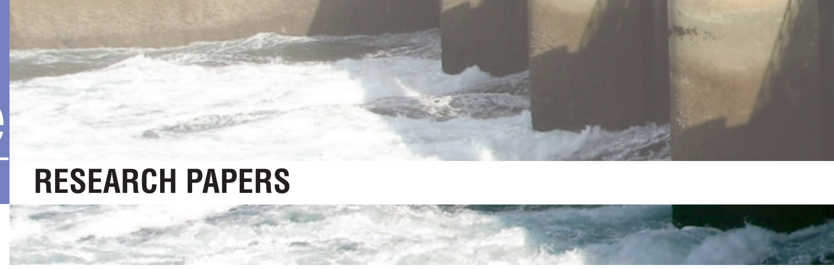

The XX century variability of West African Monsoon

We compare the West African atmospheric circulation reproduced by the global reanalyses NCEP-NCAR and ERA40 for the period 1961-2000, focusing on the structure of the mean African Easterly Jet and of the high-frequency disturbances (AEWs) developing on its flanks. As AEWs play a significant role in determining the amount of variability over this region, a realistic representation of such dynamics is crucial for correct climate prediction and seasonal forecast. We also analyze the seasonal cycle of the precipitation over West Africa

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La variabilità del Monsone Africano nel XX Secolo

L'articolo riporta la circolazione atmosferica dell'Africa occidentale così come riprodotta dai dati delle rianalisi globali NCEP-NCAR ed ERA40 relative al periodo 1961-2000, con particolare riferimento alla struttura della corrente a getto africana (African Easterly Jet) e delle onde (African Easterly Waves - AEW) che si sviluppano sui suoi fianchi e si propagano verso ovest. Le AEW svolgono un ruolo rilevante nella determinazione della variabilità del monsone in questa regione, pertanto una rappresentazione realistica di tale dinamica si rivela fondamentale per una predizione climatica e previsioni stagionali corrette. Viene inoltre riportata l'analisi del ciclo stagionale delle precipitazioni sull'Africa occidentale

Introduction

During summer, the atmospheric circulation over West Africa exhibits a strong monsoon flow, with moist-air from the Gulf of Guinea towards the interior of the continent. Such a highly nonlinear circulation is driven by the meridional gradient of the boundary layer temperature which develops across the Gulf of Guinea and the Western African continent (Elthair and Gong, 1996). The West African Monsoon (WAM) is characterized by a mid-tropospheric zonal wind maximum (the African Easterly Jet - AEJ), peaking at 600-700 hPa and flanked by synoptic systems (African Easterly Waves, AEW) which develop on its sides and determine a consistent amount of the total precipitation in the area. The AEJ is confined to a width of 5°-10° of latitude, with the jet core placed approximately at 15°N on the west coast and over the Atlantic ocean, and maximum easterly velocities of about 10-11 m/s. It is sustained by lower tropospheric dry convection in the Sahara and deep moist convection in the intertropical con-

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vergence zone (ITCZ) (Thorncroft and Blackburn, 1999).

The synoptic systems growing on the AEJ flanks have been argued to result from the interaction of barotropic and baroclinic instabilities of the AEJ (Hall et al, 2006; Kiladis et al, 2006; Chen 2006; Hsieh and Cook, 2007). AEWs are the primary synoptic-scale disturbances affecting tropical northern Africa climate during the rainy summer season, and are connected to the occurrence of Atlantic hurricanes and of rainfall events over Africa (e.g., Burpee 1974; Reed et al. 1977; Thompson, et al. 1979). These disturbances typically show periods of 3-5 days, wavelengths of about 2000-4000 km, and westward mean propagation speed of about 6°–7° day^{-1} (7-9 m s^{-1}), being located at a mean latitude of 11°N over land and of 12°N over the ocean (e.g., Reed et al.1977). The AEWs propagating at the northern flank of AEJ are thought to be generated by baroclinic instability of the lower troposphere. The track of these disturbances lies primarily over the land, where the baroclinic processes and the diabatic interactions with the surface and in particular with the Sahara desert environment seem to be dominant (Thorncroft and Hoskins 1994, Chang 1993). On the contrary, the AEWs propagating on the southern flank of the jet are liable to be a result of barotropic-baroclinic instability mechanisms such as the Charney-Stern process (Charney and Stern, 1962) at the jet core level, induced by cumulus moist convection within the ITCZ (Thompson et al 1979; Hsieh and Cook 2007). However, there is still an ongoing debate about both the location of the source region of the aAEWs and the mechanisms of their genesis (Mekonnen et al 2006), prompted by the necessity of a proper treatment of such processes in Climate Models. As a matter of fact, being usually associated with rainfall, they play a relevant role in determining precipitation variability over the affected region, and their improper representation would impose a severe constraint on the feasibility of climate prediction and seasonal forecast in this area (Fyfe, 1999).

Although the time scales characterizing the variability of such phenomena range from intra-seasonal to interdecadal, we mainly focus on the mean state of the AEJ during the summer season, and on its relation with the intra-seasonal variability of the AEWs and of the associated rainfalls. Our analysis covers 40 years, from 1961 to 2000.

In next section, the NCEP-NCAR and ERA40 re-analysis datasets. Results from two global reanalyses NCEP-NCAR and ERA40 are reported in section 3. Summary and conclusions are drawn in section 4.

Datasets

The NCEP reanalyses are produced with the T62 version of the operational T126 model, attaining a horizontal resolution of about 200 km. Vertical resolution is variable, as 28 levels are unevenly distributed from the surface to 3 hPa. The ERA40 reanalyses have a finer resolution, deriving from the T159 spectral truncation and the higher number of vertical levels (60), with the upper boundary at 0.1 hPa. We also examine the precipitation climatology provided by the Global Precipitation Climatology Centre (GPCC). The GPCC provides a global dataset of monthly gridded precipitation data derived from station observations (Beck et al 2005).

Background: AEJ and AEWs as simulated by the NCEP-NCAR and ERA40 assimilation systems

In order to characterize the climatology of the zonal wind in the area of interest, we averaged the summer mean (JJAS) of the *u* component over the longitudinal belt comprised between 15W and 10E and over the whole period 1961-2000, and analysed the resulting meridional cross-section for each of the two Reanalyses. Important circulation features are apparent in the zonal wind cross sections shown in panels *a* and *b* of Fig. 1, derived from NCEP and ERA40, respectively. The low-level monsoon flow onto the Guinean coast is revealed by the low-level westerly zonal wind maximum confined below 800 hPa between latitudes 5° S-20°N, characterized by a maximum velocity of about 3-4.5 m/s, penetrating well onto the continent. Most of the onshore monsoon flow is located in the deep convection area of the ITCZ between 5°N and 10°N. The easterlies exhibit two well defined maxima: the AEJ, located at 600hPa between 10°N-15°N, and the Tropical Easterly Jet (TEJ) at 200 hPa and further southward. The surface easterlies which prevail north of the thermal low are associated with the monsoon flow and give rise to the Harmattan winds. The main discrepancy between the two reanalyses appears on the southern flank of the AEJ, where NCEP-NCAR produces a stronger easterly pattern, which seems to emanate from the AEJ and to penetrate into the Southern Hemisphere, a feature that is clearly weaker in the ERA40 dataset.

The AEJ structure is thought to be maintained by the diabatically forced meridional circulation associated with dry convection in the Saharan thermal low region, and by the meridional circulation induced by

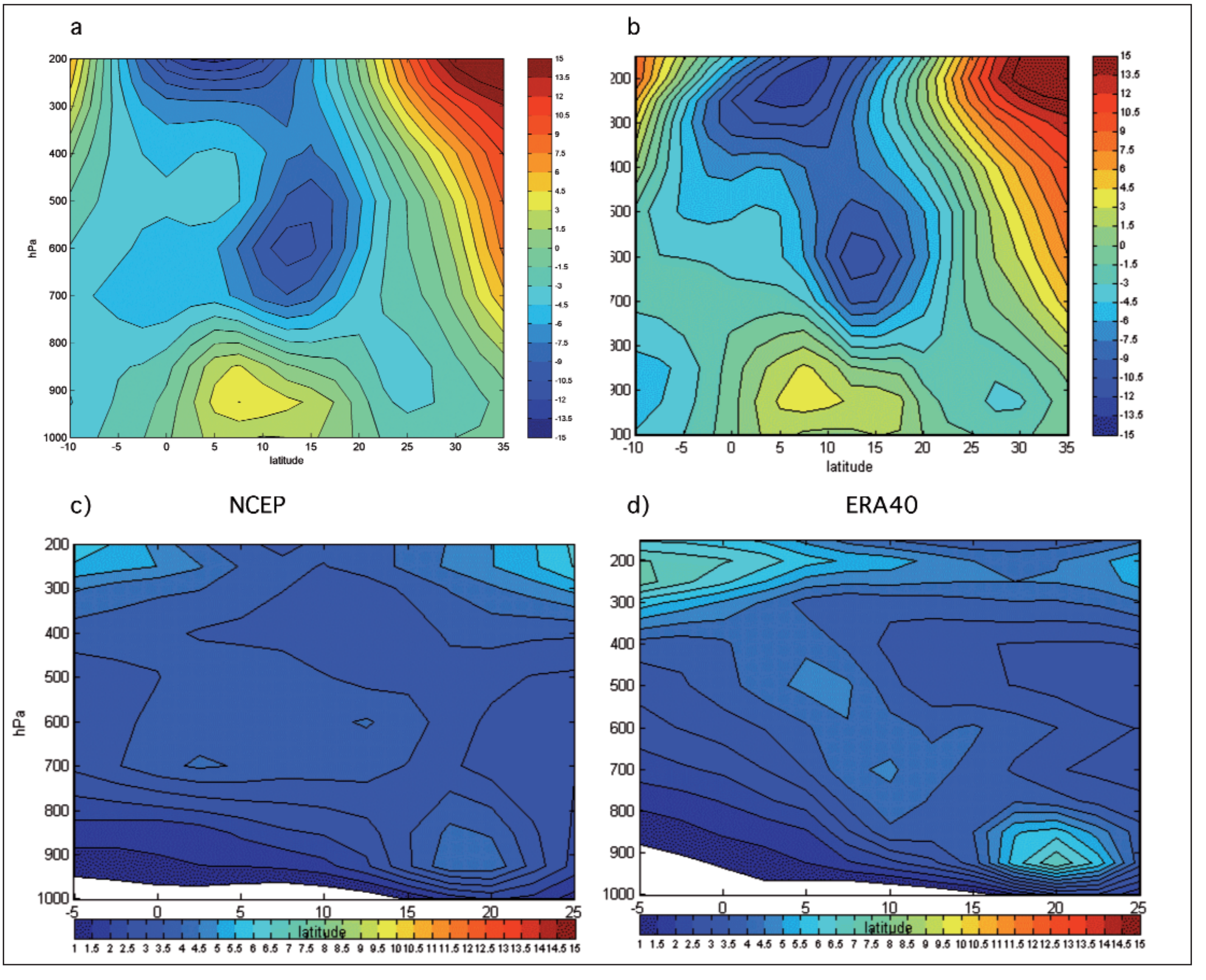

FIGURE 1 a-b) Mean state for zonal wind for NCEP and ERA40, respectively. Unit: m/s
c-d) Band-pass 2-6 days variance of meridional wind for NCEP and ERA40, respectively. The cross sections are obtained averaging the fields over the longitudinal bans 15W-10E. Unit: $(m/s)^2$

deep moist convection in the ITCZ (Thorncroft and Blackburn 1999). The AEJ is characterised by vertical and meridional shears and it is dynamically unstable. Instabilities could arise at the flanks of the AEJ through barotropic and baroclinic energy conversions (Burpee 1972, Thorncroft and Hoskins 1994). In particular, it has been suggested that baroclinic processes are more important over the land while barotropic process are dominant over the sea (Norquist et al 1977, Thorncroft and Hoskins 1994). The meridional structure of the zonal wind in Fig. 1a-b corresponds to a distribution of (not shown here) that satisfies the Charney Stern instability criterion (Charney and Stern, 1962). As a matter of fact, the mean state is characterised by negative values of in correspondence of the jet core and by positive values of at the flanks (Thorncroft and Blackburn 1999). Therefore changes sign in the fluid interior, thus allowing the growth of unstable disturbances. Such reversal of the PV meridional gradient at the southern flank of the AEJ has been associated to convective heating in the ITCZ, suggesting that convection processes in the ITCZ play a relevant role in giving birth to unstable easterly waves in the West African region (Schubert et al 1991).

The spectra of the meridional wind variance over the West African region exhibit a peak for 2-6 day periods (Mekonnen et al 2006). In Fig. 1c-d we show the latitude-height cross-sections of the meridional wind variance (longitudinally averaged 15W-10E) after a 2-6 day band-pass filter has been applied, for NCEP-NCAR and ERA40 reanalyses respectively. In accordance with the results reported in Pytharoulis and Thorncroft (1999) and Chen (2006), we find two local maxima at both flanks of the AEJ (located at about 12N-600 hPa), in correspondence of positive gradients. Both reanalyses show a well defined maximum in the lower troposphere below 850 hPa at about 20°N, associated with anticyclonic-shear at the northern flank of the AEJ. This feature is in conjunction with clear sky conditions and large values of kinematic wave activity, as well as with vorticity anomalies (Thorncroft and Hoskins, 1994; Kiladis et al 2006). The second maximum is located at the southern flank of the AEJ, but its location is different in the two reanalyses sets. In the NCEP-NCAR reanalysis the maximum is placed over the Gulf of Guinea and does not extend far below 700 hPa, while ERA40 sets it northward over the continent and describes it as a deeper tropospheric structure stretching from 800 hPa to 500 hPa. Some authors (Burpee 1974 among others) suggest that the mid-tropospheric instability south of the AEJ is generated by the Charney-Stern barotropic–baroclinic mechanism for energy conversion, which is thought to be directly linked to the dynamics of the ITCZ (Schubert et al 1991, Hsieh and Cook, 2007). Therefore, the different representation of the ITCZ structure and location in the two datasets (here not shown) is to be held responsible for a different structure of the field, thus justifying the dissimilarities of Figs. 1c and 1d . The NCEP-NCAR and the ERA40 reanalyses also differ as to the PV gradient distributions (figure not shown), which is again a consequence of the discrepancies in the representation of the ITCZ between the two datasets, probably due to distinct treatments of deep convection in the underlying models. Hereafter we fix our attention mainly on the representation of the southern lobe of the variance, intimately related to convection and rainfall over West Africa.

In order to further validate the representation of the mean circulation over West Africa given by the reanalyses, for both datasets we show the seasonal cycle of local precipitation averaged over longitudes comprised between 15 W and 10E as a function of latitude, and compare the results with those reported in the observational land-based dataset GPCC (Fig. 2). In the GPCC dataset the rainfall peak changes location during summer, moving from 5N (June) up to 10 N (July-August). Both reanalyses capture this behaviour, although precipitations appear to be concentrated over the coastal region and do not extend farther than 10N. Moreover, the early summer peak observed at 5N in June appears to be shifted in time in the ERA40 reanalyses, which anticipate it to May, while it is much weaker and shifted northward in the NCEP dataset. In addition, ERA40 generally overestimates summer rainfall while NCEP underestimates it.

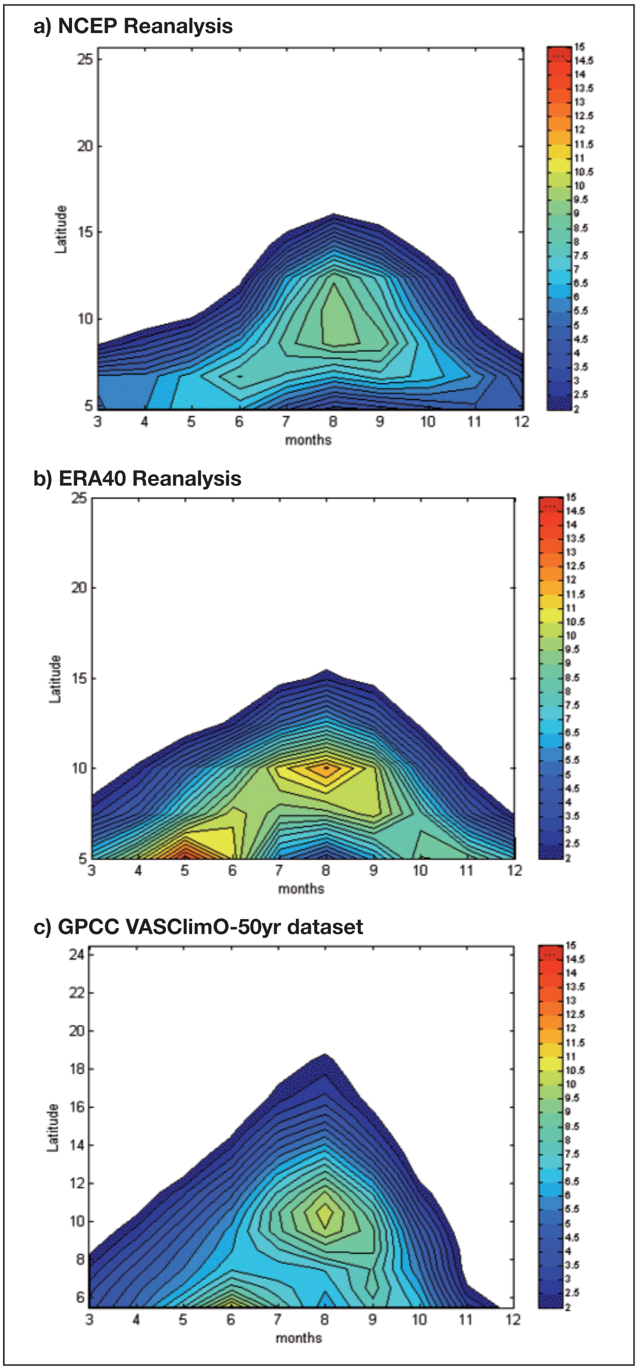

FIGURE 2 Season cycle for precipitation in mm/days over West Africa longitudinally averaged between 15W-10E for
a) NCEP Reanalysis
b) ERA40 Reanalysis
c) GPCC VASClim0-50yr dataset

Summary and discussion

The northern and the southern track of AEWs have been treated separately, in agreement with Reed et al. (1988), who analysed ECMWF data from 1985 onwards showing that the AEWs followed two different paths over the land (on either side of the jet), while over the ocean they merged and moved at a latitude of about 15°N. Particular attention is paid to the southern track of AEWs, as it is thought to be strictly linked to the occurrence of convection and rainfall over the Sahel region (Thorncroft and Hoskins 1994).

The two reanalyses show a similar mean circulation over West Africa, with minor discrepancies in the representation of the southern flank of the AEJ, but significant differences in the representation of the AEWs, especially as to the position of the major centre of variability. The NCEP reanalysis locates AEWs over the Gulf of Guinea and over the West African coast interested by monsoon circulation. On the other hand, in ERA40 a high variance pattern broadly extends over the African continent in the latitudinal band 5N-10N, in agreement with the analysis of the 2-6 day band pass variance of brightness temperature in this region carried out by Mekonnen et al (2006).

The differences between the two reanalyses appear to be robust features, which persist if our analysis is restricted to the time window 1979-2000 (figure not shown), over which better accordance is generally observed (Dell'Aquila et al. 2005). In spite of such discrepancies, the two reanalyses agree in their estimate of the percentage of total intra-seasonal variance over West Africa which is attributable to AEWs variability. The vertical structure of the perturbations (in particular the baroclinic tilt at lower levels) has been characterized by means of a PC analysis of the longitude-height cross-section of 2-6d band-pass filter meridional wind, revealing that the two datasets ascribe the generation of disturbances to the same dynamical processes, i.e. barotropic energy conversion at jet core level and baroclinic energy conversion in the lower tropospheric levels. However, comparison with an observational land-based dataset shows that ERA40 overestimates tropical rainfall in the area while NCEP underestimates it.

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