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RESEARCH ARTICLE

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Effects of vertical wind shear on intensities of mesoscale convective systems over West and Central Africa

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Abstract

Vertical wind shear is known to play a key role in the organization and intensity of mesoscale convective systems (MCSs) in West and Central Africa. A decadal increase in vertical wind shear has recently been linked to a decadal increase in intense MCSs over the Sahel. Here, the effects of vertical wind shear on MCSs over West and Central Africa have been investigated using a 10-year (1998–2007) MCS dataset. Strong vertical shear is associated with long-lived, moderate speed, moderate size and cold (deep) storms with high rain rates. The observed cloud top heights of storms over the oceans are closer to their level of neutral buoyancies (LNBs) compared to their land counterparts on the same latitudes. We hypothesize that this is due to greater entrainment dilution over land compared to storms over the ocean. Vertical shear allows storm anvils to reach higher altitudes relative to their LNB, this is consistent with the colder top storms over the Sahel (a region with a high vertical shear) compared to the Congo, despite a higher LNB in the Congo. It is not possible to diagnose the exact mechanisms for this impact of vertical shear from the data, but it is consistent with recent work showing that shear reduces entrainment dilution of squall-line updrafts. We conclude that modelling impacts of vertical shear, which are normally missed in convection parameterizations, are not only important for predictions of high impact weather, but also for modelling the mean distribution of storm heights across Africa.

KEYWORDS

brightness temperature, cloud top height, mesoscale convective system, vertical wind shear, West Africa

1 | INTRODUCTION

Mesoscale convective systems (MCSs) and their associated precipitation, wind and lightning are one of the most devastating high-impact weather systems in West

Abbreviations: AEJ, African Easterly Jet; BTavg, average brightness temperature; LNB, level of neutral buoyancy; MCS, mesoscale convective system.

and Central Africa. MCSs (particularly squall lines) contribute to about 90% of the rainfall in the West African Sahel (Laurent et al., 1998; Maranan et al., 2018; Nicholson, 2013) and about 56% in Southern West Africa (SWA) (Maranan et al., 2018). In Central Africa, they provide much of the annual rainfall in March–April–May (MAM) and September–October–November (SON) (Jackson et al., 2009). MCSs range from tens to hundreds of kilometres (Houze Jr, 2018). MCSs are not explicitly resolved in global weather and climate models and the convection parameterizations commonly used struggle to represent the different stages of MCS lifecycles (Dai et al., 1999; Guichard et al., 2004). An improved understanding of the dynamics of MCSs is important to represent them more accurately in numerical weather prediction models and to inform forecasting.

Studies have shown that vertical wind shear plays a key role in the intensification of MCSs (Klein et al., 2020; Richardson, 1999; Taylor et al., 2017, 2018; Weisman & Rotunno, 2004). However, the exact mechanism through which vertical wind shear affects an MCS has not been thoroughly understood. Rotunno et al. (1988) described the role played by vertical wind shear on the lifetime and self organization of storms. According to Rotunno et al. (1988), an intense MCS results when the horizontal vorticity generated by the cold pools from an MCS is balanced by the vorticity generated by the environmental low-level vertical wind shear, with many studies (e.g. Bryan et al., 2006) now using and testing this theory. Alfaro and Khairoutdinov (2015) and Alfaro (2017) provide an alternative explanation for the role of vertical wind shear. They developed the "Layer Lifting Model of Convection" (LLMC) which places importance on the thermodynamic role of vertical wind shear on moist convection and describes how low-level vertical shear modulates the inflow of convectively unstable air and water vapour, determining latent heating. Recently Peters et al. (2019) and Mulholland et al. (2021) have shown how in idealized numerical model simulations vertical shear decreases entrainment dilution of updraft cores in supercells and squall lines respectively.

Over West Africa, the conditions necessary for intense MCSs may be created by a strong meridional temperature gradient between the hot Sahara and the cooler more humid Gulf of Guinea. Warming in the Sahara intensifies the Saharan heat low and increases the meridional temperature gradient (Nicholson, 2013) which results in a stronger African easterly jet (AEJ). The intense Saharan heat low also causes a stronger monsoon flow (Lavaysse et al., 2009), creating a stronger 600–925 hPa wind shear which, along with a high convective available potential energy (CAPE) and high convective inhibition (CIN) environment, favours intense MCSs (Klein et al., 2020; Taylor et al., 2017).

Using a 35-year brightness temperature dataset from satellites Taylor et al. (2017) found an increase in extreme storms in recent years due to an increase in low-level vertical shear. A similar work over the Congo basin showed a remarkable increase in intense MCS frequency in early spring, again due to an increased meridional temperature gradient and low-level vertical wind shear (Taylor et al., 2018). Klein et al. (2020) repeated this study over Southern West Africa by combining 34 years of cloud top temperatures with rainfall and reanalysis data. They found that although both low-level vertical shear and humidity were important for MCS intensification, low-level vertical shear played a dominant role.

The role of vertical shear in trends in intense Sahel storms has since been investigated in modelling studies. For idealized simulations of Sahelian squall lines, Bickle et al. (2021) found that increased trends in vertical shear are expected to have intensified storms, as proposed by Taylor et al. (2017), but in their runs uncertain thermodynamic changes dominated the effects of vertical shear. In contrast, studies using a convection permitting climate model with a 4.4-km grid-spacing showed no correlation between present day vertical shear and precipitation rates although the study showed a relationship between shear and outgoing longwave radiation which is a proxy for cloud top temperatures (Fitzpatrick et al., 2020; Senior et al., 2021). These findings raise the question of how best to use such state-of-the-art models for projections of changes in extremes. A better understanding of the processes from observations is therefore needed to constrain climate models. Improving our understanding of the effect of vertical shear on the dynamics of MCSs in the different sub-regions of West Africa is key to addressing the challenges associated with MCS prediction across time-scales.

We focus on mature West African MCSs and investigate the effect of vertical shear on cloud-top temperatures and rainfall rates of observed MCSs under different environmental conditions in the different West African sub-regions. We address whether vertical shear affects observed cloud top heights by investigating the effect of vertical shear on the difference between the cloud top heights and level of neutral bouyancies (LNBs) from reanalysis. The relationships between low-level vertical wind shear, MCS speed and lifetimes are also investigated. Section 2 provides a description of the study regions and the different datasets used in this study. The effect of vertical wind shear on MCSs is addressed in Section 3. The main results are summarized and concluded in Section 4.

2 | STUDY AREA AND DATA SOURCE

2.1 | Study area and MCS dataset

The study area is divided into six sub-regions: Sahel, SWA, Coast, the North Atlantic ("N. Atlantic"), the Gulf of Guinea ("Gulf") and the Congo area (Figure 1). This demarcation was necessary due to the spatial variability of the climate of the region from south to north (Nicholson et al., 2018). A 10-year MCSs dataset (1998–2007) of MCS tracks was generated from Cloud Archive User Service (CLAUS) brightness temperatures using the algorithm introduced by Huang et al. (2018). The Huang et al. (2018) tracking algorithm combines the traditional area overlap method with Kalman filter enabling small and fast moving MCSs to be tracked. An area threshold of 5000 km^2 and a brightness temperature threshold of 233 K were used. The effect of vertical wind shear on West African MCSs is investigated by studying the relationship between shear and the brightness temperature, associated CAPE, CIN and temperature at the LNB of mature MCSs, defined here as the point in the lifetime of an MCS where its brightness temperature is coldest. Mature MCSs typically occur between 15–18 UTC for most land storms and 06–09 UTC for most oceanic storms (not shown). The MCS properties used here were selected or calculated at the centre of each storm defined as the centroid (weighted centre) and not the geometric centre of the each storm. The CAPE and CIN were calculated from ERA-interim profiles based on the formula adopted from Wallace and Hobbs (1977). The rain-rates and (thermo)-dynamic environments of each MCS were selected from TRMM 3B42 and ERA-Interim, respectively, at the time of the occurrence of the matured storm.

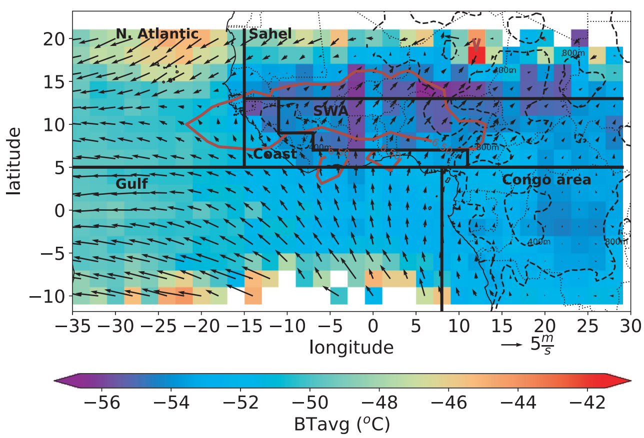

FIGURE 1 Mean brightness temperatures (BTavg, °C) associated with MCSs (1998–2007) are shown in shading. The average 925-hPa horizontal wind (m·s^{-1}, arrows) and the 600-hPa wind speed greater than 6.5 m·s^{-1} (burgundy contours) are overlaid. The black boxes indicate the sub-regions used: Gulf, N. Atlantic, Congo area, Sahel, SWA and Coast. The elevations greater than 400 m above sea level are displayed as dashed contours

2.2 | Precipitation and reanalysis datasets

The TRMM 3B42 version 7 precipitation product is used as the main rainfall data in this study. This precipitation data was used because in situ measurements are sparse over the region. The TRMM 3B42 estimates precipitation at 0.25° × 0.25° spatial resolution and at a 3-h interval. This product combines inputs from microwave and infrared sensors on board a variety of low Earth orbit satellites (Chen et al., 2013; Huffman et al., 2007). Studies with TRMM 3B42 have shown an improved representation of rainfall distribution (Michot et al., 2018; Zulkafli et al., 2014) compared to the previous TRMM versions although the product is still generally more accurate over the oceans than over land (Chen et al., 2013; Ebert et al., 2007; Kubota et al., 2009). Studies over West Africa have shown a good agreement with rain gauge data (Dembélé & Zwart, 2016; Nicholson et al., 2003).

ERA-Interim reanalysis data is used for the investigation of the (thermo-)dynamic environments of the MCSs studied. The dataset consist of a large range of 3-h surface parameters and 6-h upper air parameters available from 1989 to 2018 (Dee et al., 2011). The spatial resolution of the datasets is 0.7° × 0.7°. A detailed description of the ERA-Interim product archive is provided by Berrisford et al. (2009). In this study, we use ERA-Interim upper air data and TRMM 3B42 version 7 for the period 1998–2007. Vertical wind shear was calculated by computing the vector difference between the wind at 925 and 600 hPa. Although ERA-Interim undoubtedly has errors, given the scarcity of data in this region, it is expected to capture the main synoptic features that affect shear and mid-level humidity (Agustí-Panareda et al., 2010; Taylor et al., 2017). In addition, Klein and Taylor (2020) showed that ERA5 produces realistic pre-storm environment which includes the locations of vertical wind shear and specific humidity maxima. Though the current work uses ERA-Interim, the association of a strong vertical wind shear with coldest brightness temperatures found and discussed in the next section provides a strong support for the use of ERA-Interim reanalysis data in our study.

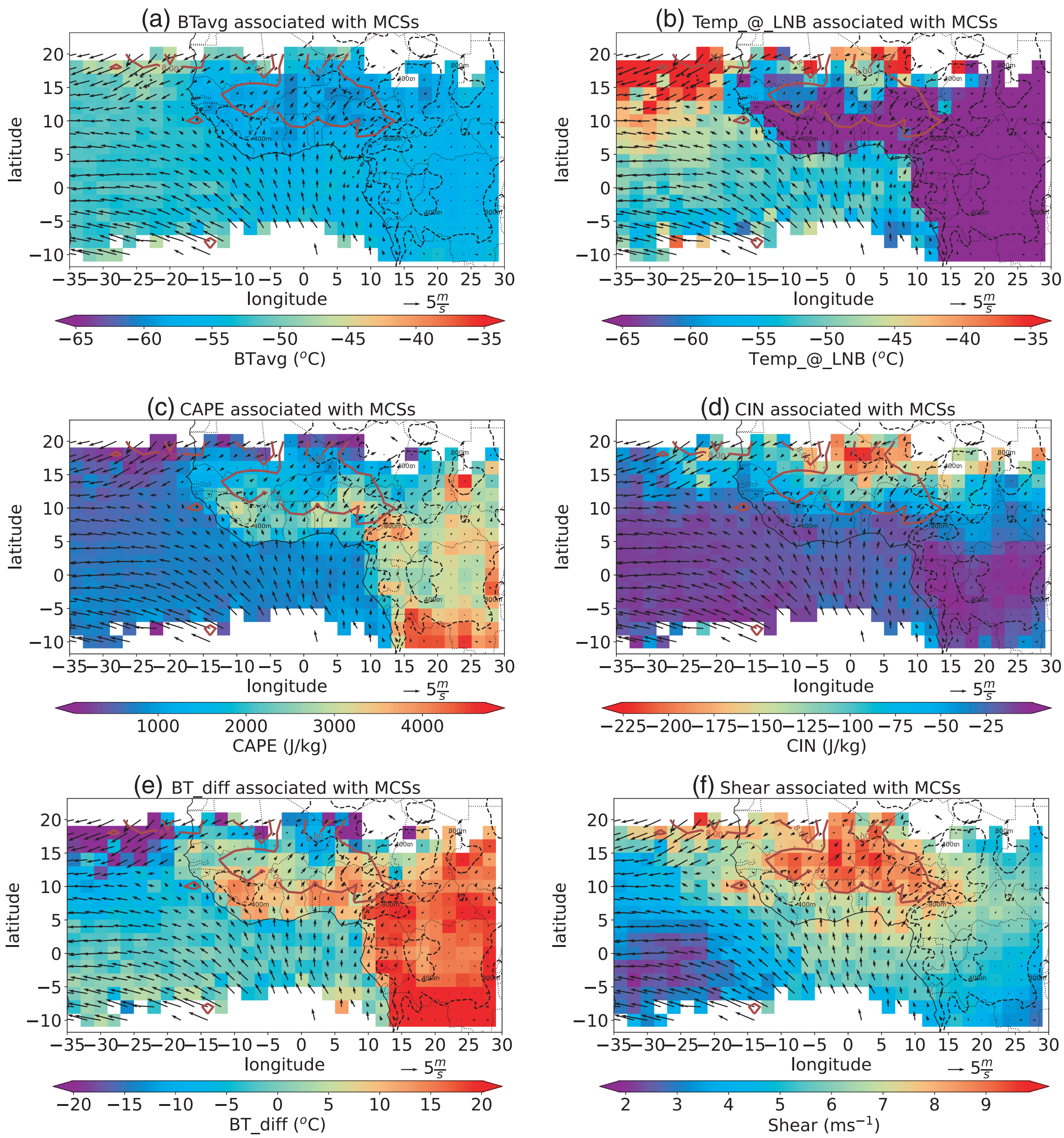

FIGURE 2 (a) Mean brightness temperature (BTavg, °C), (b) temperature at the LNB (°C), (c) CAPE (J·kg^{-1}), (d) CIN (J·kg^{-1}), (e) brightness temperature difference (BTavg - temperature at the LNB, °C) and (f) vertical wind shear associated with MCSs (1998–2007; m·s^{-1}). The associated 925-hPa winds (arrows, m·s^{-1}) and the wind shear of 8 m·s^{-1} (burgundy contours) are overlaid. Bins with a standard error of the mean greater than the 95th percentile are eliminated

3 | EFFECT OF VERTICAL WIND SHEAR ON MCSS

3.1 | The relationship between vertical wind shear and storms with coldest brightness temperatures

The relationship between the 925-hPa wind, wind speed at 600 hPa and the mean MCS brightness temperature is investigated (Figure 1). Colder average brightness temperatures (BTavg) are found over land, with the coldest values over the Sahel and SWA, which have strong shear between 925 and 600 hPa. Storms over the Coast and Congo have relatively warmer brightness temperatures and have either lower 925-hPa winds, lower 600-hPa winds or both.To further investigate the relationship between vertical wind shear and MCS brightness temperatures, Figure 2a–d separates out the thermodynamic factors: CAPE, CIN and the temperature at the LNB. The regions with the strong vertical wind shear (greater than 8 m·s^{-1}) and coldest observed average brightness temperature (Figure 2a) are not the regions with high CAPE values (Figure 2c) or low CIN values (Figure 2d). High CAPE alone does not explain the colder observed brightness temperatures in West Africa. Similarly, the areas of lowest average brightness temperatures (Figure 2a) are not simply explained by the coldest (predicted) temperatures at the LNB (Figure 2b). The results show colder brightness temperatures over the Sahel than the Congo, despite a colder LNB and higher CAPE in the Congo, suggesting that the high vertical shear found in the Sahel is important for the storms to achieve the low brightness temperatures seen there.

In order to compare the observe MCS brightness temperatures with those expected if the anvils were to detrain at the theoretical LNB, Figure 2e was created which shows the relationship between the brightness temperature difference (hereafter "BT_diff"), that is, the observed average brightness temperature (BTavg) minus the theoretical temperature at the LNB. Generally, the BT_diff is positive over almost the entire land domain studied (Figure 2e) indicating that the observed cloud top heights are lower (have warmer brightness temperatures) than their (theoretical) LNBs (consistent with Takahashi & Luo, 2012. The few regions with negative BT_diff are found in areas with few storms and are consistent with the emissivities of clouds being less than 1 and do not necessarily show anvils located higher than the LNB (Allen, 1971; Protopapadaki et al., 2017), or over the Sahara errors in analysed low-level water vapour may give underestimation of LNBs (Trzeciak et al., 2017). Furthermore, BT_diffs are higher over the Congo than over the Sahel, with the low BT_diffs in the Sahel collocated with regions of high vertical wind shear (Figure 2f). The brightness temperatures used are of the whole anvil, not just the overshooting top, and therefore the results are consistent with high vertical shear allowing decreased entrainment (Mulholland et al., 2021; Peters et al., 2019) and therefore anvils that reach higher altitudes relative to their LNB. This effect was further confirmed with an r value of -0.16 and p value less than 0.01.

The observed cloud top heights of storms over the oceans are closer to their LNBs compared to their land counterparts on the same latitudes. We hypothesize that entrainment of drier air over land, and possibly higher entrainment rates over land (Becker & Hohenegger, 2021), resulting in higher entrainment-driven dilution of updraft cores prevents storms from reaching as high cloud top heights relative to their LNBs compared with oceanic storms. Further studies are required to identify the exact role of these mechanisms on the cloud-top height of MCS.

3.2 | Vertical wind shear and MCS properties

Here, we assess how vertical wind shear affects MCS speed, brightness temperature, rain-rate and lifetime. Figure 3 shows the mean MCS size, brightness temperature, rain-rate, lifetime, BT_diff and the relative humidity at 600 hPa for West African land storms (Sahel, SWA and the Coast) as a function of the vertical wind shear and MCS speed. Figure 4 shows the same variables (except for BT_diff and relative humidity) as a function of MCS speed and lifetime. Slow moving storms tend to be short-lived and small in size compared with other MCSs (Figures 3a,d and 4a). Fast moving storms tend to be larger (Figures 3a and 4a), but the longest lived storms are found for moderate speeds 10–25 $m{\cdot}s^{-1}$) and high vertical shear (Figures 3d and 4d). Although these moderate-speed high-shear storms are not always large (Figure 3a), the long-lived ones are larger (Figure 4a). Moderate-speed (10–30 $m{\cdot}s^{-1}$) long-lived systems give the coldest brightness temperatures (Figures 3b and 4b) with vertical shear giving colder brightness temperatures for this range of storm speeds (Figure 4b).

Figure 3e confirms the results of the preceding sub-section, showing that for any MCS speed, higher vertical shear tends to give colder cloud-tops relative to the LNB, except perhaps for the fastest storms, where the sample size is reduced and there are no cases of high vertical shear. The lowest brightness temperature differences, that is, the storms that reach higher altitudes relative to their LNBs, are seen for the largest vertical shear values, which are found for MCS speeds of 5–30 $m{\cdot}s^{-1}$. Figure 3e is repeated for land MCSs in each sub-region separately with the results confirming this same relationship for each of the regions (Figure S1).

The overall effects of mid-level moisture are unclear. Lower BT_diffs from high shear could not be explained by variations in CAPE: high CAPE gave high BT_diffs and for any given CAPE shear gave lower BT_diffs (not shown). Figure 3e,f shows that for moderate shear, there is some increase in BT_diff with relative humidity (RH), that is, lower cloud tops with moist mid-levels, and that dry mid-levels are associated both with low vertical shear high BT_diff storms, and high shear low BT_diff storms. Examining the effects of mid-level humidity by region (Figure S2) shows that this complex picture may be a result of impacts that vary by region. For the Coast, the Congo area, Gulf of Guinea and N. Atlantic, there is some evidence that moist mid-levels, for any value of vertical shear, favour colder cloud-tops, possibly from reduced drying through entrainment. Conversely for the Sahel and SWA there is perhaps some hint of the reverse, that is, dry mid-levels favouring cold cloud tops and low BT_diff, possibly through favouring strong cold pools and so convective organization (Fitzpatrick et al., 2020; James & Markowski, 2010). We conclude that it is plausible that effects of mid-level moisture vary by

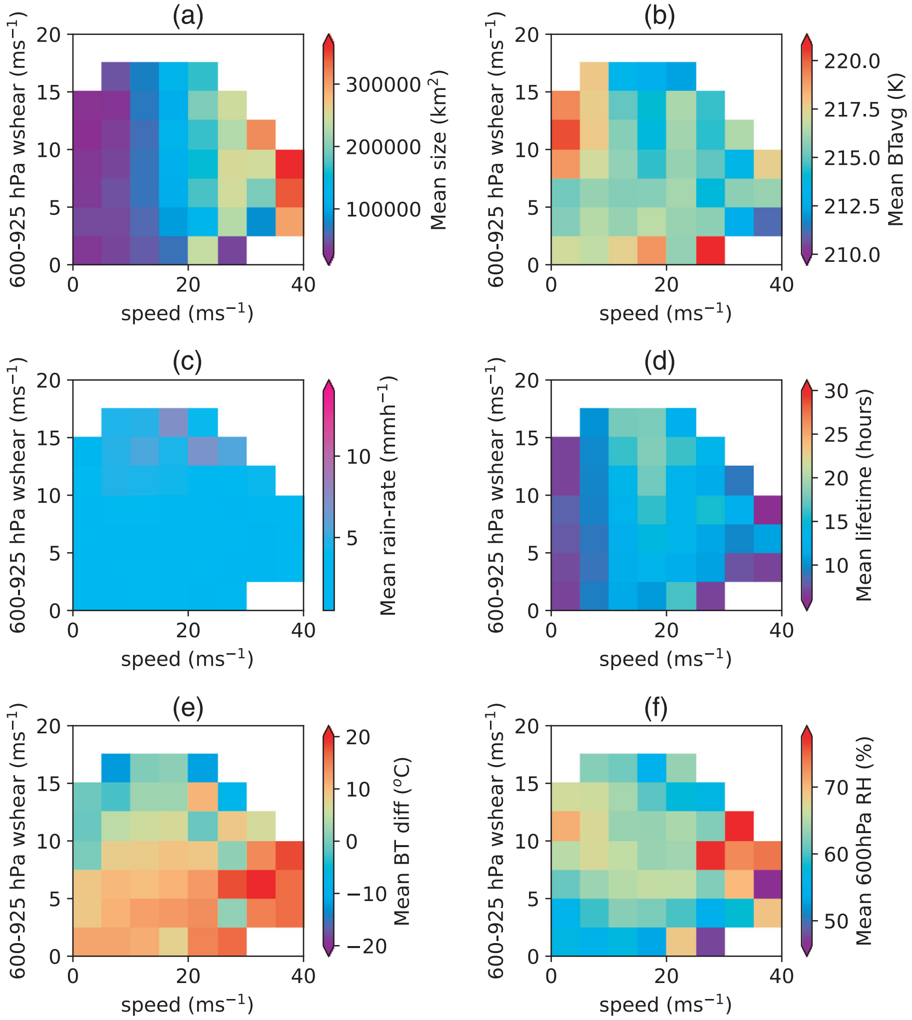

FIGURE 3 Vertical wind shear against speed for (a) MCS size, (b) mean brightness temperature, (c) rain-rate, (d) lifetime, (e) brightness temperature difference and (f) relative humidity at 600 hPa over the period 1998–2007

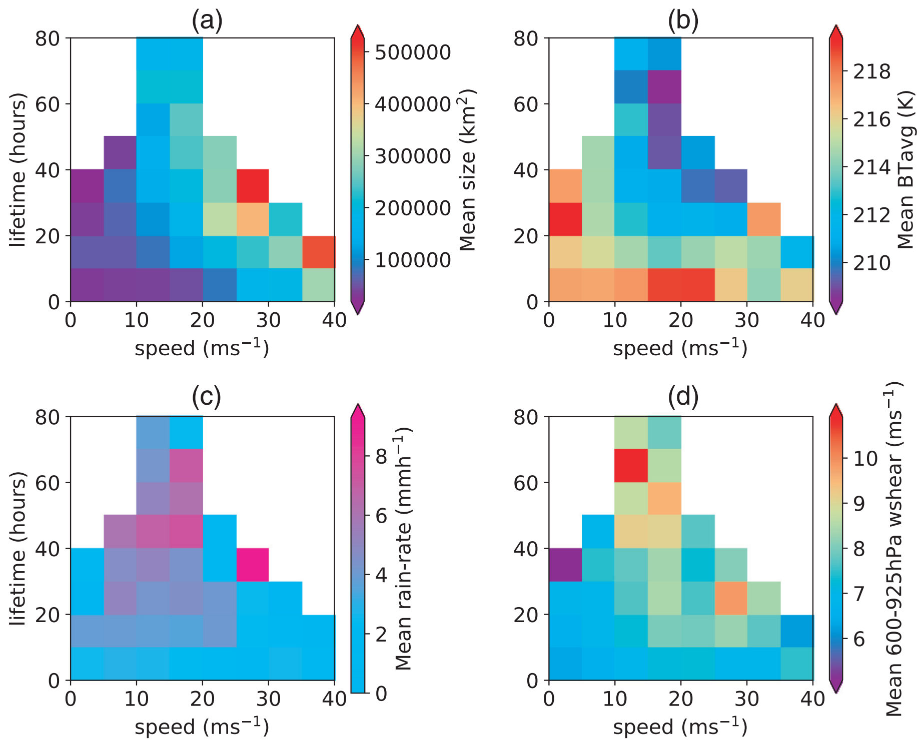

FIGURE 4 MCS lifetime against speed for (a) mean MCS size, (b) mean brightness temperatures (BTavg), (c) mean rain rate and (d) mean wind shear for the period 1998–2007

region, due to effects on both entrainment drying and cold pool production, and that this requires further research.

Vertical shear also gives higher rain rates for all but the fastest and slowest storms (Figure 3c), with the heaviest rain rates coming from long lived storms, which tend to have moderate speeds (5–25 $m \cdot s^{-1}$). It is important to note that the TRMM 3B42 product makes use of infrared imagery, so impacts of shear on cloud-top height may be falsely converted to rain rates.

We conclude that longest lived storms have moderate speeds ($\sim$15 $m \cdot s^{-1}$). These are associated with the highest vertical shear values (Figures 3d and 4d). For any speed, the longest lived storms are associated with both the coldest brightness temperatures (Figure 4b), and colder brightness temperatures relative to their LNB (Figure 3e), with these associated with high vertical shear.

4 | CONCLUSIONS

The observed impact of vertical wind shear on MCSs has been investigated over West and Central Africa, using the 10-year dataset of MCS tracks from Huang et al. (2018). The associated environments and rain-rates of the MCSs were taken from ERA-Interim and TRMM 3B42 datasets, at the time of storm maturity, defined as the time of coldest mean brightness temperature in the life-cycle of a storm.

The results show that a strong vertical wind shear is associated with long-lived, moderate-speed and size storms with colder brightness temperatures. These storms were also associated with high rain-rates.

To isolate the effects of shear on cloud-top height from the effect of the thermodynamic profile temperatures, we compare the storm brightness temperatures with the temperatures at the LNB. It was found that storms over the oceans could reach higher relative to their LNBs compared to storms over land, which we hypothesize may be due to greater entrainment dilution from drier air over land (Becker & Hohenegger, 2021). Importantly, greater vertical shear gives clouds that are higher relative to the LNB. Storms are observed to reach higher heights relative to their LNB in the presence of larger shear. Notably, storms reach higher relative to their LNB in the Sahel, where vertical shear is strong, compared to storms over the Congo, where vertical shear is weaker but CAPE and LNBs are both higher. This impact of vertical shear on cloud-top heights relative to the LNB is consistent with recent idealized numerical model simulations showing that vertical shear can reduce entrainment dilution in both supercells and squall-lines (Mulholland et al., 2021; Peters et al., 2019). However, assuming storms move with mid-level winds increased vertical shear will tend to give greater system-relative inflow of low-level air compared with mid-level air, which may also increase the mean positive buoyancy of the inflow in the LLMC of Alfaro (2017). The exact balance of mechanisms by which shear controls cloud-top heights is left to future work.

We conclude that not only is it important to capture the role of vertical shear in modelling the organization of convection and high impact weather, but that vertical shear is also important for the climatology of anvil heights, therefore affecting the profile of diabatic heating from storms and the earth's radiation budget. We also hypothesize that a poor representation of vertical shear impacts on entrainment might be one reason why 4.4-km grid-spacing convection-permitting models struggle to capture the observed effects of vertical shear on rain rates over Africa (Fitzpatrick et al., 2020; Senior et al., 2021), consistent with greater impacts of shear on idealized simulations of squall lines at higher resolution (Bickle et al., 2021). Since grid-spacings less than or around 100 m are needed to model entrainment (Bretherton et al., 1999), this raises challenges for modelling and predicting future high-impact weather from squall-lines, which we expect to be impacted by future changes in vertical shear, as well as thermodynamics (Taylor et al., 2017).

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AUTHOR CONTRIBUTIONS

Michael Baidu: Conceptualization; data curation; formal analysis; investigation; methodology; software; visualization; writing – original draft; writing – review and editing. **Juliane Schwendike:** Data curation; funding acquisition; investigation; methodology; project administration; resources; supervision; writing – review and editing. **John H. Marsham:** Conceptualization; funding acquisition; investigation; methodology; project administration; resources; supervision; validation; writing – review and editing. **Caroline Bain:** Funding acquisition; project administration; resources; supervision; validation; writing – review and editing.

CONFLICT OF INTERESTS

The authors declare that there are no conflict of interests.

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REFERENCES

Agustí-Panareda, A., Beljaars, A., Cardinali, C., Genkova, I. & Thorncroft, C. (2010) Impacts of assimilating AMMA soundings on ECMWF analyses and forecasts. *Weather and Forecasting*, 25, 1142–1160.

Alfaro, D.A. (2017) Low-tropospheric shear in the structure of squall lines: impacts on latent heating under layer-lifting ascent. *Journal of the Atmospheric Sciences*, 74, 229–248.

Alfaro, D.A. & Khairoutdinov, M. (2015) Thermodynamic constraints on the morphology of simulated midlatitude squall lines. *Journal of the Atmospheric Sciences*, 72, 3116–3137.

Allen, J. (1971) Measurements of cloud emissivity in the 8–13 μ waveband. *Journal of Applied Meteorology and Climatology*, 10, 260–265.

Becker, T. & Hohenegger, C. (2021) Entrainment and its dependency on environmental conditions and convective organization in convection-permitting simulations. *Monthly Weather Review*, 149, 537–550.

Berrisford, P., Dee, D., Fielding, K., Fuentes, M., Kallberg, P., Kobayashi, S. and Uppala, S. (2009) The ERA-Interim archive. ERA Report series. No. 1. Technical (ERA) report. European Centre for Medium-range Weather Forecasting, Shinfield Park, Reading, UK.

Bickle, M.E., Marsham, J.H., Ross, A.N., Rowell, D.P., Parker, D.J. & Taylor, C.M. (2021) Understanding mechanisms for trends in Sahelian squall lines: roles of thermodynamics and shear. *Quarterly Journal of the Royal Meteorological Society*, 147, 983–1006.

Bretherton, C.S., MacVean, M.K., Bechtold, P., Chlond, A., Cotton, W.R., Cuxart, J. et al. (1999) An intercomparison of radiatively driven entrainment and turbulence in a smoke cloud, as simulated by different numerical models. *Quarterly Journal of the Royal Meteorological Society*, 125, 391–423.

Bryan, G.H., Knievel, J.C. & Parker, M.D. (2006) A multimodel assessment of RKW theory's relevance to squall-line characteristics. *Monthly Weather Review*, 134, 2772–2792.

Chen, Y., Ebert, E.E., Walsh, K.J. & Davidson, N.E. (2013) Evaluation of TRMM 3B42 precipitation estimates of tropical cyclone rainfall using PACRAIN data. *Journal of Geophysical Research: Atmospheres*, 118, 2184–2196.

Dai, A., Giorgi, F. & Trenberth, K.E. (1999) Observed and model-simulated diurnal cycles of precipitation over the contiguous United States. *Journal of Geophysical Research: Atmospheres*, 104, 6377–6402.

Dee, D.P., Uppala, S., Simmons, A., Berrisford, P., Poli, P., Kobayashi, S. et al. (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, 137, 553–597.

Dembélé, M. & Zwart, S.J. (2016) Evaluation and comparison of satellite-based rainfall products in Burkina Faso, West Africa. *International Journal of Remote Sensing*, 37, 3995–4014.

Ebert, E.E., Janowiak, J.E. & Kidd, C. (2007) Comparison of near-real-time precipitation estimates from satellite observations and numerical models. *Bulletin of the American Meteorological Society*, 88, 47–64.

Fitzpatrick, R.G., Parker, D.J., Marsham, J.H., Rowell, D.P., Guichard, F.M., Taylor, C.M. et al. (2020) What drives the intensification of mesoscale convective systems over the West African Sahel under climate change? *Journal of Climate*, 33, 3151–3172.

Guichard, F., Petch, J., Redelsperger, J.-L., Bechtold, P., Chaboureau, J.-P., Cheinet, S. et al. (2004) Modelling the diurnal cycle of deep precipitating convection over land with cloud-resolving models and single-column models. *Quarterly Journal of the Royal Meteorological Society*, 130, 3139–3172.

Houze, R.A., Jr. (2018) 100 years of research on mesoscale convective systems. *Meteorological Monographs*, 59, 17.

Huang, X., Hu, C., Huang, X., Chu, Y., Tseng, Y.-H., Zhang, G.J. et al. (2018) A long-term tropical mesoscale convective systems dataset based on a novel objective automatic tracking algorithm. *Climate Dynamics*, 51, 3145–3159.

Huffman, G.J., Bolvin, D.T., Nelkin, E.J., Wolff, D.B., Adler, R.F., Gu, G. et al. (2007) The TRMM multisatellite precipitation analysis (TMPA): quasi-global, multiyear, combined-sensor precipitation estimates at fine scales. *Journal of Hydrometeorology*, 8, 38–55.

Jackson, B., Nicholson, S.E. & Klotter, D. (2009) Mesoscale convective systems over western equatorial Africa and their relationship to large-scale circulation. *Monthly Weather Review*, 137, 1272–1294.

James, R.P. & Markowski, p.M. (2010) A numerical investigation of the effects of dry air aloft on deep convection. *Monthly Weather Review*, 138, 140–161.

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

Klein, C. & Taylor, C.M. (2020) Dry soils can intensify mesoscale convective systems. *Proceedings of the National Academy of Sciences of the United States of America*, 117, 21132–21137.

Kubota, T., Ushio, T., Shige, S., Kida, S., Kachi, M. & Okamoto, K. (2009) Verification of high-resolution satellite-based rainfall estimates around Japan using a gauge-calibrated ground-radar dataset. *Journal of the Meteorological Society of Japan. Series II*, 87, 203–222.

Laurent, H., d'Amato, N. & Lebel, T. (1998) How important is the contribution of the mesoscale convective complexes to the Sahelian rainfall? *Physics and Chemistry of the Earth*, 23, 629–633.

Lavaysse, C., Flamant, C., Janicot, S., Parker, D.J., Lafore, J.-P., Sultan, B. et al. (2009) Seasonal evolution of the West African heat low: a climatological perspective. *Climate Dynamics*, 33, 313–330.

Maranan, M., Fink, A.H. & Knippertz, P. (2018) Rainfall types over southern West Africa: objective identification, climatology and synoptic environment. *Quarterly Journal of the Royal Meteorological Society*, 144, 1628–1648.

Michot, V., Vila, D., Arvor, D., Corpetti, T., Ronchail, J., Funatsu, B.M. et al. (2018) Performance of TRMM TMPA 3B42 V7 in replicating daily rainfall and regional rainfall regimes in the Amazon Basin (1998–2013). *Remote Sensing*, 10, 1879.

Mulholland, J.P., Peters, J.M. & Morrison, H. (2021) How does vertical wind shear influence entrainment in squall lines? *Journal of the Atmospheric Sciences*, 78, 1931–1946.

Nicholson, S.E. (2013) The West African Sahel: a review of recent studies on the rainfall regime and its interannual variability. *ISRN Meteorology*, 2013, 453521.

Nicholson, S.E., Funk, C. & Fink, A.H. (2018) Rainfall over the african continent from the 19th through the 21st century. *Global and Planetary Change*, 165, 114–127.

Nicholson, S.E., Some, B., McCollum, J., Nelkin, E., Klotter, D., Berte, Y. et al. (2003) Validation of TRMM and other rainfall estimates with a high-density gauge dataset for West Africa. Part II: validation of TRMM rainfall products. *Journal of Applied Meteorology*, 42, 1355–1368.

Peters, J.M., Nowotarski, C.J. & Morrison, H. (2019) The role of vertical wind shear in modulating maximum supercell updraft velocities. *Journal of the Atmospheric Sciences*, 76, 3169–3189.

Protopapadaki, S.E., Stubenrauch, C.J. & Feofilov, A.G. (2017) Upper tropospheric cloud systems derived from IR sounders: properties of cirrus anvils in the tropics. *Atmospheric Chemistry and Physics*, 17, 3845–3859.

Richardson, Y. P. (1999) *The influence of horizontal variations in vertical shear and low-level moisture on numerically simulated convective storms*. PhD thesis, School of Meteorology, The University of Oklahoma, Norman, OK.

Rotunno, R., Klemp, J.B. & Weisman, M.L. (1988) A theory for strong, long-lived squall lines. *Journal of the Atmospheric Sciences*, 45, 463–485.

Senior, C.A., Marsham, J.H., Berthou, S., Burgin, L.E., Folwell, S.S., Kendon, E.J. et al. (2021) Convection-permitting regional climate change simulations for understanding future climate and informing decision-making in Africa. *Bulletin of the American Meteorological Society*, 102, E1206–E1223.

Takahashi, H. & Luo, Z. (2012) Where is the level of neutral buoyancy for deep convection? *Geophysical Research Letters*, 39, L15809.

Taylor, C.M., Belušić, D., Guichard, F., Parker, D.J., Vischel, T., Bock, O. et al. (2017) Frequency of extreme Sahelian storms tripled since 1982 in satellite observations. *Nature*, 544, 475–478.

Taylor, C.M., Fink, A.H., Klein, C., Parker, D.J., Guichard, F., Harris, p.P. et al. (2018) Earlier seasonal onset of intense mesoscale convective systems in The Congo basin since 1999. *Geophysical Research Letters*, 45, 13–458.

Trzeciak, T.M., Garcia-Carreras, L. & Marsham, J.H. (2017) Cross-Saharan transport of water vapor via recycled cold pool outflows from moist convection. *Geophysical Research Letters*, 44, 1554–1563.

Wallace, J. & Hobbs, P. (1977) *Atmospheric science: an introductory survey*. New York: Academic Press.

Weisman, M.L. & Rotunno, R. (2004) "A theory for strong long-lived squall lines" revisited. *Journal of the Atmospheric Sciences*, 61, 361–382.

Zulkafli, Z., Buytaert, W., Onof, C., Manz, B., Tarnavsky, E., Lavado, W. et al. (2014) A comparative performance analysis of TRMM 3B42 (TMPA) versions 6 and 7 for hydrological applications over Andean–Amazon river basins. *Journal of Hydrometeorology*, 15, 581–592.

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