M., B. Rodríguez-Fonseca, I. Gómara, E. Mohino, A. L. Dieng, and A. T. Gaye, A., 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. Nature Climate Change, **5**, 757–760. doi: 10.1038/nclimate2664

Druyan, L.M., and R.D. Koster, 1989: Sources of Sahel precipitation for simulated drought and rainy seasons, *J. Clim.*, **2**, 1438 – 1446, doi:10.1175/1520-0442(1989)002<1438:SOSPFS>2.0.CO;2.

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., Y.N. Palmer, and D.E. Parker, 1986: Sahel rainfall and worldwide sea temperatures 1901–85. *Nature*, **320**, 602–607. doi:10.1038/320602a0.

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, doi:10.1002/joc.2108.

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, https://doi.org/10.1002/2015JD024305.

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. https://doi.org/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, https://doi.org/10.1175/2009JCLI3123.1.

Giannini, A., S. Salack, T. Lodoun, A. Ali, A. 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. Clim.*, **32**, 8791–8811.

Held, I. M., and B.J. Soden, 2006: Robust responses of the hydrological cycle to global warming. *J. Clim.*, **19**, 5686–5699, https://doi.org/10.1175/JCLI3990.1

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, https://doi.org/10.1029/2004JD004949.

Janicot, S., S. Trzaska, and I. Poccard, 2001: Summer Sahel-ENSO teleconnection and decadal time scale SST variations. *Clim. Dyn.*,**18**, 303–320, doi:10.1007/s003820100172.

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, https://doi.org/10.1002/2017JD027080.

Klein, C., D. Belušić, D., 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. https:// doi.org/10.1002/2017JD027432.

Klein, C. and C. M. Taylor, 2020: Dry soils can intensify mesoscale convective systems. Proc. Natl. Acad. Sci., **117** (35), 21132–21137.

Klein, C., F. Nkrumah, C. M. Taylor and E. A. Adefisan, 2020: The seasonality of drivers of storm trends in southern West Africa. J. Clim., doi 10.1175/JCLI-D-20-0194.1, in press

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. Meteorol. Soc. Japan*, **93**, 5−48, doi:10.2151/jmsj.2015-001.

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, doi:10.5194/acp-19-2655-2019.

Lin, P., D. Paynter, Y Ming, and V. Ramaswamy, 2017: Changes of the tropical tropopause layer under global warming. *J. Clim.*, **30**, 1245–1258, https://doi.org/10.1175/JCLI-D-16-0457.1.

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, doi:10.1002/2015GL065765.

Mohino, E., S. Janicot, and J. Bader, 2011: Sahel rainfall and decadal to multi-decadal sea surface temperature variability. *Climate Dyn*., **37**, 419–440, doi:10.1007/s00382-010-0867-2.

Nicholson S.E., 2013: The West African Sahel: a review of recent studies on the rainfall regime and its interannual variability. *ISRN Meteorol.*, **2013**, 1–32, doi: 10.1155/2013/453521.

Noguchi, S., y. Kuroda, Y., K. Kodera, K., 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 RC, and A.A. Akinsanola, 2017: Recent assessment of West African summer monsoon daily rainfall trends. *Weather*. https://doi.org/10.1002/wea.2965.

Panthou, G., T. Vischel, and T. Lebel, 2014: Recent trends in the regime of extreme rainfall in the Central Sahel. *Int. J. Climatol*., doi:10.1002/joc.3984.

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.

Pu, B., and K. H. Cook, 2011: Role of the West African westerly jet in Sahel rainfall variations, *J. Clim.*, **25**, 2880–2896, doi:10.1175/JCLI-D-11-00394.1.

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, doi:10.1002/asl.308.

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, Y. 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. Clim.*, **28**(10), 4034–4060, https://doi.org/10.1175/JCLI-D-14-00130.1

Rowell, D.P., 2003: The impact of Mediterranean SSTs on the Sahelian rainfall Season, *J. Clim*., **16**, 849-862.

Rowell, D.P., 2013: Simulating SST teleconnections to Africa: what is the state of the art? *J. Clim.*, **26**:5397–5418. doi:10.1175/JCLI-D-12-00761.1.

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, https://doi.org/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**, 1–20.

Taylor CM, 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**(7651): 475–478. doi: /10.1038/nature22069.

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**(24): 13,458-413,467.

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, doi:10.1002/jgrd.50776

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, doi:10.1175/MWR-D-14-00109.1.

List of Figures

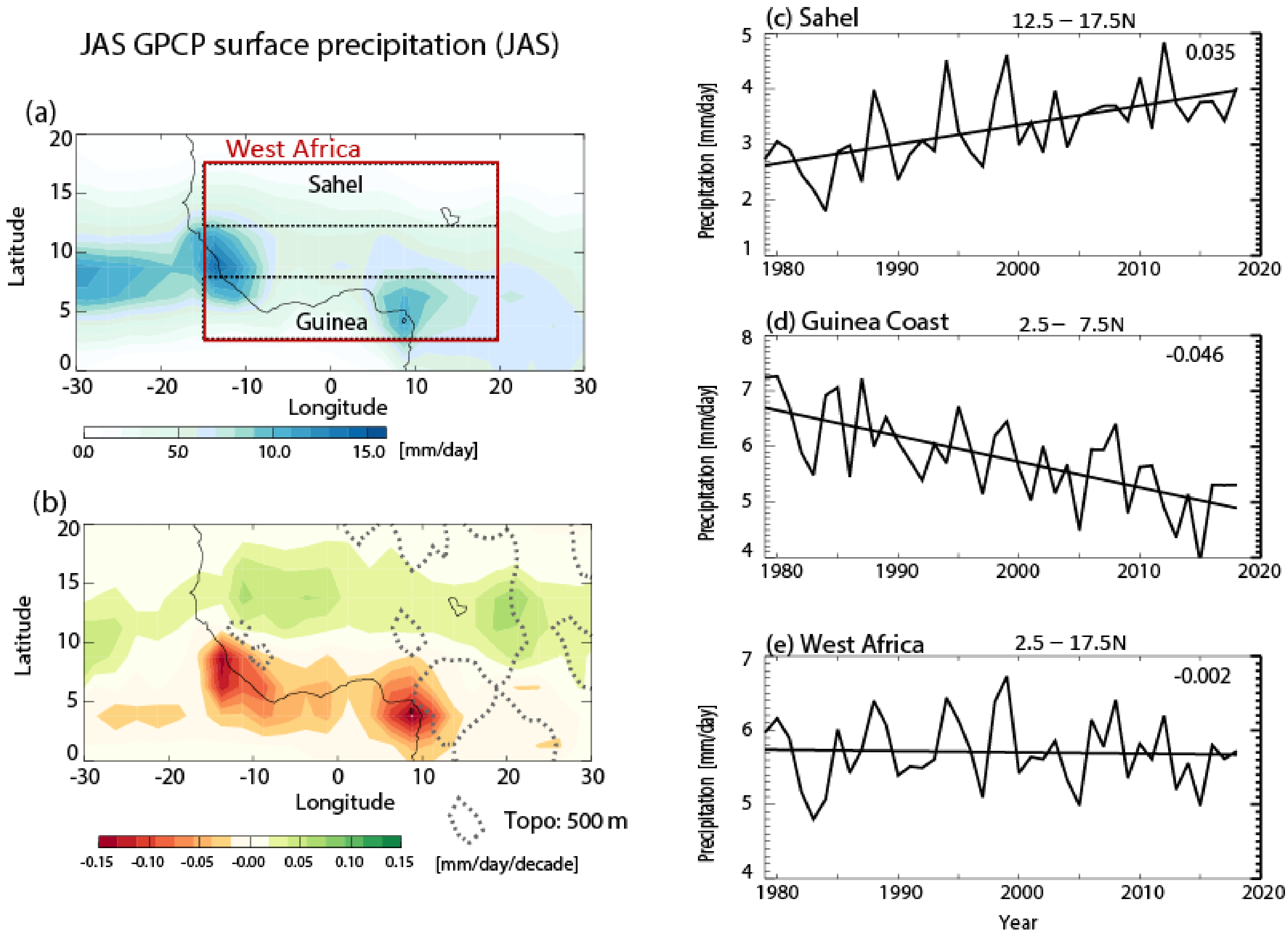


Fig. 1 (a) Climatological mean surface precipitation over West Africa during JAS and (b) its linear trend over the period 1979–2018. (c, d, and e) Time series of JAS mean precipitation averaged over (c) the Sahel, (d) the Guinea Coast, and (e) West Africa. Straight lines and numbers indicate linear trend (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.

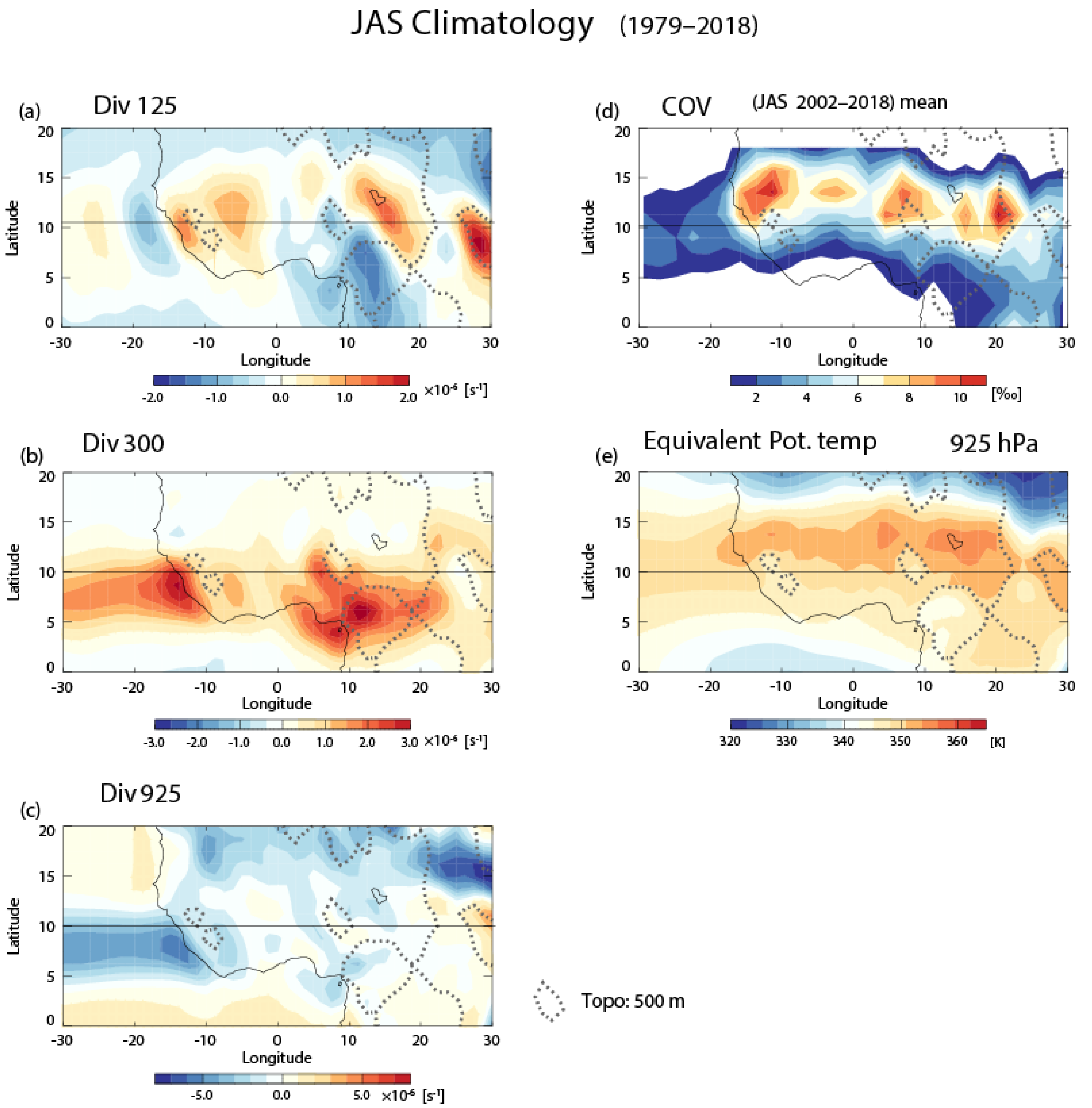


Fig. 2 Climatology for JAS. Horizontal divergence at (a) 125, (b) 300, and (c) 925 hPa. (d) Frequency of convective overshooting. (e) Equivalent potential temperature at 925 hPa. Contours with dotted lines indicate topography of 500 m.

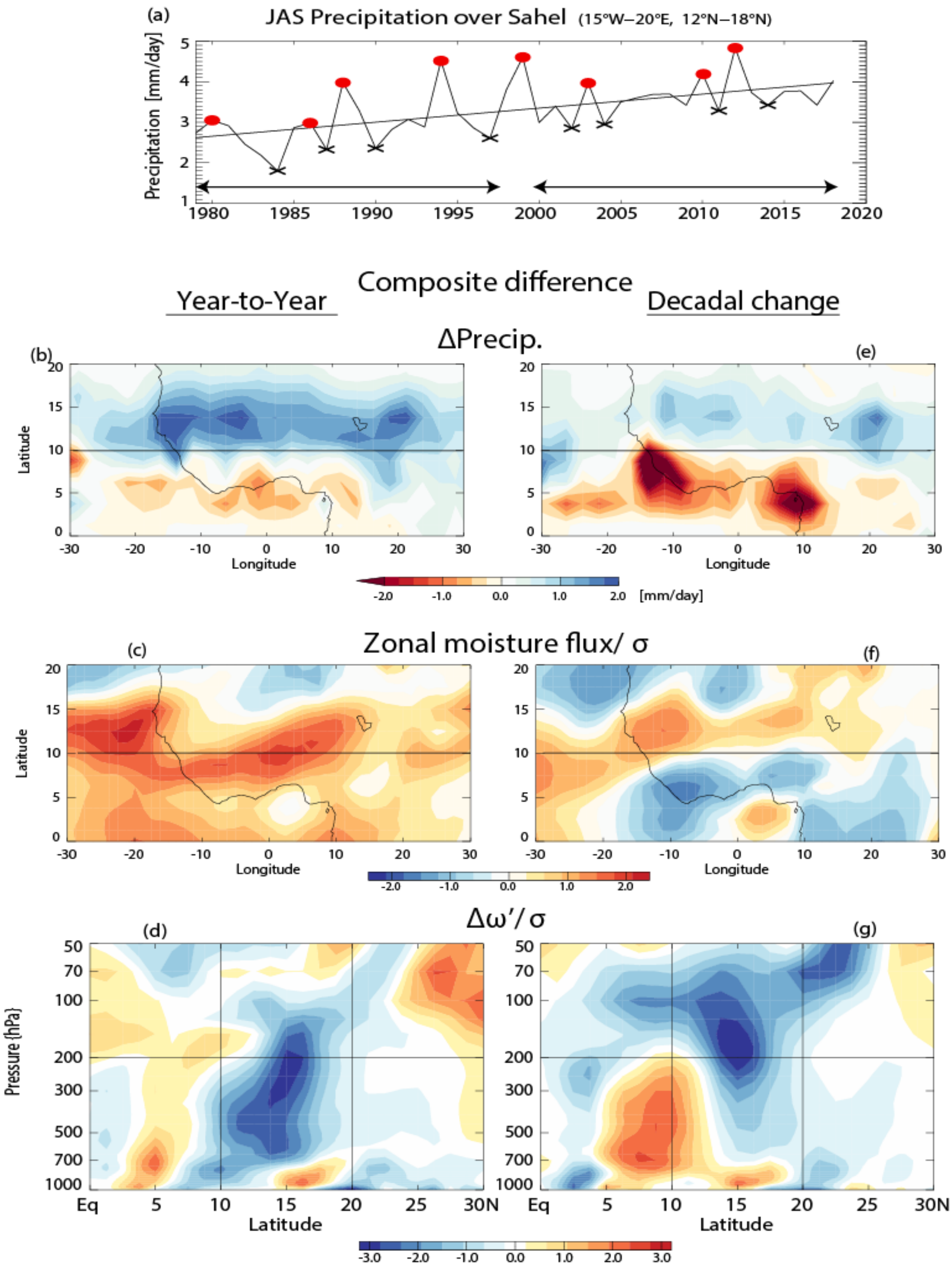


Fig. 3 (a) Time series of JAS mean surface precipitation over the Sahel from GPCP. Red dots and black crosses indicate wet and dry summers, respectively. (b–d) Composite mean differences between wet and dry summers: (b) surface precipitation, (c) standardized anomalous zonal moisture flux at 850 hPa, 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).

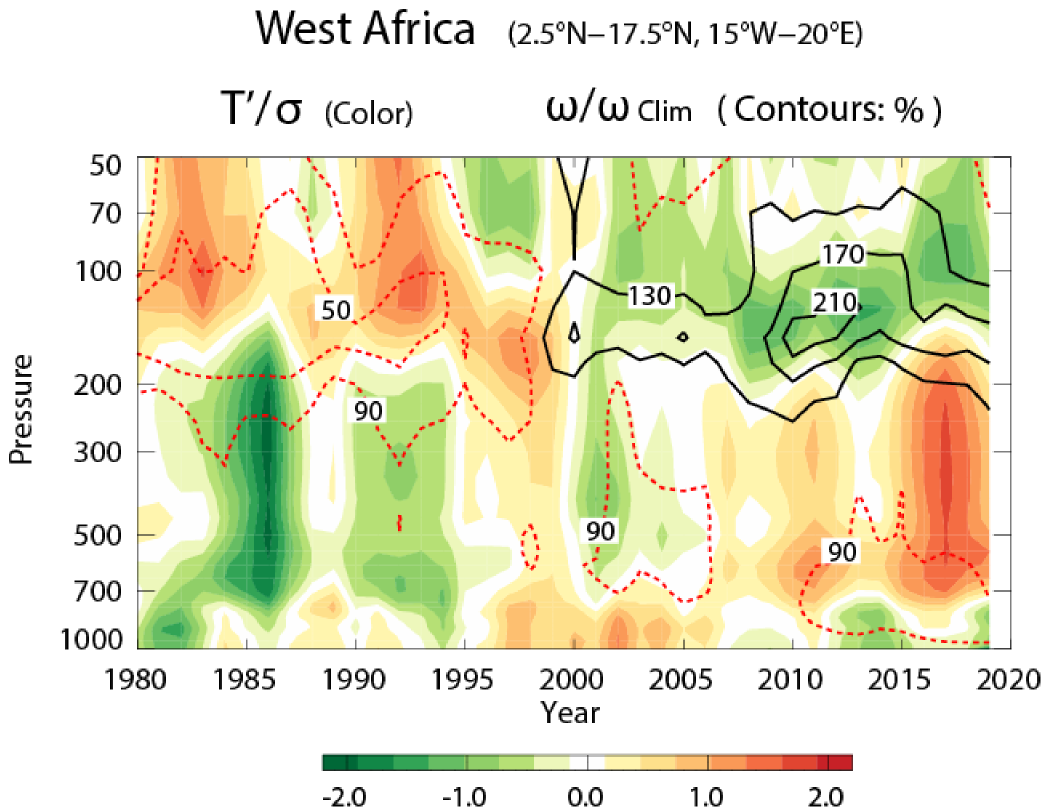


Fig. 4 Height–time cross-section over West Africa of JAS mean standardized anomalous temperature (color shading) and amplitude (%) of pressure vertical velocity relative to its climatological value (contours: 100% > by black lines, and < 100% by red dashed lines). A 3-year running mean has been applied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

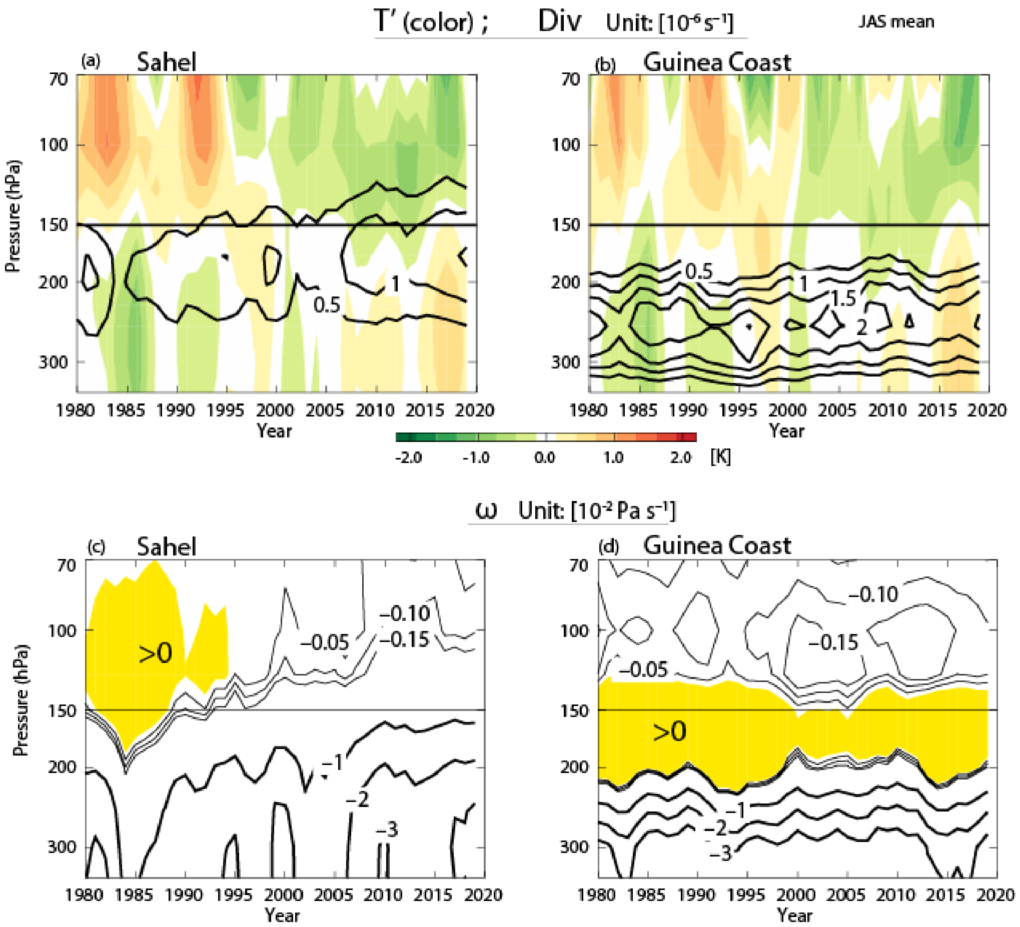


Fig. 5 JAS mean (a, b) horizontal divergence (contours) and anomalous temperature (color shading) and (c, d) pressure vertical velocity (ω) (contours). Yellow shading indicates the region of downward velocity. Left- and right-hand panels are for the Sahel (12.5°−17.5°N ) and Guinea Coast (2.5°−7.5°N),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

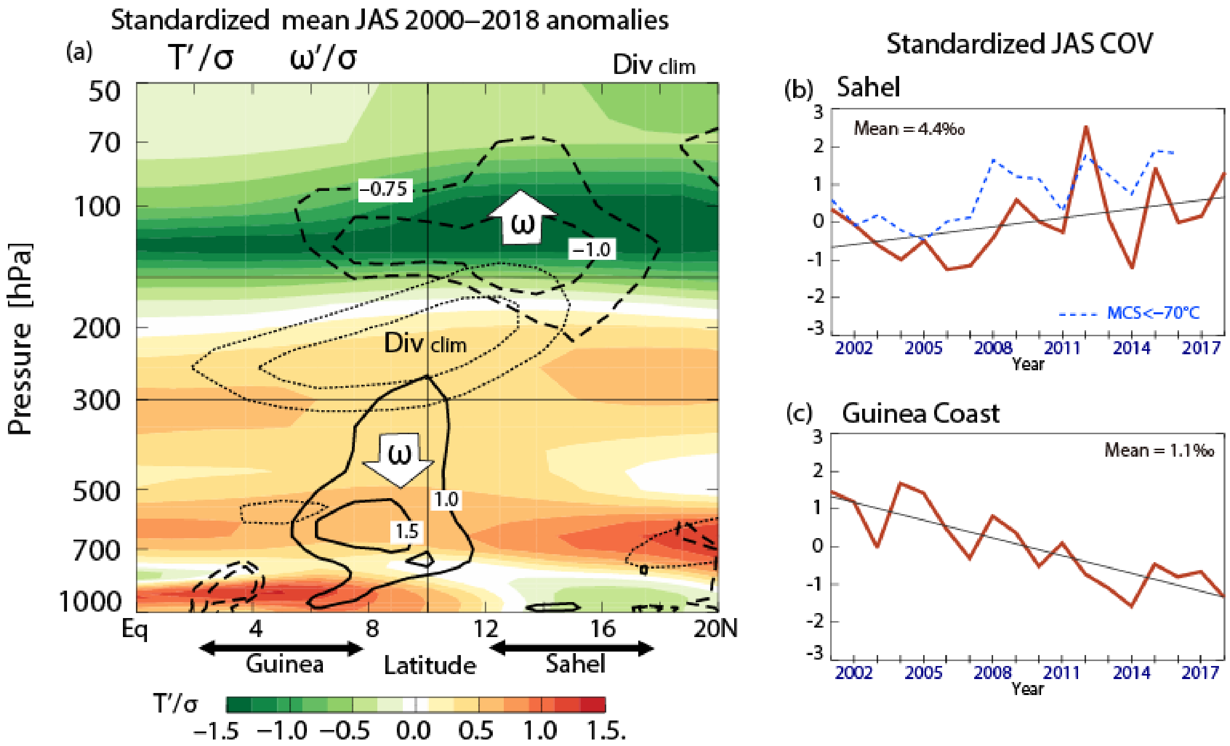


Fig. 6 (a) Meridional cross-section of standardized mean JAS 2000–2018 anomalies over the West African sector (15°W–20°E). Temperature is shown by color shading, and pressure vertical velocity are shown by contour lines (positive by solid lines, and negative by dashed lines). Climatology of the horizontal divergence is shown by dotted lines. Contours are for 1, and 2 $\times 10^{-6}$ $s^{-1}$. (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).

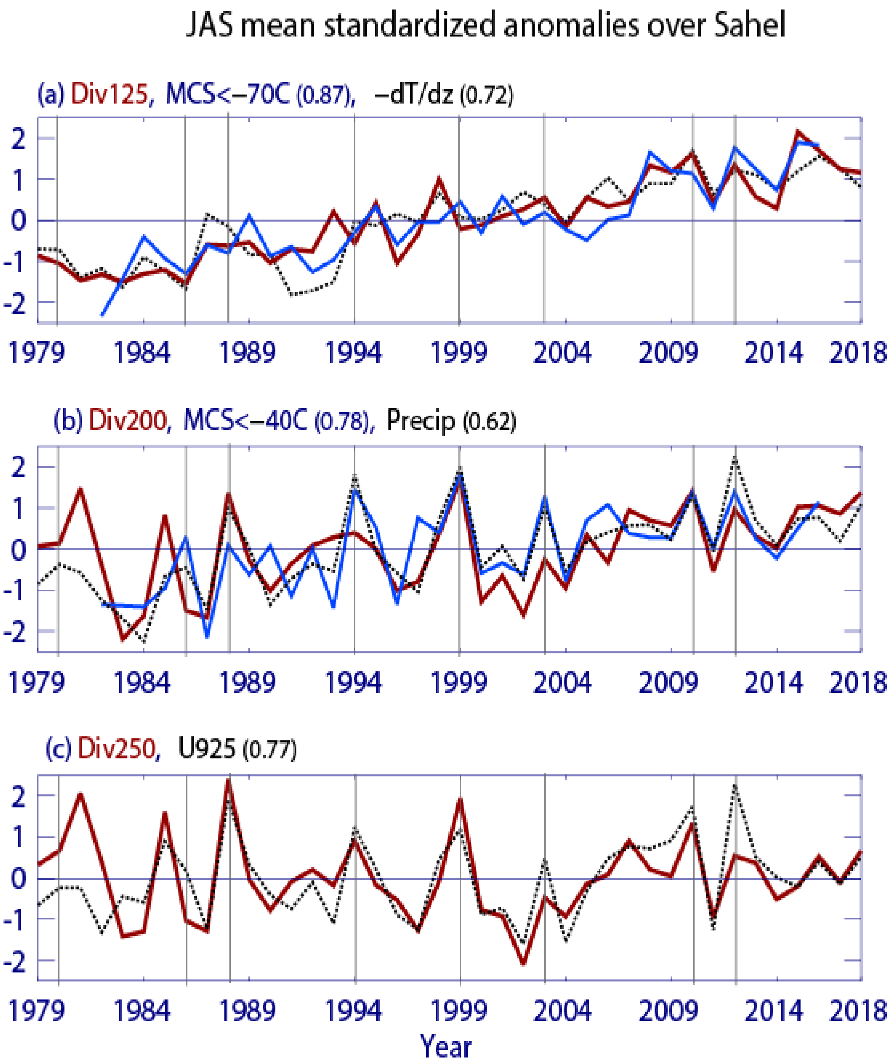


Fig. 7 Time series of JAS mean standardized anomalies. (a) Horizontal divergence at 125 hPa (brown lines), occurrence frequency of MCSs with a CTT below −70°C (blue lines), and anomalous temperature differences between 125 and 175 hPa (black dotted lines). (b) Horizontal divergence at 200 hPa (brown 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°N–15°N, 30°W–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.

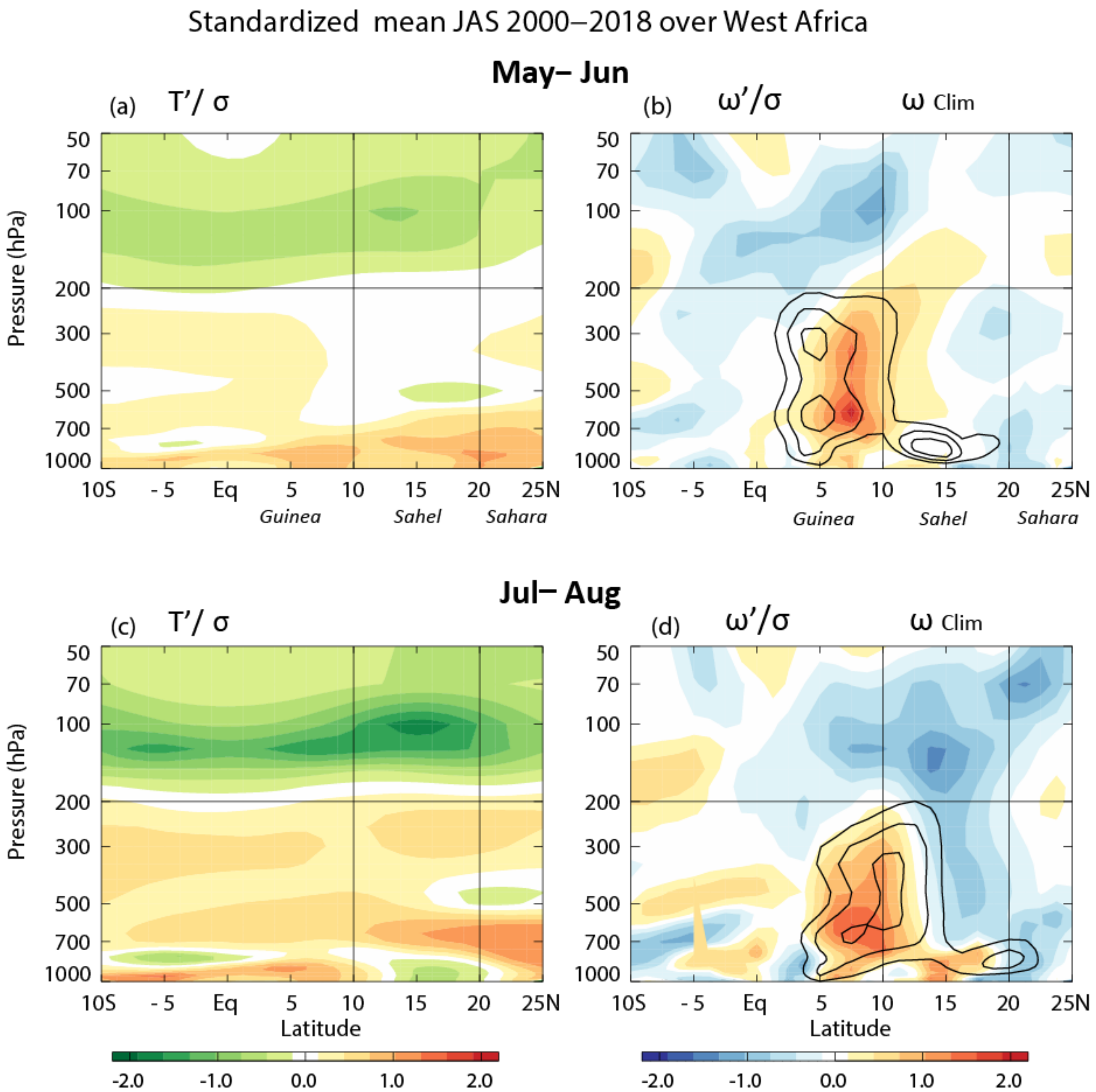


Fig. 8 Meridional cross-sections of standardized seasonal mean anomalies over the West African sector (15°W–20°E) between 2000 and 2018: (Top) May–June and (Bottom) July–August. (a, c) Air temperature, (b, d) pressure vertical velocity. Climatological pressure vertical velocity is shown by contours for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

## Supporting Figures

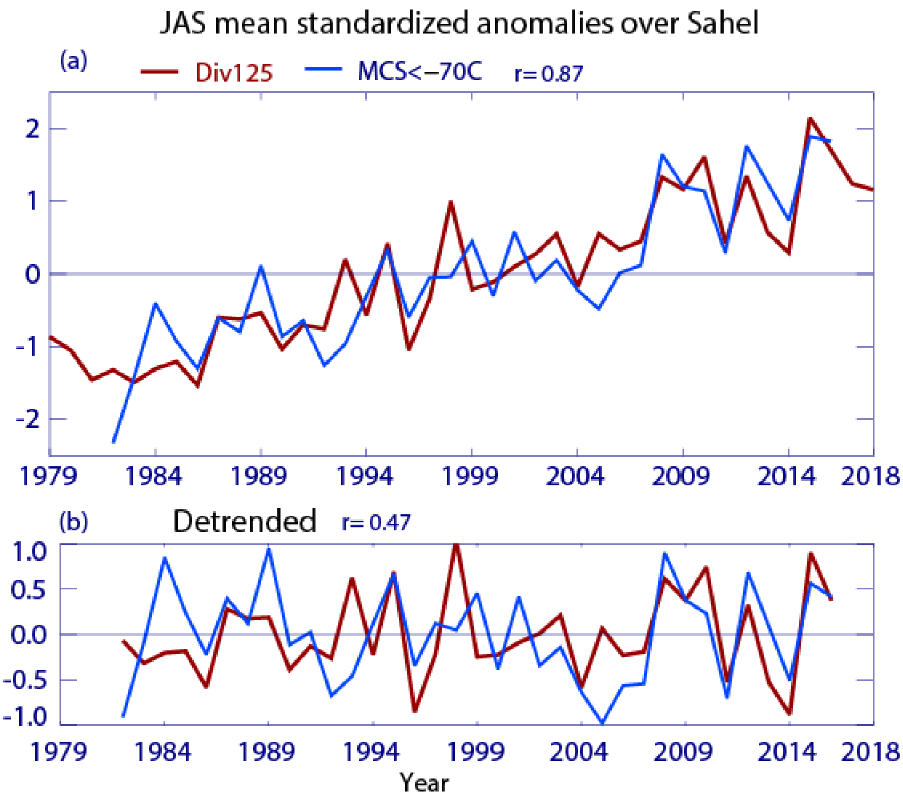


Fig. S1 (a) Time series of JAS mean standardized anomalies for horizontal divergence at 125 hPa (brown lines), occurrence frequency of MCSs with CTT below −70°C (blue lines) same as in Fig. 7a. (b) Same as (a), but for the detrended time series. Correlation coefficients between the two variables are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

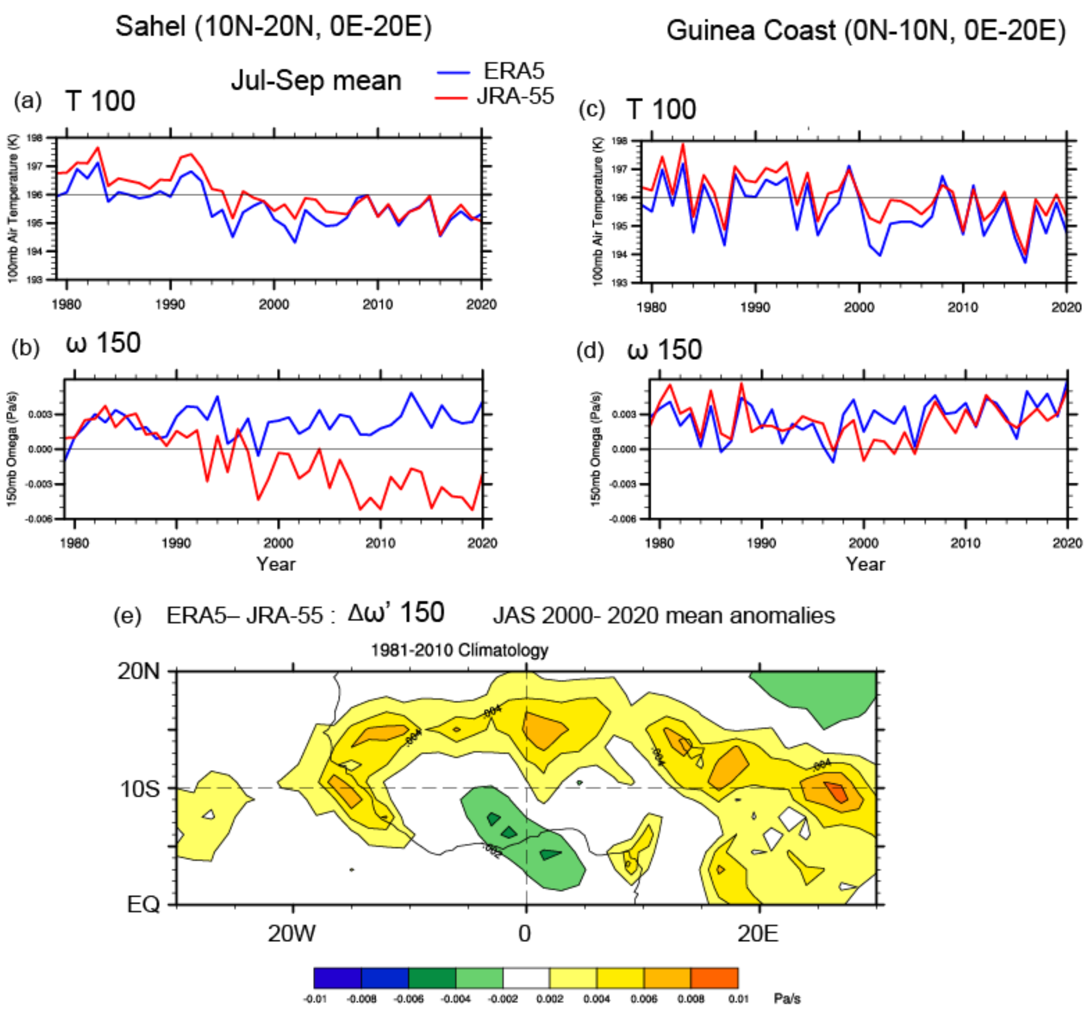


Fig. S2 Comparison between JRA-55 and ERA5 reanalyses. (a) JAS mean air temperature at 100 hPa over Sahel (10°N−20°N, 0°E−20°E) from 1979 to 2020. Red and blue lines are for ERA5 and JRA-55 reanalyses, respectively. (b) Same as in (a), except for pressure vertical velocity at150 hPa (ω150). (c and d) Same as (a and b) except for over Guinea Coast (0°N−10°N, 0°E−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/.