A Characterization of African Easterly Waves on 2.5–6-Day and 6–9-Day Time Scales

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ABSTRACT

This study shows that the African easterly wave (AEW) activity over the African monsoon region and the northern tropical Atlantic can be divided in two distinct temporal bands with time scales of 2.5–6 and 6–9 days. The results are based on a two-dimensional ensemble empirical mode decomposition (2D-EEMD) of the Modern-Era Retrospective Analysis for Research and Applications (MERRA). The novel result of this investigation is that the 6–9-day waves appear to be located predominantly to the north of the African easterly jet (AEJ), originate at the jet level, and are different in scale and structure from the well-known low-level 2.5–6-day waves that develop baroclinically on the poleward flank of the AEJ. Moreover, they appear to interact with midlatitude eastward-propagating disturbances, with the strongest interaction taking place at the latitudes where the core of the Atlantic high pressure system is located. Composite analyses applied to the mode decomposition indicate that the interaction of the 6–9-day waves with midlatitude systems is characterized by enhanced southerly (northerly) flow from (toward) the tropics. This finding agrees with independent studies focused on European floods, which have noted enhanced moist transport from the ITCZ toward the Mediterranean region on time scales of about a week as important precursors of extreme precipitation.

1. Introduction

This article investigates African easterly waves (AEWs) with the goals of understanding different regimes and unveiling teleconnections with the extratropics. Disturbances with time scales of about 2–5 days developing over Africa and the tropical Atlantic at latitudes between the African easterly jet (AEJ) and the intertropical convergence zone (ITCZ), with wavelengths ranging from 2000 to 4000 km and propagation speeds of about 15 m s$^{-1}$, have been known for a long time (e.g., Burpee 1972). They began receiving special attention after the Global Atmospheric Research Program (GARP) Atlantic Tropical Experiment (GATE) field campaigns (Burpee 1975; Reed et al. 1977; Thompson et al. 1979). In the following decades, evidence was provided that the range of time scales for African wave–like disturbances may be wider, and various authors started investigating a 2–10-day time window to properly encompass all time scales associated with AEWs (e.g., Dickinson and Molinari 2000).

The possibility that wave activity is not homogeneously distributed across the 2–10-day time scale was first explored by de Felice et al. (1990, 1993), who presented evidence of wave activity acting on a time scale of about 6–9 days, separate and different from the 2–5-day wave time scale. At that time, neither analyses nor

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models had the capability of accurately representing such phenomena and unveiling possible mechanisms. Since a widely accepted explanation of the 6–9-day time scale was lacking, the idea of two separate wave regimes was not further investigated until the seminal work by Diedhiou et al. (1998) in which a spectral analysis along the 17.5°N parallel was computed on the 700-hPa meridional wind obtained from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalyses. By using fast Fourier and wavelet transforms on a large sample, inclusive of all summers between 1979 and 1995, Diedhiou et al. provided evidence of two time scales within the easterly wave regime. One of the two subregimes, appearing on the 6–9-day time scale with a wavelength of about 6000 km, was attributed to oscillations within subtropical high belts. In the more extensive follow-up study by the same team (Diedhiou et al. 1999), the spectral analysis and wave tracks were computed from both NCEP and European Centre for Medium-Range Weather Forecasts (ECMWF) daily reanalyses, confirming those results and providing more robust evidence of two bands, one between 3 and 5 days and the other between 6 and 9 days. Diedhiou et al. (2002) further corroborated these findings by performing a comprehensive 17-yr climatology of the energetics of the two wave types. Despite this set of studies, the possibility of two separate wave regimes on different time scales within the 2–10-day range was not further explored for several years.

While the idea of separate AEW time scales did not generate wide interest, several studies investigated the possibility that AEW tracks could cluster around different families of trajectories. Among these, Carlson (1969) was perhaps the first to locate, based upon 33 observed waves, a hint of two activity maxima, coincident with two vortices, one at higher elevation (10 000 ft) located at about 12°N and one at lower elevation (2000 ft) at about 20°N, with the former displaying a westward propagation tendency toward the Atlantic Ocean and the latter appearing to vanish along the coastline. Carlson (1969) also noted a semipermanent trough close to the coast of northwestern Africa.

Reed et al. (1977) analyzed eight waves observed during August–September 1974 and found evidence of two circulation centers at the surface, both over land, with the northernmost one located at about 10° north of the monsoonal trough.

The Norquist et al. (1977) investigation of wave energetics revealed two centers of energy conversion: one characterized by the predominance of moist convective processes to the south of the AEJ at about 700 hPa and a drier, lower-elevation conversion to the north, dominated by baroclinic processes. Similar results were obtained by Albignat and Reed (1980), who emphasized the baroclinic tilt of the waves produced to the north of the AEJ and the dominance of latent heat release for the waves produced south of the AEJ. Nitta and Takayabu (1985) and Reed et al. (1988) presented evidence of two different (although coupled) tracks for AEWs over North Africa (to the north and south of the AEJ respectively), the latter study indicating a merging tendency over the ocean at about 15°N.

A comprehensive study by Duvel (1990) reviewed the preceding literature and investigated, based on ECMWF analyses, the AEW modulation of cloudiness. Among this work’s findings, two centers of actions seemed to be characterized by consistent cloudiness–wave phase relationships: one at about 7.5°N over the ocean, where convective activity was concentrated at or ahead of the wave trough, and the other at about 17.5°N over the Sahelian region, characterized by a convective maximum east of the trough.

Pytharoulis and Thornicroft (1999), using radiosonde data and the Met Office global analysis for the 1995 hurricane season, were able to provide further observational evidence in support of the existence of low-level easterly wave structures to the north of the AEJ, attributing their originating mechanism predominantly to baroclinic instability. The same study showed that there is strong coherence between the low-level AEWs and the well-known cold core AEWs that propagate south of the jet, confirming that both AEWs are associated with a combined barotropic–baroclinic instability mechanism. The authors did not detect different propagation speeds, at least over the African continent.

Ceron and Gueremy (1999) compared GCM simulations with the ECMWF analyses during the 1982–88 period, using a multitaper spectral technique and complex empirical orthogonal functions analysis, and documented the existence of two main modes of variability for AEWs defined as “northern single-track mode” and “dual-track mode.” Thornicroft and Hodges (2001), based on the location of the vorticity maxima obtained by compositing AEWs, demonstrated the existence of two tracks over northern Africa, one equatorward and one poleward of 15°N respectively, the former dominated by 600-hPa activity and the latter by 850-hPa activity. The two tracks become collocated over the Atlantic.

Grist (2002) and Grist et al. (2002) investigated the seasonal cycle and interannual variability of AEWs, demonstrating higher wave activity in wet versus dry years. For our purpose, these studies are particularly noteworthy because they are among the very few showing
evidence of different time scales. In particular, Grist (2002) found that time scales of about 6.25–7.5 days provide a higher contribution in the second part of the summer, whereas at lower levels the activity appears confined to 3.75–5 days. Grist et al. (2002) also performed a Charney–Stern instability analysis and demonstrated that, while the barotropic and baroclinic terms are of the same magnitude in dry years, only the barotropic term increases significantly in wet years. Consistent results were found by Lavaysse et al. (2006) on the presence of larger and stronger AEWs during wet sequences.

Evidence of a merging tendency over the Atlantic between different vorticity sources, which were previously separate over the African continent, was presented in a case study of an intense wave (Berry and Thorncroft 2005). Mekonnen et al. (2006) carried out spectral analysis of 3-hourly satellite brightness temperature for 18 years of July–September (JAS) months and found two prominent variance maxima in the 2–6-day period range (with one active predominantly in wet years).

Ross and Krishnamurti (2007) demonstrated that two wave regimes were present during 2001: a dry regime to the north (at about 20°N) and a wet regime to the south (at about 10°N), with substantial merging, splitting, and dissipation between the two, finding a predominance among lower level vorticity centers. Hopsch et al. (2007), by examining coherent vorticity structures, showed evidence of two prominent AEW source regions north and south of 15°N. From these source regions, two separate families of tracks could be detected, with the southern one being responsible for most of the storms that reach the main development region (MDR).

The modeling study by Cornforth et al. (2009) found evidence consistent with previous work by Thorncroft and Hodges (2001), Grist (2002), Grist et al. (2002), and Hsieh and Cook (2008) on the existence of jet-level amplitudes to the south of the jet and low-level amplitudes to the north of the jet. Moreover, the study showed the importance of moist processes in the development of the stronger waves and in giving rise to different wave time scales, conveying the idea of the AEJ and AEWs as an integrated dynamical system with many scales of interaction.

The theoretical study by Leroux et al. (2011) in addition to others (e.g., Hsieh and Cook 2005; Hall et al. 2006; Thorncroft et al. 2008) demonstrated the importance of precursors for the formation of waves (indicating that these do not arise out of AEJ instability alone) and suggested the possibility of an interaction with midlatitude North Atlantic storm tracks.

It is worth noting that the previously mentioned studies by Diedhiou et al. (1998, 1999), which are among the few to have shown evidence of two different wave regimes based on their time scale, also provided evidence through composite analysis that the spatial domains of those two regimes are different: according to their findings the 6–9-day wave regime appears to be affected by the interaction with large anticyclonic subtropical cells and is active on a more northern track. Diedhiou et al. (1999) further strengthened the evidence and added the information that these two main tracks, over West Africa at about 5° and 15°N, appear to merge over the Atlantic at a latitude of about 17.5°N. However, a fundamental question is posed by these findings. What is the relationship between the northern tracks detected on 6–9-day time scales and those studies that provide evidence of low-level disturbances growing baroclinically on the poleward flank of the AEJ?

In summary, several studies suggest a geographical separation between two wave regimes in terms of source and/or track, but most of them [with the exception of Diedhiou et al. (1998, 1999)] do not venture to confirm or oppose the claim that the two regimes had different time scales. On the contrary, several previously mentioned studies considered two belts of AEW activity on the 2.5–6-day time scale, one located at about 8°–12°N coincident with the reversal of the meridional gradient of potential vorticity south of the AEJ, and the other near 20°N and mostly constrained below 800 hPa in the surface baroclinic zone (e.g., Norquist et al. 1977; Pytharoulis and Thorncroft 1999; Kiladis et al. 2006). It can be said that the northern and southern tracks have been generally regarded as part of the same 2.5–6-day phenomenon, distinguishing a dry, predominantly baroclinic low-level component acting to the north of the jet, from a higher level, moist component acting on the south of it (Céron and Guéry-Oury 1999; Thorncroft and Hodges 2001; Mekonnen et al. 2006).

The investigation of the 6–9-day time scale did not receive attention again until the study by Wu et al. (2012, hereafter WA12). WA12 investigated the 6–9-day periodicity using the Hilbert–Huang transform, defined in Huang et al. (1998), and, while confirming the results of Diedhiou et al. (1998, 1999), hypothesized that the periodicity arises as a tropical–extratropical interaction, rather than from a purely tropical mode originated within the subtropical height belt.

The purpose of the present work is threefold. The presence of two wave regimes will be examined from the point of view of 1) time scales, 2) tracks and track mergers, and 3) possible interaction with midlatitude disturbances. To produce a comprehensive assessment of the 6–9-day periodicity and shed some light on its contributing mechanisms, the Modern-Era Retrospective Analysis for Research and Applications (MERRA),
recently produced by the National Aeronautics and Space Administration (NASA) Global Modeling and Assimilation Office (GMAO) and documented extensively in Rienecker et al. (2011), will be used. The main diagnostic tool will be the recently developed two-dimensional ensemble empirical mode decomposition (2D-EEMD), a spectral technique particularly designed for the investigation of nonlinear and nonstationary transient data, documented in Huang et al. (1998) and previously used by, among others, M.-L. Wu et al. (1999, 2009a,b). The 2D-EEMD methodology produces oscillatory modes not requiring any assumption about specific functions (e.g., sinusoidal) and is applied to unfiltered data.

Section 2 describes the data and methodology adopted. Section 3 provides the results, including the climatology, the modes resulting from the 2D-EEMD, a description of wave structure and propagation, and some dynamical implications. As an example of tropical–extratropical interaction, section 3e shows two cases of synoptic-scale event on the 6–9-day time scale with extratropical interaction, section 3e provides the results, including the climatic functions (e.g., sinusoidal) and is applied to unfiltered data.

Because of the reliance upon MERRA data, the focus of this article is on the satellite era from 1980 onward. In particular, 10 ENSO-neutral years, classified as neither El Niño or La Niña, are selected. The years selected are 1980, 1982, 1983, 1984, 1985, 1989, 1995, 1996, 2000, and 2001, to be consistent with our previous study (WA12).

The quantities used in this work are zonal and meridional wind, moisture transport, and precipitation. All of the data are interpolated from the original resolution to 1° × 1° grids. As in WA12, spectral analysis based on Huang et al. (1998) is used as an investigating tool. In particular, the 2D-EEMD methodology, as in M.-L. Wu et al. (2009a,b) and Huang and Shen (2005), is applied to the 700-hPa meridional wind. The 2D-EEMD is an adaptive method, based on the Hilbert–Huang transform (Huang et al. 1998). Unlike the Fourier transform, this methodology does not need any assumptions about sinusoidal or wave functions and is therefore particularly
designed to analyze nonstationary and nonlinear processes. The frequency is computed from the intrinsic mode functions (IMFs) through a Hilbert–Huang transform and the final result is a time–frequency–energy joint distribution, designated as the Hilbert spectrum. The IMF decomposition, also known as empirical mode decomposition (EMD), is a method to separate the variations according to their time scale in physical temporal space. The basis is generated adaptively as discussed in detail in Huang et al. (1998, 1999) and Z. Wu et al. (2009). Applications to atmospheric analysis include M.-L. Wu et al. (2009a,b) and WA12.

In addition to the investigation based on the 2D-EEMD methodology, two filters, designed to isolate the time windows of 2.5–6 days and 6–9 days, are applied to the unprocessed data. The choice of the windows follows previous work documented in WA12 and is made to show the consistency with the modes extracted from the Hilbert spectral analysis. The 2.5–6 (6–9)-day time window is obtained by using the symmetric four-pole low-pass tangent Butterworth filter described in Oppenheim and Schafer (1975). The filter is applied twice, first retaining time scales longer than 2.5 (6) days and then retaining time scales longer than 6 (9) days. The bandpassed data are obtained by subtracting the two filtered datasets. Composites and correlations are computed using the filtered data in both 2.5–6-day and 6–9-day time windows, again to show consistency with the results obtained by the 2D-EEMD decomposition.

### 3. Results

#### a. Climatology

Prior to the application of the 2D-EEMD methodology, it is useful to summarize the main features of the circulation over the African monsoon and the tropical Atlantic regions, which will be the focus of the investigation in this article. To this purpose, Fig. 1 displays the JAS climatology of the 700-hPa zonal (u700) and meridional (v700) wind. Since the focus of this article is on the existence of two time scales of activity, the circulation is superimposed on the v700 variance (hereafter $\sigma^2_{v700}$) computed in the 2.5–6-day and 6–9-day time windows respectively. Total wind and filtered variances are computed over the 10 ENSO-neutral years listed in section 1. In Fig. 1, surface temperatures and moisture transport at 700 hPa are also shown. The well-known, zonally elongated, double-centered anticyclonic circulation over the central Atlantic and northern Africa is very evident, with the two centers located at a latitude of about 30°N, one over the ocean at about 45°W and the other over northwestern Africa, slightly east of 0° longitude. Easterly flow dominates the latitude band south of the anticyclone centers (between approximately 6°N and 26°–28°N), whereas westerly flow prevails to the north of them. Between the two centers of the anticyclonic circulation there is a climatological trough with its axis parallel to the northwest coast of West Africa, hereafter referred to as the “West African coastal trough” (WACT). This semi-permanent feature of the northwestern African climate is partly controlled by the orographic effect of the nearby Atlas range and the steep ocean-to-land temperature gradients.

It is worth noting that the spatial structure of $\sigma^2_{v700}$ computed in the 2.5–6-day and 6–9-day time windows differ substantially. While both filtered variances are higher in the midlatitudes where the westerly baroclinic flow dominates, $\sigma^2_{v700}$ in the 2.5–6-day passband has two well-separated maxima confined to the easterlies on the southern side of the anticyclone: one close to the African coast at about 10°N and the other at about 20°N, over the central northern tropical Atlantic.

In contrast, the 6–9-day filtered $\sigma^2_{v700}$ is very small at latitudes lower than 15°N and generally increases poleward, being predominantly associated with the midlatitude westerly flow. However, a maximum on the 6–9-day scale is present on the southern side of the subtropical high, although weaker than the corresponding 2.5–6-day filtered $\sigma^2_{v700}$ maximum. Most interesting for our purpose is a localized small, but relatively intense, maximum located at about 27°N, 22°W, slightly to the southwest of the maximum that also appears in the 2.5–6-day $\sigma^2_{v700}$ in connection with the WACT.

Also in Fig. 1, the surface temperature map emphasizes the large thermal contrast between land and ocean and, particularly noteworthy, the presence of a cold SST tongue in correspondence to the WACT that contributes to the strongest zonal thermal gradients over that part of the coastline. In addition, the streamlines representing the moisture transport, while confirming the overall circulation seen before, emphasize the northward deflection exerted by the Atlas range on the predominantly westerly flow to the west of it. It is intuitive, considering the important dynamical role represented by the Atlas range over northwestern Africa (which is well known to trigger orographically induced baroclinic cyclones), that the region may be particularly interesting from the point of view of tropical–extratropical interaction (e.g., Knippertz 2003).

A plot similar to Fig. 1, but computed at 600 hPa, shows the same circulation except that the two variance maxima in the 6–9-day time window, evident at about 22°–27°N over the eastern Atlantic, are stronger and better defined (not shown).
b. Modes resulting from 2D-EEMD analysis

To understand wave activity over the Atlantic and West Africa, the 2D-EEMD is applied to the unfiltered \( \nu_{700} \) field for the JAS period. The EEMD, applied to any one-dimensional dataset such as a time series, produces a number of so-called intrinsic mode functions (IMFs) from which the Hilbert transform can be applied to obtain instantaneous frequency data. The procedure to create IMFs is called “sifting” and is stopped when a given convergence criterion is met.

In our case, since \( \nu_{700} \) is a function of both latitude and longitude, a time series \( \nu_{700}(t) \) could be extracted from every point \((x, y)\). Therefore, we zonally scan the area of interest by producing a decomposition \( \nu_{700}(x, t) \) for each latitude \(y\). More precisely, the 2D-EEMD is performed over 2° latitude bands from the equator to 50°N on two different longitude ranges: from 80° to 20°W, to cover the Atlantic and from 25°W to 35°E, to cover northern Africa. The 2D-EEMD decomposes the \( \nu_{700} \) into several modes, which are essentially frequency bands. The modes can also be conceived as oscillatory time series in which frequency can vary with time within the range of that particular band. Mode 1 represents higher frequencies than our focus (in the domain of mesoscale evolution of weather systems, which could
not be resolved with the dataset at our disposal). Mode 2 corresponds to longer time scales than mode 1 but shorter than 6 days, mode 3 is composed of time scales of about 6–9 days, and modes 4 and 5 represent even longer time scales, which again could not be investigated as part of this study because of our sampling choice that is limited to the JAS months. Therefore, the focus of this article is on modes 2 and 3, with the goal of demonstrating that they are physically meaningful and correspond well, spatially and temporally, to 2.5–6- and 6–9-day waves.

When a decomposition of \( v_{700} \) is performed across a latitude band, any of the modes produced can be conveniently illustrated as a function of time and longitude with a Hovmöller diagram. In Figs. 2 and 3, mode 2 is shown for the latitude band centered at 12°N in the deep tropics, covering the longitude range from 80° to 20°W (over the ocean) and from 25°W to 35°E (over the African continent). A comparison between these and the same figures computed for a latitude band in the midlatitudes (e.g., 44°N, not shown) covering both longitude ranges from 80° to 20°W (over the ocean) and 25°W to 35°E (over the Mediterranean region) show that waves propagate westward at 12°N and eastward at 44°N, in agreement with Fig. 1 which showed prevailing easterlies (westerlies) south (north) of the anticyclonic centers located at about 30°N.

Moreover, easterly wave propagation in mode 2 over the African continent (Fig. 3) shows that disturbances with a 2.5–6-day time scale originate from two preferred regions of Africa: one at longitudes west of 0° and the other east of 20°E (corresponding to the Darfur area) with some of the waves produced in the latter region undergoing temporary attenuation and recovery at the transition from land to ocean, consistent with previous studies (e.g., Thornicroft and Hodges 2001; Mekonnen et al. 2006).

As previously stated, it is relevant for this investigation to demonstrate that modes 2 and 3 correspond to waves on time scales of 2.5–6 and 6–9 days respectively. To further corroborate this statement, Fig. 4 shows the spectral density for mode 2 and mode 3 at four selected points: 12°N, 30°W; 26°N, 21°W; 12°N, 18°W; and 26°N, 31°W. The four locations are chosen based on Fig. 1 so as to correspond to two local maxima of the \( \sigma^2_{v_{700}} \) computed in the 2.5–6-day and 6–9-day time windows and to two additional points at the same latitudes. The spectra at these four points show fictitious maxima at frequencies about 10^{-1/2}, which correspond to a time scale of approximately 90 days. These maxima are sampling artifacts since they are not resolved in the JAS season. The local maxima that we assert have physical significance are all at higher frequencies than the spurious maxima.

In particular, the physically meaningful aspects are the 2.5–6-day peaks at 12°N, 18°W and 12°N, 30°W, representing the dominant period for mode 2, and the peaks centered at about 7–8 days at 26°N, 21°W and 26°N, 31°W, representing the dominant period for mode 3. The absence of a 6–9-day peak at 12°N, 18°W and 12°N, 30°W is noteworthy. In fact, these, and similar plots computed for other locations (not shown), suggest that mode 3 can be detected at latitudes north of a certain threshold. These spectral peaks agree with, and strengthen, the aforementioned previous findings by de Felice et al. (1990, 1993) and Diedhiou et al. (1998, 1999).

To better understand the spatial distribution of the two modes and demonstrate their physical meaningfulness, their variances are computed over a domain comprising northern Africa and the tropical northern Atlantic. More precisely, from 0° to 45°N, 80°W to 30°E the 2D-EEMD is applied at every degree in longitude on 2° latitude bands, thus obtaining a “sifted” two-dimensional time series of \( v_{700} \), from which the variance can be calculated. To avoid confusion with the quantity \( \sigma^2_{v_{700}} \) discussed in Fig. 1, which was a variance computed from the \( v_{700} \) filtered through the 2.5–6- or 6–9-day passbands respectively, we name the variances computed from the 2D-EEMD decomposed \( v_{700} \) as \( \sigma^2_{v_{700}^{2M}} \) (variance of \( v_{700} \) computed from mode 2) and \( \sigma^2_{v_{700}^{3M}} \) (variance of \( v_{700} \) computed from mode 3).

Figure 5 shows the maps of \( \sigma^2_{v_{700}^{2M}} \) and \( \sigma^2_{v_{700}^{3M}} \) and their relative magnitudes across the northern tropical Atlantic and part of Africa, computed for the aforementioned 10 ENSO neutral years. It is important to clarify that these variances are obtained from an unfiltered wind field, on which only the 2D-EEMD is applied. In contrast, the variance in Fig. 1 was computed from a filtered wind field. A comparison between Figs. 1 and 5 reveals a strong similarity between the variance of the 2.5–6 (6–9) day filtered wind and \( \sigma^2_{v_{700}^{2M}} \) (\( \sigma^2_{v_{700}^{3M}} \)).

The overall comparison between \( \sigma^2_{v_{700}^{2M}} \) and \( \sigma^2_{v_{700}^{3M}} \) reveals a very different structure. In particular, the two maxima in the top panel of Fig. 5, referring to mode 2, seem to be consistent with the well-established concept of two distinct tracks for 2.5–6-day waves exiting the coast of West Africa. The high variance associated with the northern and southern tracks, to the north and south of the AEJ respectively, has some correspondence with the aforementioned previous findings by de Felice et al. (1990, 1993) and Diedhiou et al. (1998, 1999).
FIG. 2. Mode 2 of meridional wind at 700 hPa ($v_{700}$, m s$^{-1}$) sifted at 12°N between 80°W and 20°W using 2D-EEMD analysis for JAS of the 10 selected ENSO-neutral years.
FIG. 3. As in Fig. 2, but computed between 25°W and 35°E.
the northern maximum is actually connected with low-level amplitudes peaking at about 850 hPa. From Fig. 5 it can also be seen that the merger location for the two tracks over the Atlantic is at about 20°W. The amplitudes for mode 2 are weak over central and eastern Africa, in agreement with Mekonnen et al. (2006), whose previously mentioned spectral analysis of satellite brightness temperatures identified a 2–6-day spectral peak but with values rapidly decreasing eastward and becoming very small on the continent at about 25°E. Also, the study by Chauvin et al. (2005) showed an inland decrease of filtered variance. However, notwithstanding the general eastward decrease in wave amplitude, it is possible that MERRA data overrepresents it, since the relative magnitude of the variance filtered in the 2.5–6-day scale was noted to decrease eastward less prominently in the ERA-40 dataset than in MERRA (e.g., WA12, their Fig. 11).

Focusing on $\sigma_v^2$ (Fig. 5), it can be noted that the variance generally increases with latitude but with two local maxima: one corresponding to the WACT region and the other at about 40°W. This is the same pattern that was shown in Fig. 1 from the $v_{700}$ obtained from the 6–9-day bandpass filter. In addition, a smaller local maximum seen at about 20°N over land appears to be stronger at lower levels (as will be shown later in the vertical cross sections) and may result from the interaction of moisture during active/inactive phases of the monsoon (e.g., Cornforth et al. 2009). It is also worth remembering that the corresponding 6–9-day time scale discussed by Diedhiou et al. (1998, 1999) appeared to be more active at the beginning and the end of the summer season, thus hinting at a contribution by midlatitude dynamics. This subject will be discussed more extensively in section 3e. Figure 5 also shows the ratios between $\sigma_v^2$ and their sum: these indicate that mode 2 dominates in the southern part of the domain, with a clear partition at approximately 24°N.

c. Wave structure and propagation

Up to this point, these results confirm the existence, documented from previous studies, of two families of tracks for the 2.5–6-day disturbances: the southern track at the jet level originates from the Guinea Highlands...
and Cape Verde, while the northern track (peaking at lower levels) is close to the coast of northwest Africa and the Canary Islands. In particular, Fig. 5 does not contradict the previous findings on the existence of a dual regime for 2.5–6-day disturbance tracks (e.g., Carlson 1969; Burpee 1974; Reed et al. 1977, 1988; Diedhiou et al. 1998; Ross and Krishnamurti 2007; Nitta and Takayabu 1985; Céron and Guéry-Odelin 1999). However, this work is meant to provide further insight on the 6–9-day time scale and particularly to show its relationship and/or differences with the 2.5–6-day track.

Figure 6 shows the results of compositing the wind obtained from the 2D-EEMD in mode 2 or 3 with the wind filtered through the 2.5–6-day or 6–9-day windows respectively. The procedure to generate the composites starts with a time series (called “index”) of the meridional wind \( u_{700}(t) \) and \( v_{700}(t) \) that is used to characterize the waves and is computed from the 10 neutral-ENSO years by applying the 2D-EEMD decomposition for mode 2 or mode 3 to any chosen point \((x_o, y_o)\). Three locations are selected along the 20°W meridian (at 12°, 20°, and 28°N). From each index a standard deviation \( \sigma_{u_{700}} \) or \( \sigma_{v_{700}} \) is extracted. The time series can then be composited with the total filtered wind field \((u_{700}, v_{700})\) over the entire domain shown in the maps. To produce the composites at each time \( t \) and point \((x, y)\) in the domain, the total filtered wind \((u_{700}, v_{700})\) is retained only if the local meridional component at that point \( v_{700}(x, y) \) is equal or greater than one standard deviation \( \sigma_{v_{700}} \). All values exceeding the threshold at each point are then added up and divided by the number of occurrences, thus generating a composite for each point. The chance for the local wind at a generic point \((x, y)\) to satisfy the condition \( v_{700}(x, y) \geq \sigma_{v_{700}} \) becomes generally smaller with increasing distance from the point \((x_o, y_o)\) selected to compute the variance because of a reduced likelihood for the wind components to be in phase. Finally, to further isolate the wave from the noise, only the magnitudes and vectors exceeding the significance level of 90% are plotted. The composites so generated reveal the mean wave structure in terms of wavelength, amplitude, and propagation direction.

Three prominent findings can be extracted: the disturbances on the 2.5–6-day scale, which correspond to mode 2, propagate from the Guinea Highlands on an east-southeast to west-northwest track, while the disturbances on the corresponding 6–9-day scale (mode 3), which are relatively weak at 12°N and become much more prominent at the higher latitudes, propagate on a westerly track at 20°N and on a east-northeast to west-southwest track at 28°N. The third finding that can be inferred from this figure is that the tracks of the two modes appear to have a merging point at approximately 20°N in the main development region, suggesting a coherent low-level structure that may have implications for cyclogenesis. It is also worth noting the opposite horizontal tilt of modes 2 and 3 waves, particularly evident comparing the mode 2 waves at 12°N with the mode 3 waves at 20°N. We can speculate that the opposite tilt could be associated with opposite sign changes in the potential vorticity gradient.

Figure 7 is the same as Fig. 6 but computed at 925 hPa. It shows, as in the previous figure, that mode 2 waves are stronger farther to the south and decrease moving northward, whereas mode 3 waves do the opposite. However, one goal of this article is specifically to show evidence that waves on a 6–9-day time scale are different from the low-level northern tracks acting on a 2.5–6-day time scale. In this regard, evidence is provided by the lower panels of Figs. 6 and 7. These show that the amplitude of the 2.5–6-day wave corresponding to mode 2 is larger at 925 hPa (particularly at the location 20°N, 20°W) than it is at 700 hPa, whereas the amplitudes of the mode 3 wave are larger at 700 hPa (at both locations 20°N, 20°W and 28°N, 20°W). This indicates that the northern tracks obtained in mode 2 are consistent with
the low-level 2.5–6-day amplitudes discussed in previous studies but differ substantially from mode 3 (6–9 day).

As stated before, another purpose of this article is to demonstrate the consistency between the results obtained from the 2D-EEMD methodology (which is applied to unfiltered data and therefore finds time scales without assumptions) and the results extracted by other more established techniques such as filtering, which,
however, do require a priori assumptions on the specific passbands to be extracted. Therefore, to further corroborate the findings from Fig. 6, an empirical orthogonal function (EOF) analysis is performed on the 2.5–6- and 6–9-day filtered JAS $\nu_{700}$, computed as before on the 10 neutral-ENSO years (Fig. 8). The plot shows an apparent west-northwestward propagation for the 2.5–6-day filtered disturbances, whereas the amplitudes filtered through the 6–9-day time window seem to align from the east-northeast toward the west-southwest.

To better understand the propagation of mode 3 waves, composites of the wind $\nu_{700}$, $\nabla_{700}$ filtered in the 6–9-day window with the wind obtained from the 2D-EEMD in mode 3 are produced. An index $\nu_{700}^{M_3}(t)$ at one
selected location (28°N, 20°W) is chosen to correspond with the maximum of $\sigma^2_{v_{700}}$ filtered in the 6–9-day window, previously seen in Fig. 1. In Fig. 9, the mode 3 wave propagation at 700 hPa is shown in the form of a set of four snapshots at lag intervals of two days. The wavelength and propagation indicate how dynamically different the 6–9-day waves are from the classical AEWs. In fact, the entire 6–9-day disturbance progresses on an east-northeast to west-southwest track from Africa across the Atlantic with a propagation speed of about 6° day$^{-1}$ and a wavelength spanning 25° longitude. In the same figure, composites are also produced for the $v_{925}$, $v_{925}$ wind in order to better understand the vertical structure of the waves. Wave propagation at the same location, but at 925 hPa, shows that the 6–9-day amplitudes are substantially smaller than they are at 700 hPa, consistent with Figs. 6 and 7. On the contrary, the same plot produced for mode 2 waves (not shown) at the same selected location (28°N, 20°W) shows that the 2.5–6-day waves are slightly larger at 925 hPa. This indicates that mode 2 (even if this particular point is chosen a little to the north of the maximum low-level 2.5–6-day activity) reflects the low-level northern 2.5–6-day tracks previously identified in the literature (e.g., Thorncroft and Hodges 2001; Cornforth et al. 2009) and differs substantially, in terms of altitude and amplitude, from the 6–9–day track emphasized in mode 3.

It is also relevant to notice the strong enhancement of southerly and northerly flow associated with the westward propagation of the 6–9-day system. Figure 9 shows that 6–9–day waves, unlike the 2.5–6-day waves which are more confined in the tropical environment, allow substantial transport of air masses from the tropics into the midlatitudes and vice versa. We will return to this aspect later in the article (section 3e).

To better understand the 6–9-day wave propagation, another 2D-EEMD is produced at 45°W, 22°N. The index $\tilde{v}^{M}_{700}(t)$ obtained is composited with the $v_{700}$ filtered in the 6–9-day window over the entire domain. The variance of the composited wind is then calculated with different time lags. The specific location to compute the index is chosen because $\sigma^2_{v_{700}}$, calculated from the

![Figure 8: EOF analysis of filtered $v_{700}$ (m s$^{-1}$) for (top four panels) 2.5–6- and (bottom four panels) 6–9-day passbands during the ENSO-neutral years. The green lines represent the principal component associated with each EOF.](image-url)
6–9-day filtered $v_{700}$, has a local maximum there (recall Fig. 1). The consistency between $v_{700}$ and the $v_{700}$ filtered through the 6–9-day window has already been noted. Figure 10 shows the variance of the composited meridional wind at 700 hPa from 80°W to 0° longitude in a sequence of composite snapshots lagging from −4 to 0 days, with 1 day as time interval. The plot shows two bands of higher values of $\sigma^2_{700}$; one at about 23°N, slightly sloping southward with increasing western longitudes, and the other at higher latitudes. On the southern band one can note that a $\sigma^2_{700}$ maximum close to the WACT appears almost stationary within the
given time window, whereas the central Atlantic maximum displays a clear westward progression. The stationary behavior of the maximum of variance close to the West African coastal trough is confirmed by Fig. 11, which is a Hovmöller diagram computed in a similar fashion as previously done in Fig. 3, but in this case for mode 3 and on a more northern point (28°N). The figure confirms that westward propagation is almost absent to the east of 20°W, which corresponds approximately to the longitude of the WACT.

To understand the vertical structure of the filtered $\sigma^2_{y}$ at both time scales, a set of meridional vertical cross sections spanning from the equator to 40°N are shown at different longitudes over the Atlantic and northern Africa (Fig. 12). The plot indicates that the maximum of the 2.5–6-day filtered $\sigma^2_{y}$ is concentrated at about 600–700 hPa from 40°W to 0° (with a secondary low-level maximum) and that the highest values occur in the section taken at 20°W. It is worth noting that the 6–9-day filtered $\sigma^2_{y}$ maximum at 20°N, 600 hPa is much more to the north than the corresponding maximum on the 2.5–6-day scale and corresponds, indeed, to a location where relatively lower values of the latter occur. At the same time, the low-level 2.5–6-day variance maximum evident at about 18°N in the section at 20°W longitude is a signature of the well-known northern tracks (e.g., Thorncroft and Hodges 2001; Berry and Thorncroft 2005; Mekonnen et al. 2006; Ross and Krishnamurti 2007) and appears clearly different from the 6–9-day maximum located at higher elevation (about the jet level) and at 25°N. These plots further confirm the idea that the two time scales are dynamically different phenomena.

The seasonal evolution of the waves, going from the drier months of June and July to the wettest months of August and September, indicate that both 2.5–6-day jet-level waves and 6–9-day waves tend to be stronger toward the second half of the monsoon at the jet level, whereas the northern low-level 2.5–6-day activity tends to weaken during the season (not shown). This is consistent with the results by Grist et al. (2002), which suggest the greater importance of the barotropic term in wetter years; in fact, the northern low-level 2.5–6-day amplitudes are more baroclinically driven than the corresponding 2.5–6-day amplitudes located at the jet level and more to the south. Moreover, the increased 6–9-day activity during the second half of the monsoon is consistent with the results by Diedhiou et al. (1999).

d. Dynamical implications of mode 3

Up to this point, it has been shown that the 6–9-day time scale obtained through a 6–9-day filter is consistent with the disturbances resulting from the 2D-EEMD decomposition and defined as mode 3. Similarly, the activity in mode 2 obtained from the same decomposition coincides with waves obtained from 2.5–6-day filtering. Most importantly, it has been shown that the 6–9-day time scale is distinct from the 2.5–6-day time scale both geographically and temporally.

A further step is to unveil aspects of the dynamical implications of mode 3. In particular, the composite in Fig. 9 suggests that strong southerly and northerly advection is associated with the propagation of mode 3 disturbances. As suggested in WA12, enhanced southerly flow from the deep tropics, ahead of eastward-moving cold fronts, is one major source of moist tropical air in the midlatitudes as far north as the Mediterranean and central European regions. Patterns very similar to
As in Fig. 2, but for mode 3, sifted at 28°N.

Fig. 11. As in Fig. 2, but for mode 3, sifted at 28°N.
the southerly flow at lag time 0 day in Fig. 9 are often observed in the satellite imagery and can be detected in analyses as well, as will be shown later. At the same time, enhanced northerly flow ahead of a westward progressing tropical wave is a factor that can inhibit tropical development. The implications of our analysis of the 6–9-day time scales, which were just hinted at in WA12, are that mode 3 could be a key element of an ongoing interaction between the deep tropics and the midlatitude disturbances. It is not the purpose of this article to claim a cause-and-effect relationship between the two, but simply to show that important interactions take place between AEWs and midlatitude disturbances and that such interactions are particularly evident on 6–9-day time scales.

To support this idea, correlations of 6–9-day filtered zonal and meridional moisture transport at 700 hPa, total wind at 300 hPa, and precipitation with the \( \sigma^2 \) obtained from a 2D-EEMD decomposition at 44°N, 9°E, are computed. The point (44°N, 9°E) is chosen in the Gulf of Genoa as a very representative location for the so-called Mediterranean or Alpine cyclogenesis, a type of baroclinic, orographically induced lee cyclogenesis caused by the interaction of baroclinic flow with the Alps (e.g., Buzzi and Tibaldi 1978), often referred to as “Genoa cyclones” for the high incidence of them in the Gulf of Genoa. Genoa cyclones are among the players in some of the flood-producing precipitation events that characterize most of the northern Mediterranean countries and central Europe. Some of these extreme precipitation events are known to have produced accumulated values of 500 mm or more (e.g., Turato et al. 2004), which correspond to about half of the annual mean local precipitation. Some of the case studies for these events have emphasized a prominent contribution of moisture from the deep tropics (e.g., Reale et al. 2001; Turato et al. 2004). Figure 13, in which 700-hPa moisture transport, upper-level circulation, and precipitation correlations are displayed, shows an example of 700-hPa southwesterly flow from the ITCZ into the Western Mediterranean, bearing a remarkable similarity to actual observed patterns in the synoptic fields. The importance of northward moisture transport from the deep tropics in triggering anomalous precipitation events in
the midlatitudes has been extensively demonstrated also by Knippertz et al. (2003) and Knippertz (2003) with a focus on northwest Africa.

On the other hand, northerly flow from the mid-latitudes, which is also seen in the same figure, and particularly cold spells across the Sahara are another example of tropical–extratropical interaction since cold surges are known to cause tropical suppression and breaks in the African monsoon (e.g., Vizy and Cook 2009). The enhanced northerly and southerly advection between tropics and extratropics, evident in Fig. 13, represents something that is intrinsic to the 6–9-day mode since it is computed over 10 years of data. To show that this mode is not an artifact of the methodology but corresponds to real observed patterns on the synoptic scale, we next examine two cases characterized by extreme precipitation events.

e. Examples: European and Mediterranean floods of 2000 and 2002

In this section, two examples based on major synoptic-scale events are briefly discussed in the context of the 6–9-day time scale. The first of the two extreme precipitation events, which is discussed in detail in Turato et al. (2004), occurred over northwestern Italy between 13 and 16 October 2000 and is a clear example of tropical–extratropical connection.

As for all large-scale flood-producing precipitation events, a number of factors are always needed: 1) a large-scale moisture source acting on spatial and temporal scales larger than the precipitation event, 2) a mechanism of transport and concentration in a non-precipitating environment so that the moisture is not lost on the way, and 3) an upper-level forcing combined with local orography or other factors, producing the trigger that releases a large fraction of the moisture as precipitation into a relatively small time and over an area much smaller than the originating source of moisture. These elements are discussed in detail in Turato et al. (2004) with the aid of water vapor back trajectories and synoptic analyses, showing a clear extratropical origin for a substantial fraction of the moisture involved in the event.

In the following, we show that the 6–9-day time scale variability fits well in this context. The top panel of Fig. 14 shows the 8-day average for meridional moisture transport at 700 hPa and the corresponding total transport, between 0000 UTC 7 October and 0000 UTC 15 October 2000. The figure clearly displays a “plume” of moisture advected from the ITCZ straight into the region where the floods occur at the end of the averaging period (northwestern Italy between 12 and 15 October).

In the same figure, another example is provided. Central Europe and northern Italy were hit by a 100-yr flood in August 2002 (e.g., Ulbrich et al. 2003). Several precipitation extreme values were recorded in various locations of Europe between 10 and 16 August 2002. Figure 14 (lower panel) shows an 8-day average (from 0000 UTC 3 August to 0000 UTC 11 August 2002) of the same quantities, indicating again a plume of moisture from the WACT into the Mediterranean region. Also noteworthy in both pictures is the evidence of dry northerly flow being advected toward lower latitudes. Although not as important for weather forecasting as the flood-producing moisture, it has already been noted that cool dry spells are possible factors inhibiting tropical cyclogenesis (Vizy and Cook 2009).

Figure 15 shows the event of October 2000 through a set of instantaneous snapshots of 700-hPa flow, vorticity, and specific humidity. At 1200 UTC 9 October 2000 a strong wave (evident from the high vorticity values) is present between 0° and 10°E over tropical Africa. In the following images as the wave progresses westward, a plume of moisture elongated from southwest to the northeast stretches as far north as the central Mediterranean, advecting moisture from the deep
tropics straight into central Europe (particularly evident at 1200 UTC 13 October). The intense southwesterly moist flow appears to precede a cold front (evident from the vorticity pattern) that stretches from northwestern Africa to central Europe, and its origin is in the core of the African wave whose axis appears around 20°W. The pattern appears to be an interaction between the westward progressing AEW and the eastward progressing cold front in the midlatitudes. At 1200 UTC 17 October and even more so at 1200 UTC 19 October, the intense southwesterly moist flow from the deep tropics and central Europe diminishes as the connection between the AEW and the midlatitude flow is broken. The whole duration of the intense southwesterly plume across the Sahara is on the scale of about 8 days.

Figure 16 shows the same variables for the August 2002 event. A very deep African easterly wave appears located at 1200 UTC 2 August 2002 between 10°W and 0° longitude. While the wave progresses westward, an impressive plume of moisture is evident over northwestern Africa, eventually breaking its connection with the deep tropics. The AEW westward propagation leaves behind a very large amount of moisture, which becomes available for eastward-moving midlatitude systems.

The similarity of both cases with the propagation of mode 3 in Fig. 9 suggests that the 6–9-day wave can be recognized in actual instantaneous synoptic patterns and also by simply averaging over the proper time scale without the need of statistical analysis.

The studies by Knippertz et al. (2003) and Knippertz (2003) on precipitation events that occurred on the southern flanks of the Atlas range bear remarkable similarities. In those cases, an anomalous subtropical trough extending deeply into the tropics appears to interact with AEWs, causing intense moisture advection above the Saharan boundary layer at about 400–700 hPa. Convergence takes place over the Atlas region in connection with orographic forcing. It is also possible that the Soudano–Saharan depressions described by Schepanski and Knippertz (2011) belong to the same type of phenomenon, resulting from the interaction of a wave with midlatitude systems. It is also worth noting that the study by Stohl et al. (2008) on the remote sources of moisture for an extreme precipitation event in Norway, investigated with the aid of back trajectories, suggests a very clear “moisture plume” elongated northeastward from the central tropical Atlantic toward Scandinavia (their Fig. 9). The authors compute the trajectories for 1, 4, 8, and 12 days preceding the event. The size of the evaporative source increases drastically from day 1 to days 4 and 8, but the difference between 8 and 12 days is small. Thus, 8 days appear to delineate the actual time scale of the event. Also the study by Lavaysse et al. (2010) on the pulsation of the African heat low may be consistent with this work, providing additional evidence of an interaction of AEWs with midlatitude systems on the same time scale.

In summary, synoptic signatures of the 6–9-day waves appear to be an interaction between the deep tropics and the midlatitude flow and are made manifest by an enhanced southerly or southwesterly moist flow (and corresponding northerly or northeasterly dry flow). When this interaction is particularly intense or amplified by an optimal phasing between easterly and westerly disturbances, the enhancement of the southwesterly flow can become so extreme as to acquire major implications for weather forecasting over a wide region spanning from the tropical Atlantic to Europe.

4. Discussion and concluding remarks

It is generally accepted that there are two spatial domains for African easterly waves and that they may
FIG. 15. Wind at 700 hPa (streamlines), moisture $q_{700}$ ($10^3$ kg kg$^{-1}$, shaded), and vorticity ($10^5$ s$^{-1}$, red/blue contours) from 1200 UTC 9 Oct to 1200 UTC 19 Oct 2000. No filtering is performed.
FIG. 16. As in Fig. 15, but from 1200 UTC 2 Aug to 1200 UTC 12 Aug 2002. No filtering is performed.
merge off the coast of western Africa. This article addresses the less extensively documented possibility that the 2–10-day time scales in which AEWs are known to exist could be further subdivided into two distinctly different wave regimes.

In particular, we have demonstrated that the 6–9-day time scales are predominantly associated with a northern track. At the same time, we have shown that the low-level tracks on 2.5–6-day time scales, developing on the northern flank of the African easterly jet, are different from the 6–9-day tracks. Finally, we have shown that the jet-level 2.5–6- and 6–9-day tracks are not completely separated: the northern track has a mean west-southwestward propagation, the southern track a mean west-northwestward propagation, and the two trajectories intersect at about 20°N, suggesting possible exchanges of energy.

The 2D-EEMD decomposition shows that the northern track is predominantly confined south of 26°–28°N whereas midlatitude baroclinic waves propagate eastward to the north of 32°–34°N. The area between 30° and 34°N, which is also the center of the Atlantic anticyclonic circulation, appears to be the transition zone. A coastal climatological trough to the northwest of Africa, characterized by strong land–ocean thermal contrast and steep orography, appears to be the preferred area for exchanges of energy between midlatitude synoptic disturbances and the 6–9-day African waves. While the interaction of midlatitude waves and 6–9-day waves is a subject that requires further exploration, this study indicates that the importance of the 6–9-day time scale is not confined to the tropics but extends into the midlatitudes as well. In fact, the presence of moisture plumes across the Sahara or the eastern Atlantic, being advected ahead of cold fronts and providing moisture to Mediterranean cyclones, has been noted operationally and discussed in WA12. At the same time, the presence of cold spells across the Sahara or the tropical Atlantic is an important factor being considered operationally in the prediction of developing or nondeveloping waves. With the results from this work we can speculate that if the 6–9-day waves and the baroclinic waves are in a certain phase, larger than normal oscillations can be produced, leading to abnormal northward transport of moist air toward the extratropics and southward transport of cool dry air toward the tropics.

Finally, from this work some general theoretical considerations can be extracted. While it is accepted that the structure of the zonal wind is determined by the specific land–sea distribution on the continental scale, we suggest that the particular structure of the zonal wind also provides the necessary environment for an interaction between tropical waves and midlatitude disturbances. In fact, Bennett and Young (1971) reported that a necessary condition for midlatitude Rossby waves to penetrate into the tropics is that their zonal phase speed be westward relative to the local zonal mean wind. At the location where the interaction occurs, which is off the coast of northwest Africa, one can note from Figs. 1, 2, and 9 that the local zonal mean wind has a maximum, and the phase speed is westward relative to the zonal wind maximum. These findings are consistent with the Bennett–Young interpretation. When midlatitude disturbances interact with the tropical flow, they are provided with an excess of moisture with respect to “pure” midlatitude systems, thus often becoming more intense, a fact confirmed by the previously noted peak in the $v_{700}$ variance.

In summary, we have addressed the main purpose of this study by, first, verifying the existence of two distinct time scales in AEWs, confirming previous work by Diedhiou et al. (1999), and, second, showing that the waves at the longer time scales are predominantly confined to a more northern track and that they are different from the low-level waves, which are known to develop on the northern flank of the AEJ. These findings unify the vast body of scientific literature that focused on the 2.5–6-day scale with the much smaller body of literature concerned with the existence of two distinct time scales within the 2–10-day time window. Finally, this work further corroborates the idea that 6–9-day AEWs interact with midlatitude systems. In conclusion, this work demonstrates the existence of two AEW regimes corresponding to two spatial and temporal domains and hints at an important interaction existing between the northern reaches of such regimes with midlatitude systems.

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