A weather regime characterisation of winter biomass aerosol transport from southern Africa

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Abstract

During austral winter, a compact low cloud deck over the South Atlantic contrasts with clear sky over southern Africa, where forest fires triggered by dry conditions emit large amount of biomass burning aerosols (BBA) in the free troposphere. Most of the BBA burden crosses the South Atlantic embedded in the tropical easterly flow. However, midlatitude synoptic disturbances can deflect part of the aerosol from the main transport path towards southern extratropics.

In this study, the first objective classification of the synoptic variability controlling the spatial distribution of BBA in southern Africa and the South Atlantic during austral winter (August to October) is presented. By analysing atmospheric circulation data from reanalysis products, a 6-class weather regime (WR) classification of the region is constructed. The classification reveals that the synoptic variability is composed of four WRs representing disturbances travelling at midlatitudes, and two WRs accounting for pressure anomalies in the South Atlantic. The WR classification is then successfully used to characterise the aerosol spatial distribution in the region in the period 2003-2017, in both reanalysis products and station data. Results show that the BBA transport towards southern extratropics is controlled by weather regimes associated with midlatitude synoptic disturbances. In particular, depending on the relative position of the pressure anomalies along the midlatitude westerly flow, the BBA transport is deflected from the main tropical route towards southern Africa or the South Atlantic. Moreover, the WRs accounting for midlatitude disturbances show organised transition sequences, which allow to illustrate the evolution of the BBA northerly transport across the region in the context of a wave pattern.

~~This paper presents the first objective classification of the winter synoptic circulation over South Atlantic and southern Africa. The classification shows skills in characterising the BBA transport, indicating~~The skill in characterising the BBA transport shown by the WR classification indicates the potential for using it as a diagnostic/predictive tool for the aerosol dynamics, which is a key component for the full understanding and modelling of the complex radiation-aerosol-cloud interactions controlling the atmospheric radiative budget in the region.

1. Introduction

Natural and anthropogenic tropospheric aerosols are fundamental ingredients of the climate system. They influence the radiative properties of the atmosphere by deflecting and absorbing radiation (direct effect) and the cloud formation and properties by absorption (semi-direct effect) as well as by acting as cloud condensation nuclei (indirect effect). As a consequence, aerosols can influence the atmospheric and climate ~~synoptic and large-scale~~ dynamics (Bellouin et al., 2020).

Africa is the Earth's largest source of biomass burning aerosol (BBA; e.g. van der Werf et al., 2010, 2017). The transport of BBA, originating from central Africa and embedded in the tropical midtropospheric easterly flow, occurs mostly above the Atlantic Ocean (Fig. 1a), and is a prominent feature during austral winter (June to October; Fig. 1b) between the Equator and 20°S, when dry conditions in central Africa favour the development of forest fires (Horowitz et al., 2017). However, extratropical rivers of smoke are also observed to extend to 30-40°S between August and October (Fig. 1b). The term 'river of smoke' refers to the sharply defined boundaries of the smoke plume, which can be several hundred kilometres wide and flow over a few thousands kilometres above southern Africa towards Southern and Indian Oceans (McMillan et al., 2003; Swap et al., 2003). Depending on the transport path (e.g. either above the continent or recirculated above the ocean), physical and chemical properties of the BBA may change (Abel et al., 2003; Eck et al., 2003; Formenti et al., 2003; Haywood et al., 2003; Pistone et al., 2019; Wu et al., 2020). The characterisation of BBA transport in terms of synoptic atmospheric circulation is therefore one of the key elements to shed light on the already complex picture of the radiation-aerosol-cloud interactions (Adebiyi and Zuidema, 2018; Formenti et al., 2019; Haywood et al., 2003, 2021; Lindesay et al., 1996; Mallet et al., 2020; Redemann et al., 2021; Swap et al., 2003; Zuidema et al., 2016). Additionally, the extent and direction of BBA transport may condition the atmospheric remote supply of nutrients and pollutants to the South Atlantic, the Southern Ocean, and the Indian Ocean, as well as to Antarctica (Baker et al., 2010; Barkley et al., 2019; Gao et al., 2003, 2020; Swap et al., 1996; Wai et al., 2014).

Understanding the role of the radiation-aerosol-cloud interaction in controlling the atmospheric radiative budget and, consequently, climate dynamics is a key aspect for the improvement of climate modelling. Indeed, even state-of-the art climate models still struggle in reliably representing the atmospheric radiative forcing, due to inaccurate parametrizations of the radiation-aerosol-cloud interaction (Mallet et al., 2020; Stier et al., 2013; Tang et al., 2019). This is particularly relevant in the South Atlantic, where the incomplete knowledge of the smoke-cloud regime generates large discrepancies in the modelling of radiative forcing and sea surface temperature (SST) in the region, eventually affecting climate simulations at regional and global scale (Zuidema et al., 2016). While a conceptual understanding of the meteorological conditions determining the transport of aerosols and pollutants at the subcontinental scale exists (Diab et al., 1996; Garstang et al., 1996; Tyson, 1997), the large-scale drivers of the aerosol spatial distribution in the region are still not understood and an objective synoptic characterisation of the wintertime BBA transport is still missing to date. In particular, an objective synoptic characterisation of the wintertime BBA transport in the region is still missing to date. Indeed, synoptic circulation in the southern Africa/South Atlantic sector is discussed in literature mainly in relationship with convection and precipitation during austral summer (e.g. Crétat et al., 2019; Dieppois et al., 2016; Fauchereau et al., 2009; Macron et al., 2014; Pohl et al., 2018; Vigaud et al., 2012).

The scope of this paper is to fill the gaps in the understanding of atmospheric and aerosol dynamics during austral winter in the southern Africa/South Atlantic sector, by providing a characterisation of the synoptic variability of the atmospheric circulation, and determining the circulation patterns controlling the transport of BBA from the tropics to the extratropics. To this aim, an objective weather regime (WR) classification of the winter atmospheric circulation in the southern Africa/South Atlantic sector is presented for the first time, and used to characterise the BBA transport in the region. In particular, the study focuses on the characterisation of the southward deflection of BBA from the mean tropical easterly flow from August to October (ASO) in the period 2003-2017. Atmospheric circulation data from a reanalysis product are first used to classify the synoptic circulation patterns. Then, the classification is used to characterise the BBA transport anomalies in reanalysis data and in situ observations in the region. The paper is organised as follows: in Section 2, data and methods used in the analysis are presented; in Section 3, the WR classification is presented and the synoptic characterisation of BBA anomalies is discussed; conclusions and perspectives are summarised in Section 4.

2. Data and Methods

2.1. Reanalysis and gridded observations

The atmospheric circulation and the spatial distribution and optical properties of the BBA over southern Africa and the South Atlantic in ASO 2003-2017 are analysed using data from the Copernicus Atmospheric Monitoring Service reanalysis product (CAMS; Flemming et al., 2017) at 6h time steps (00:00, 06:00, 12:00, and 18:00) and 0.75° horizontal resolution. The BBA emission is estimated by the organic matter mixing ratio at 10m, the BBA transport is estimated as the product of organic matter mixing ratio and wind at 700 hPa, and the aerosol spatial distribution is represented by the aerosol optical depth (AOD) at 550 nm (Fig. 2a). Data from the fifth generation ECMWF reanalysis (ERA5; Hersbach et al., 2020), available at hourly time steps and 0.25° horizontal resolution, are used to validate the WR classification on a longer time period (1981-2020). ERA5 data are selected at 6h time steps (00:00, 06:00, 12:00, and 18:00) and regridded to the CAMS product grid at 0.75°. For both the reanalysis products, daily values are obtained at each grid point as the average of 6h time steps, and daily anomalies are computed by removing the low frequency (LF) component of the time series, estimated by computing monthly means from daily data and interpolating them to daily time steps using a cubic spline interpolation. The limited coverage of the CAMS reanalysis (15 years) does not allow a robust definition of the climatological seasonal cycle, which would be too dependent on the interannual variability. Therefore, in order to isolate the synoptic variability alone, the definition of a LF component, accounting for the seasonal cycle and the interannual variability, is preferred and applied to both the reanalysis products.

Global reconstructions of the observed sea surface temperature (SST) are used to investigate the teleconnections controlling the synoptic variability. Data are extracted from the Met Office Hadley Centre HadISST dataset (Rayner et al., 2003), available from 1871 at monthly time scale and 1° horizontal resolution, and from the NOAA Extended Reconstructed Sea Surface Temperature (ERSST) Version 5 dataset (Huang et al., 2017), available from 1854 at monthly time scale and 2° horizontal resolution.

2.2. In situ aerosol observations

Observed daily values of the AOD at 500 nm from AERONET stations (https://aeronet.gsfc.nasa.gov/) are used to validate the synoptic characterisation performed on CAMS data. Stations are selected among the ones with at least 2 years of level 2 data obtained from the Version 3 Direct Sun algorithm (Giles et al., 2018). Stations are selected outside the source region in tropical Africa, namely south of 20°S and west of 10°E (Fig. 2a, Table 1), in order to focus on BBA transport only, not being influenced by the BBA emission which is assumed not to be directly related to synoptic conditions. Among the available stations, St. Helena [15.9°S, 5.7°W] and Wits University [26.2°S, 28.0°E] are not included because of the limited coverage (less than 100 observations during the study period). Moreover, the stations closer to the greater Johannesburg and Pretoria urban areas (namely, Durban UKZN [29.8°S, 30.9°E], Pretoria CSIR-DPSS [25.8°S, 28.3°E] and Skukuza [25.0°S, 31.2°E]) are not included, because too affected by the proximity ~~with~~ of urban sources (Fig. 2a). Three Namibian stations, namely Gobabeb, Henties Bay and HESS, are located very close to each other, in comparison with the size of the rivers of smoke affecting western Namibia (see Fig. 2a). Therefore, the combination of the AOD observations in the three stations would be more representative of regional conditions and filter out local effects on the AOD measurements. Indeed, Henties Bay is a coastal site, exposed to both marine and mineral dust aerosols; Gobabeb is in the Namib Desert, exposed to mineral dust aerosols; HESS is located inland in the savannahs, exposed to possible local sources of BBA. A daily time series associated with the three stations (referred as

Namibian Stations, NS) is built by computing the average AOD when observations are available in at least 2 stations out of 3, leading to a time series longer than the three individual time series (276 observations, spanning from 2013 to 2017, see Table 1).

For each station, daily AOD anomalies are computed by removing the LF component of the time series, accounting for both the seasonal cycle and the interannual variability, as described in Section 2.1. However, the sparseness of the AERONET observations makes difficult the definition of a daily LF component. Therefore, CAMS AOD at 550 nm is selected in an area defined by the grid point the closest to the station coordinates and the adjacent grid points, and averaged to estimate the daily LF component of the AOD at 500 nm. Empirical evidence shows that a quadratic relationship exists between the natural logarithm of AOD and wavelength (Eck et al., 1999). However, at such close wavelengths the relationship can be assumed to be linear, and the relationship between the natural logarithm of AOD at 500 and 550 nm can be modelled as follows:

$$\log AOD_{500nm} = a \log AOD_{550nm} + b.$$

At each AERONET station, the logarithm of observed and CAMS AOD well correlates during ASO 2003-2017 (correlations coefficients lie between 0.71 and 0.90, all significant at 99% level of confidence, see Fig. 3). Therefore, the daily LF component of the observed AOD is estimated by means of a linear regression onto the CAMS LF component. In order to minimise the effect of possible large discrepancies between AERONET and CAMS data, the difference between AERONET and CAMS AOD is computed and the values in the lowest and highest 5% are discarded before the linear regression is performed (the coefficients used in the regression model at each station are displayed in Fig. 3).

2.3. Weather regime classification

The WR classification is performed on the geopotential height at 700 hPa, which is the level where BBA transport is maximal, in the domain [20°W-40°E, Eq-40°S] (see Fig. 2bc). The selection of the domain is made to include the main BBA transport routes in the tropical belt and towards the extratropics. However, during the dry season the synoptic variability in the tropics is reduced in comparison with the extratropics (Baldwin, 2001). Therefore, the southern border of the domain is set to 40°S, not to let the dominant midlatitude modes mask variability in the tropical belt. The atmospheric circulation is first characterised by isolating the main modes of variability represented by the empirical orthogonal functions (EOFs) derived from a principal component analysis (PCA) of the geopotential height daily anomalies. Each mode is represented by a spatial anomaly pattern and a standardized time series (namely, the principal components, PCs) accounting for the amplitude of the anomaly pattern (for more details on PCA, see Storch and Zwiers, 1999). The first 4 EOFs, accounting for at least 80% of the total variance (Fig. S1), are used to classify the WRs by means of a k-means algorithm, using k = [2, 10] (Michelangeli et al., 1995). For each k, the classification is performed 100 times, to ensure reproducibility of the results. A red-noise test is performed to assess the significance of the class partition (Michelangeli et al., 1995), resulting in 6 and 7 classes (Fig. S3). The synoptic characterisation of the BBA transport is performed by using both the 6-class and the 7-class partitions. This study focuses on the 6-class partition, i.e. the classification with the lowest significant number of WRs, which leads to physically coherent atmospheric patterns describing the main features of the synoptic variability (see Section 3.1). Furthermore, the comparison between the 6 and 7 class partitions shows that the 6 WR classification performs better in characterising the BBA transport in the region (see Section S3). The robustness of the 6-class partition is tested against different choices of time period (1981-2020), geographical domain ([20°W-40°E, 10°S-50°S]) and retained variance (at least 90%, accounted for by the first 7 PCs).

2.4. Aerosol synoptic characterisation

The WR classification is used to characterise the observed AOD data from the AERONET stations in the region (Table 1). Two approaches are used:

1) Daily AOD anomalies are linked to the corresponding WR and grouped, and statistical differences among groups are investigated (circulation-to-environment approach, C2E). The significance of the C2E characterisation is assessed by a one-way analysis of variance (ANOVA) with the null hypothesis that the distributions associated with each WR are derived from populations with the same mean. Furthermore, for each WR the significance of the associated AOD anomalies with the respect of the full sample is assessed by a non-parametric Kolmogorov-Smirnov (KS) test.

2) Daily AOD anomalies are divided into quartiles, and the changes in the WR occurrences within each quartile are studied (environment-to-circulation approach, E2C). The significance of the E2C characterisation is assessed by computing the chi-squared statistics for each quartile, with the null hypothesis that the associated WR frequencies are derived from the same distribution of the full sample. The chi-squared statistics is tested against the critical value for 5 degrees of freedom and at the 95% level of confidence. The degrees of freedom are estimated as the number of the observation categories (6 WRs) minus the parameters of the distribution to be fitted (the mean WR occurrence, i.e. 1).

3. Results

3.1. Synoptic characterisation of the regional atmospheric variability

The mean atmospheric conditions over the South Atlantic and southern Africa in ASO are illustrated in Fig. 2a. The atmospheric circulation at 700 hPa is characterised by a continental high centred at 25°S over southern Africa and extending over the eastern South Atlantic, and a subtropical trough west of South Africa deflecting the midlatitude westerly flow southward. Massive quantities of BBA are emitted from tropical southern Africa, and are driven westward over the South Atlantic by the southern African easterly jet (Adebiyi and Zuidema, 2016), while the anticyclonic gyre associated with the continental high recirculates the BBA towards South Africa along the Namibian coast. This recirculation merges with smaller BBA amounts emitted from sources located in South Africa in the urban area of Johannesburg and Pretoria, to be eventually transported eastward to the Indian Ocean embedded in the westerly flow.

The WR classification shows two synoptic patterns accounting for the oscillation of the pressure field in the South Atlantic and four synoptic patterns accounting for midlatitude pressure anomalies (Fig. 4). These four WRs represent the fingerprint of propagative disturbances travelling along the midlatitude mean westerly flow with wave number 8-12, as shown by the EOF analysis (see Section S1). The synoptic variability is dominated by the South Atlantic positive pattern (SA+), which occurs at a frequency of 22.3% and is characterised by a high pressure anomaly in the South Atlantic accompanied by a reinforcement of the midlatitude westerlies (Fig. 4a). Its symmetric counterpart is represented by the South Atlantic negative pattern (SA-), which occurs at a frequency of 17.7% and is characterised by a low pressure anomaly and a weaker westerly flow in the midlatitudes (Fig. 4b). The remaining 60% of the synoptic variability in the region is characterised by eastward travelling disturbances of the westerly flow, represented by midlatitude (ML) anomaly patterns 1-4 (Fig. 4c-f). ~~WR1 and 3 occur more frequently in August-September, while WR4 and 5 are more frequent in October (Fig. 5).~~ WR sequences are characterised by short duration, 2-3 days for SA+ and SA-, with extreme persistence values above 10 days; and 1-2 days for ML1-4, with extremes not exceeding 6 days (Fig. 5a). The analysis of the WR transitions shows that SA+ and SA- are dominated by persistence (self-transitions are, respectively, 61% and 59% of the total), with reduced transition rates towards the other WRs (Table 2). Conversely, persistence is reduced in the ML patterns (self-transitions are less than 50%), which show non negligible hetero-transition rates (Table 2). Specifically, ML1 shows preference for transitions towards ML2 (28% of the transitions); ML2 prefers transitions towards ML3 (31%); ML3 tends to evolve into ML4 (24%); and ML4 towards ML1 (29%). The transitions of the ML WRs highlight the eastward propagative character of these WRs, suggesting a possible transition pattern from ML1 to ML4 (ML1 → ML2 → ML3 → ML4). The evolution of the atmospheric circulation anomalies from the occurrence of the WR to day +4 is illustrated in Fig. 6. The building and eastward propagation of midlatitude disturbances is evident for

ML1-4, which evolve into themselves on day +1 and then into each other on day +2 to +3 (Fig. 6c-f), following the transition pattern ML1 → ML2 → ML3 → ML4. This transition pattern depicts the propagation and life cycle of temperate waves embedded in the regional midlatitude dynamics. Conversely, persistence characterises the evolution of SA+ and SA-, evolving into themselves on day +1 to +2, to weaken and disappear on day +3 (Fig. 6ab).

The sensitivity of the WR classification described above (referred as "control" classification) to different choices of the retained variance (referred as "PC7" classification) and the geographical domain (referred as "shifted" classification) is assessed (see Section S2 for details). Both the "PC7" and "shifted" classifications result in two WRs (SA+ and SA- in Fig. S4) characterised by persistent (2-3 days) pressure anomalies in the South Atlantic (see the analysis of persistence Fig. S5 and transition rates in Tables S1-3) and four WRs (ML1-4 in Fig. S4) characterised by travelling pressure anomalies at the midlatitudes (see Fig. S5 and Tables S1-3), showing no substantial changes in the circulation features identified in "control". Nevertheless, one 'spurious' WR appears in both the modified classifications (ML2 in "PC7" and ML4 in "shifted"), affecting the frequencies of occurrence and the transition rates among WRs (see Fig. S5 and Tables S1-3), and limiting the rate of WR co-occurrence (the fraction of days sharing the same WR with "control") to 54% in "PC7" and 49% in "shifted". However, the frequency of the 'spurious' WRs is 13% in "PC7" (ML2) and 14% in "shifted" (ML4), and when they are not considered in the computation of the co-occurrence rates, these increase to 72% in "PC7" and 65% in "shifted". The robustness of the WR classification in the period 2003-2017 is also assessed by comparison with the classification of the ASO synoptic variability in the same domain performed on the ERA5 data in the period 1981-2020. The ERA5 classification shows two WRs accounting for pressure anomalies in the South Atlantic, and four WRs accounting for pressure anomalies at the midlatitudes (Fig. 4g-l), characterised by persistence and transitions similar to the CAMS classification (Fig. 5b and Table 3). The comparison of the spatial patterns shows a high degree of similarity between the two classifications, with the WRs almost overlapping in terms of both circulation features and location and intensity of the anomalies (Fig. 4). As expected, the classification in ERA5, performed on a longer time period limiting the influence of the interannual variability, shows reduced differences in the WR frequencies at the seasonal time scale (frequencies are between 13.2% and 19.5% in ERA5 and between 12.1% and 22.3% in CAMS, see Fig. 7). The availability of 40 year time series in ERA5 allows to robustly estimate WR frequencies at the intraseasonal time scale (Fig. 7). Differences are limited to 1-2%, with the exception of ML2 and ML3, increasing by 3% and decreasing by 4% during the season, respectively. The comparison of the WR occurrences in the overlapping period (ASO 2003-2017) shows that 81% of the days are characterised by the same WR in ERA5 and CAMS. The sensitivity tests performed on the WR classification of the CAMS data show a high degree of robustness with respect to changes in the time period, and a good degree of robustness with respect to changes in the geographical domain and the retained variance, highlighting that the classification well represents the main features of the synoptic circulation in the region.

At the global scale, the variability of the atmospheric circulation south of 20°S is dominated by the southern annular mode (SAM), which consists of out-of-phase surface pressure and geopotential height anomalies between the Antarctic region and the southern midlatitudes, resulting in the modulation of the location and intensity of the westerly wind belt (Baldwin, 2001; Limpasuvan and Hartmann, 1999). ~~Pohl and Fauchereau (2012) characterised the synoptic variability of the SAM in terms of WR, identifying 4 main variability modes in the southern midlatitudes, three of them associated with circulation patterns characterised by stationary wave-number 4. The persistent character of WR2 and 6 indicate a possible connection with the synoptic variability of the SAM.~~ The relationship between the WR occurrence and the SAM daily index is investigated applying both the C2E and the E2C approach to the ERA5 classification. When the SAM index is associated with the different WRs, the ANOVA shows that the distributions are not derived from populations with the same mean ($p<0.01$). However, the C2E characterisation of the SAM index does not show a clear association between positive and negative SAM phases and the WRs (Fig. 8a). When the SAM index quartiles are associated with the changes in the WR frequency (E2C), a significant increase in frequency of SA+ and SA- is detected for large positive values of the SAM index, while large negative values occur when ML1, 3 and 4 are significantly more frequent (Fig. 8b). Not surprisingly, the WRs characterised by travelling midlatitude disturbances are associated with negative SAM phases, i.e. with intensified westerlies. Conversely, positive SAM phases, resulting in weaker westerlies, are associated with increased frequency of the WRs accounting for the pressure anomalies in the South Atlantic. ~~WR6 shows a statistically significant association with positive SAM phases (not shown), coherently with expected weaker westerlies at midlatitudes (see Fig. 4f). However, the WR2-SAM relationship results statistically weaker, and no relationship at all is found with WR1, 3, 4 and 5 (not shown).~~

3.2. Synoptic characterisation of reanalysis aerosol optical depth

The WRs describing propagative disturbances at midlatitudes (ML1-4) are characterised by the longitudinal displacement of high-low pressure anomalies modulating the meridional circulation, which in turn drives the poleward BBA transport above the South Atlantic and southern Africa (Fig. 4c-f). In particular, ML3 favours the recirculation of BBA from the ocean towards Namibia and South Africa, leading to significant positive AOD anomalies above all the continental stations (Fig. 4e), while ML2 pushes the BBA recirculation above the South Atlantic and inhibits the BBA transport towards the Indian Ocean (Fig. 4d). Conversely, ML1 and 4 are associated with a weaker BBA transport above Namibia and South Africa, leading to significant negative anomalies above the continental stations, and larger transport towards the Indian Ocean (Fig. 4cf). BBA transport along the Atlantic coast of Namibia and South Africa is also anomalously high during SA-, which is characterised by a low pressure anomaly in the South Atlantic inhibiting the transport towards the subtropical South Atlantic, and leading to significant negative anomalies above Ascension Island, and favouring a poleward route driving anomalous BBA concentrations above the continental stations (Fig. 4b). SA+, characterised by a high pressure anomaly in the South Atlantic strengthening the easterly flow in the Tropics, is the only WR associated with a reinforcement of the main BBA transport route in the tropical South Atlantic, and positive AOD anomalies only affect the Ascension Island station (Fig. 4a).

The analysis of persistence and transitions highlights two distinct variability patterns in the WR classification, both developing at synoptic time scales (see Section 3.1). On the one hand, SA+ and SA- are characterised by a pulsating nature, with a lifetime of up to 3 days each (Fig. 6ab), which may affect the variability of the BBA transport in the Tropics. A lead-lag correlation analysis indicates an 8 day period for the AOD anomalies to build up in the tropical South Atlantic along the easterly route from tropical Africa (Fig. 9ab). On the other hand, ML1-4 represent the fingerprint of travelling midlatitude disturbances, characterised by up to 2 day persistence and subsequent up to 2 day transitions (Fig. 6c-f), possibly leading the variability of the tropics-extratropics BBA transport. The lead-lag correlation analysis shows a 6 day period for the river of smoke to build up in the South Atlantic and move eastward across southern Africa (Fig. 9cd).

3.3. Synoptic characterisation of aerosol optical depth in-situ observations

The robustness of the synoptic characterisation of the BBA transport obtained from the CAMS data is assessed by linking the WR classification to the observed AOD from AERONET stations in the region. It is highlighted that data availability and coverage in most of the stations is limited (see Table 1), resulting in circa 20-40 observations per WR on average. Only the station in Ascension Island covers the whole period analysed, providing more than 600 observations, i.e. circa 100 observations per WR on average.

The C2E characterisation of the AOD observations is presented in Fig. 10. AOD anomalies above Ascension Island show significant negative values during SA- (Fig. 10a). The significance of this characterisation is confirmed by the ANOVA with a level of confidence higher than 99%. Just south of the source region in Bonanza, significant positive anomalies are observed during ML4 (Fig. 10b). However, the statistical significance of this characterisation only reaches 93%. AOD variability at the

Namibian Stations (Gobabeb, Henties Bay and HESS) is dominated by SA-, leading to significant positive anomalies, and ML1, leading to significant negative anomalies (Fig. 10c-f). In addition, significant positive anomalies are observed in HESS during the occurrence of ML3 (Fig. 10f). The ANOVA supports this characterisation, indicating that the null hypothesis, i.e. that the distributions associated with each WR are derived from populations with the same mean, can be rejected with a level of confidence higher than 99%. Similarly to HESS, the continental station in Upington shows significant negative anomalies during ML1 and 4, and significant positive anomalies during ML3 (Fig. 10h), and the ANOVA indicates the rejection of the null hypothesis with 99% level of confidence. In South Africa, the southernmost station in Simon's Town does not show significant anomalies in association with any WR (Fig. 10g), and the ANOVA confirms that the WR classification is not able to characterise the AOD variability (p=0.09). The C2E characterisation performed using observed AOD data confirms the relationship between the WRs associated with midlatitude disturbances (ML1, 3 and 4) and the BBA transport above the AERONET continental stations, and between SA- and the BBA transport above Ascension Island, as shown by the CAMS data (cf. Fig. 4). The comparison with the synoptic characterisation performed using a 7 cluster classification highlights that the latter is less robust, showing poorer ANOVA performances. Moreover, the additional WR, accounting for a strengthening of the continental high, does not provide further characterisation of the AOD anomalies (see Section S3 for details).

The E2C characterisation of the BB AOD station data is presented in Fig. 11. AOD anomalies are divided in quartiles, with quartiles from 1st to 4th representing anomalies from the largest negative to the largest positive, and the relative change in WR occurrence is displayed for each quartile. In Ascension Island, the 3rd quartile is characterised by a significant change in the WR frequency the distribution, with increased occurrence of ML4 (Fig. 11a). The Bonanza station does not show any significant change in the WR occurrence (Fig. 11b). In the Namibian Stations (Gobabeb, Henties Bay and HESS), positive AOD anomalies are associated with significantly more frequent SA- and ML2, while negative anomalies are associated with more frequent ML1 (Fig. 11c-f). In addition, in Gobabeb negative AOD anomalies are also associated with more frequent ML2 and 4 (Fig. 11d); in HESS positive anomalies are also associated with more frequent SA+, ML3 and 4, and negative anomalies are also associated with SA- (Fig. 11f). The South African stations in Upington and Simon's Town show positive AOD anomalies associated with more frequent SA-, ML2 and 3, and negative anomalies associated with more frequent SA-, ML1 and 4 (Fig. 11gh). The E2C characterisation confirms the importance of the midlatitude disturbances in controlling the AOD anomalies at the AERONET continental stations, in particular by driving the largest anomalies (1st and 4th quartiles). However, this approach shows some inconsistencies: ML4, which is characterised by a southerly anomaly in the BBA transport along the Atlantic coast (Fig. 4f), is associated with positive AOD anomalies in HESS instead; similarly SA-, characterised by a northerly BBA transport anomaly along the coast (Fig. 4b), is associated with both positive and negative anomalies in HESS and Upington. The origin of this ambiguities is likely due to the location of these stations at the margin of the BBA transport path associated with the WR circulation patterns, making them highly sensitive to the variability of the circulation around the centroid. The comparison with the synoptic characterisation performed using a 7 class partition highlights the same ambiguities when the AOD anomalies in the continental stations are associated with the WR describing a low pressure anomaly in the South Atlantic (see Section S3 for details).

3.4. Interannual variability

The WR frequency in ASO is also analysed at the interannual time scale, by using the ERA5 classification on the period 1981-2020 (Fig. 12). All WRs show similar interannual variability in the frequency of occurrence (3-4% standard deviation) and no trend is found after a Mann-Kendall test at 95% level of confidence is performed. Possible teleconnections controlling the WR interannual variability are analysed by computing the linear correlation between the WR frequency and the SST variability at the global scale (Fig. 13). ML1-4 do not show significant correlation patterns at the global scale (see Fig. S11). Conversely, SA+ and SA- show a relationship with SST anomalies in the tropical Pacific and the North Atlantic. In particular, the occurrence of SA+ is associated with La Niña conditions and cold anomalies in the subtropical North Atlantic (Fig. 13a), while SA- is associated with El Niño conditions and warm anomalies in the subtropical North Atlantic, although the significance of the correlation is reduced (Fig. 13b). The linkage with La Niña conditions can explain the SA+ peak in 2010 (Fig. 12) associated with a strong La Niña event (Boening et al., 2012), and the minimum in 2015 (Fig. 12), associated with an extreme El Niño event (Hu and Fedorov, 2017). The analysis of the WR-SST correlations performed by using NOAA ERSST data show similar teleconnection patterns (Fig. S12). Differently from the WRs associated with travelling disturbances, SA+ and SA- are characterised by short persistence and represent a sort of stationary South Atlantic oscillatory pattern (see Chen, 2014), which might interact with Rossby-wave patterns from the equatorial Pacific during El Niño/Southern Oscillation (ENSO) active phases (e.g. Hoskins and Ambrizzi, 1993). The teleconnection mechanisms are explored by computing the correlation between the WR occurrence and the global geopotential at 200 hPa, the level where teleconnection signals are the strongest. Wave patterns connecting the tropical Pacific to pressure anomalies in the South Atlantic are found for both SA+ and SA-, though significance for SA- is weak (Fig. 13cd). A similar modulation by the ENSO of synoptic regimes in the Southern Hemisphere is also reported during austral summer by Fauchereau et al. (2009) and Pohl et al. (2018). The analysis of the WR-

SAM relationship at the interannual time scale shows poor results when the WR frequency time series are correlated with the SAM monthly index. Similarly, the correlation between the WR frequency time series and the monthly averages of the geopotential height at 700 hPa in the Southern Hemisphere does not show evident correlation patterns (not shown).

4. Conclusions

In this paper, the first objective classification of the synoptic circulation over the South Atlantic and southern Africa during the dry season is presented. By using atmospheric circulation data from a reanalysis product, a robust classification with 6 WRs is defined for August-to-October in the period 2003-2017. Four WRs (ML1-4) represent the fingerprint of the life cycle of propagative disturbances embedded in the regional midlatitude dynamics, while two WRs (SA+ and SA-) represent the oscillation of the pressure field in the South Atlantic. In particular, SA+ is associated with a reinforced South Atlantic anticyclone, and is the dominant WR during the dry season. The occurrence of ML1-4 is favoured by intensified westerlies associated with negative values of the daily SAM index, while SA+ and SA- occurrence is associated with positive SAM phases. All the identifies WRs show short persistence, not exceeding 3 days, highlighting the synoptic character of the associated circulation patterns. As a consequence, the analysis of possible teleconnections does not reveal significant remote controls of the WR occurrence at the interannual time scale. Only SA+ and SA-, characterised by slightly longer persistence (up to 3 days), show a weak connection with the El Niño/Southern Oscillation through a tropical-extratropical Rossby wave pattern.

The synoptic classification is used to characterise the transport of BBA from equatorial Africa, which dominates the aerosol atmospheric content in the region during the dry season. By analysing reanalysis data, it is found that SA+ and SA- modulate the easterly transport from tropical Africa sources, which is the main climatological transport route. The synoptic characterisation also shows that midlatitude propagative disturbances modulate the BBA transport from equatorial Africa, elucidating the mechanism responsible for the BBA transport to the extratropics, which is peculiar in this period of the year. Specifically, the formation of rivers of smoke is favoured by the low-high pressure anomaly systems characterising the ML WRs, channelling the BBA in the meridional direction (see e.g. ML2 in Fig. 4). Once the river of smoke is formed, it crosses southern Africa embedded in the anomaly pattern travelling eastwards, in turn modulating the AOD anomalies over the continent (see e.g. the ML2 → ML3 → ML4 → ML1 evolution in Fig. 4). The BBA transport characterisation is also tested by using AOD observations from AERONET stations, which show a good degree of consistency with the results based on reanalysis data. However, limited data availability in most of the stations prevents a robust statistical validation of the synoptic characterisation of observations at the regional scale. Results show that the occurrence of ML1 and

4 inhibits the BBA transport towards the continental stations (Gobabeb, Henties Bay, HESS and Upington), while ML3 favours the transport above the same locations. Along the Atlantic route, the occurrence of SA- limits the BBA transport towards Ascension Island. In-situ observations in Bonanza and Simon's Town are not well characterised by the WR classification. The former likely because of its proximity to the source region, where emission is not strongly affected by the synoptic atmospheric circulation, the latter possibly because of the poor data coverage.

Overall, WR clustering shows to be a valuable tool in discriminating aerosol transport and concentrations over the South Atlantic and southern Africa at the short timescales (day-to-day and synoptic variability). ~~However, the characterisation of the AOD variability at the interannual time scale shows limited performance, probably due to the shortness of the time period considered in the analysis. Indeed, within a 15 year time range, a large fraction of the variance is associated with daily weather patterns instead of changes from one season to another. This gap can be filled by analysing longer coverage reanalysis products.~~

A 7 class partition is also tested for the characterisation of the synoptic variability of the BBA transport. However, this classification does not improve the performance of the 6 class partition, showing overall poorer statistics and not correcting some ambiguities found in the E2C characterisation of the continental AERONET stations.

The analysis of the regional circulation patterns controlling the BBA transport the South Atlantic/southern Africa sector is reported in literature mainly as a complement in the discussion of field campaign results. During the SAFARI-92 field experiment, Lindesay et al. (1996) reported pronounced BBA transport across southern Africa towards the Indian Ocean, in association with El Niño conditions and intensified continental high. Conversely, during the SAFARI 2000 campaign (Swap et al., 2003), Stein et al. (2003) found an association between the development of rivers of smoke heading towards the Indian Ocean and increased westerly waves and weaker continental high, concomitant with La Niña conditions (see also Garstang et al., 1996). These contrasting conclusions likely originate from to the limited robustness of the analysis due to the shortness of the observation periods. Based on a longer dataset, the WR characterisation suggest a key role of the westerly waves in controlling the rivers of smoke, supporting the hypothesis of Garstang et al. (1996), although it remains inconclusive concerning the role of ENSO phases.

This paper provides new insights in the understanding of the synoptic circulation in the South Atlantic and southern Africa, by characterising for the first time the dry season circulation and the associated rivers of smoke. The characterisation of the transport routes in the region is crucial to support the characterisation of the physical and chemical properties of the BBA, and model the associated impact on clouds and radiation. The WR characterisation is also a valuable resource to develop predictive tools for the BBA spatial distribution in the region. In particular, by using reliable long coverage reanalysis products a classification for past decades can be built, and the BBA spatial distribution can be reconstructed where observations are not available. Furthermore, the WR characterisation can be used in climate model projections to estimate the future evolution of the rivers of smoke in the region.

*Data availability***.** CAMS data are freely available at the Copernicus Atmospheric Data Store (https://ads.atmosphere.copernicus.eu/). AERONET station data are made freely available by the NASA Goddard Space Flight Center (https://aeronet.gsfc.nasa.gov/). The SAM daily index is made freely available by the NOAA Climate Prediction Center (https://www.cpc.ncep.noaa.gov/).

Supplement. The supplement related to this article is available online at XXXXXXXXXXX.

Author contributions. MG conceived the study, designed and performed the analysis and wrote the paper. BP and MCAC performed the WR classification. All the authors contributed to the discussion and interpretation the results and the writing of the text. PF and CF designed the original AEROCLO-sA observational concept, and co-led the 5-year investigation.

*Competing interests***.** PF is guest editor for the ACP Special Issue “New observations and related modelling studies of the aerosol–cloud–climate system in the Southeast Atlantic and southern Africa regions”. The remaining authors declare that they have no conflicts of interests.

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