NOTES AND CORRESPONDENCE

Tropical–Extratropical Interactions Causing Precipitation in Northwest Africa: Statistical Analysis and Seasonal Variations

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ABSTRACT

In several case studies, tropical–extratropical interactions (TEIs) have been shown to contribute to the transition-season precipitation in subtropical northwest Africa. Such TEI situations are characterized by a moisture source in the Tropics, a midlevel moisture transport into the subtropics to the east of an upper-level trough, and precipitation generation over northwest Africa through upper-level divergence and orographic effects in the Atlas Mountains.

In this paper, an automatic algorithm to identify TEI episodes on the basis of a 20-yr (December 1978–November 1998) climatology of 4-day backward trajectories starting at 400 hPa over northwest Africa, calculated from ECMWF (re-) analysis, is introduced. Twelve-hourly precipitation reports from 36 synoptic stations in northwest Africa are used to investigate the climatological relevance of TEI situations for different seasons. Results show that the region with the highest relative importance of TEIs is the semiarid southern foothills of the High Atlas (up to 40% of the annual precipitation amount). Relevance clearly decreases toward the much wetter Atlantic coast. TEI contributions are largest in the transition seasons, when TEI situations are most distinct, and in summer, when TEI situations are most frequent. It is suggested to consider TEIs in future studies on the observed and modeled precipitation variability of the region around the Atlas chain.

1. Introduction

Recent studies of, in total, 12 late summer/early autumn and 1 spring rainfall event in northwest Africa have revealed that, besides the commonly examined extratropical synoptic disturbances, tropical–extratropical interactions (TEIs) are also on occasion responsible for the generation of precipitation in this subtropical area (Knippertz et al. 2003b, KFRS hereafter; Knippertz 2003; Fink and Knippertz 2003, FK hereafter). In spite of a considerable spectrum of variations in the individual synoptic evolution of the cases, the following main characteristics were identified and are summarized in a schematic picture in Fig. 1: Moisture sources of the examined precipitation events are mainly mesoscale convective clusters or squall lines over tropical West Africa or the adjacent Atlantic Ocean, which are in the late summer/early autumn cases often, but not necessarily, forced in certain phases of low-level African easterly waves (AEWs; e.g., Reed et al. 1977; Fink and Reiner 2003). The convection serves to transport moisture vertically from the low-level monsoon layer into the middle (and upper) troposphere. In particular, over the northern part of the ''source area,'' a midlevel divergent layer, which appears to be enhanced ahead of the troughs of AEWs, is frequently observed (Reed et al. 1977; Thompson et al. 1979; Druyan et al. 1997).

The moisture is transported into northwest Africa on the eastern side of an upper-level trough, where in some cases extraordinarily high wind speeds are observed. Trajectories from the Tropics often follow an ascending anticyclonic arc between 700 and 400 hPa and are therefore mostly running above the dry Saharan PBL, where in two of the KFRS cases trade winds remained widely unperturbed. The exact synoptic evolution of this moisture export from the Tropics (release of convection, propagation of the trough, etc.) varies as the case arises. In particular, in August and sometimes in September the trough is occasionally very weak, and cloud ensembles over West Africa are rather broken and scattered, so that moisture transports from the Tropics are hardly revealed by any other means but trajectory analysis. In contrast to that, the spring event described by FK revealed the cutoff of a distinct upper-level potential vorticity anomaly from the midlatitudes (see also Ziv 2001) and a distinct continuous elongated cloud band reaching from

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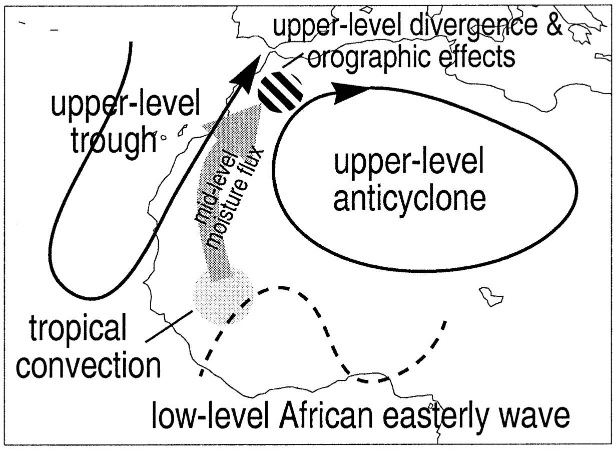

FIG. 1. Schematic picture of a typical situation of tropical–extratropical interactions over West Africa as described by Knippertz et al. (2003b) and Fink and Knippertz (2003). Note that African easterly waves are only of importance in the summer half year.

the Tropics into the subtropics [a so-called tropical plume (TP); see McGuirk et al. (1987)]. In some cases, a dynamical interaction is found between the tropical convection/AEW and the subtropical trough, as suggested by Fig. 3 in Nicholson (1981). All considered cases show at least some agreement with the dynamical characteristics of TPs or tropical ''moisture bursts'' (see section 7b in KFRS and, e.g., McGuirk et al. 1987; Ziv 2001).

When the tropical air mass reaches northwest Africa, convective precipitation is observed, triggered by upper-level divergence at the inflection point of the trough, which is associated with midlevel (moisture) convergence and large-scale uplift. Convection is possibly enhanced by orographic lifting and, particularly in late summer/early autumn, by daytime heating of elevated terrain in the Atlas Mountains. In this season, rainfalls are often restricted to the surroundings of the Atlas chain and, because of the large evaporation of rain in the deep and dry PBL, are often not very abundant. Occasionally, showers or thunderstorms with more than 20 mm in a few hours are observed; extraordinary rainfalls of up to 77 mm in 24 h were recorded in southern Morocco during the spring 2002 event (FK). In most cases, no conspicuous development is observed in the surface pressure field during the export of moisture from the Tropics. During later stages, however, a cyclogenesis might occur in the northern portion of the trough (see FK), associated with a thickening of the cloud band and more widespread and intense precipitation in the maritime cold air associated with the trough (see also case II in KFRS).

On a climatological basis, Wright (1997) investigated the relation of wintertime precipitation in subtropical Australia to the occurrence of TPs and their interactions with extratropical disturbances and found a contribution of 40%–80%. Since Wright's identification is based on the appearance of the TPs in infrared satellite imagery alone, a clear distinction between the influences of tropical and extratropical air masses was not possible. In addition to that, the results of KFRS show that TEI precipitation is not necessarily connected to a ''classical'' TP. To the best of the author's knowledge, no climatological study has yet investigated the relevance of TEI situations for northwestern Africa. In this context, it is interesting to note that the typical paths of the trajectories during TEI situations found in case studies (see Fig. 1) coincide with the geographical extension of different species of the thorny savannah (Fig. 1 in Quezel and Barbero 1993). Since these are otherwise only common in the tropical Sahel and at the eastern edge of the Sahara, this ''vegetation anomaly'' might be an indication of a climatologically relevant warm-season moisture export from the Tropics associated with northwest African TEI cases.

Building upon the results of KFRS and FK, the present paper aims at a statistical evaluation of the meaning of tropical moisture sources for the precipitation variability in northwest Africa. Section 2 introduces a method for TEI episode identification based on the analysis of trajectories reaching the area of interest. In section 3, the importance of such TEI episodes for northwest African precipitation will be investigated on the basis of 12-hourly station observations. Section 4 gives a short summary, conclusions, and an outlook on future research issues.

2. Identification of episodes with tropical–extratropical interactions

In this section, a method is presented to identify episodes of TEIs affecting precipitation in northwest Africa, as in the case studies summarized in section 1. Given the relatively large spectrum of individual synoptic evolutions in the different cases, the method will be based on the most decisive common characteristic, the midtropospheric inflow of tropical air on the eastern side of an upper-level trough. The main data basis will be twice-daily (0000 and 1200 UTC) 4-day backward trajectories calculated from 6-hourly three-dimensional European Centre for Medium-Range Weather Forecasts (ECMWF) wind fields for the 20-yr period December 1978–November 1998 [ERA-15 reanalysis before March 1994 (Gibson et al. 1997) and uninitialized operational analysis thereafter] using an algorithm by McGrath (1989). The trajectories were started from the 15 points close to the Atlas Mountains already used in KFRS (see, e.g., their Fig. 4). The starting level is 400 hPa, which proved to be most relevant for the bulk of the cases studied in detail. More information on the ECMWF data and the trajectory calculations can be found in section 3 of KFRS. Since the present study aims at analyzing the relevance of the TEI mechanism for different seasons (not only late summer/early autumn as in KFRS), all further examinations are based on 2-

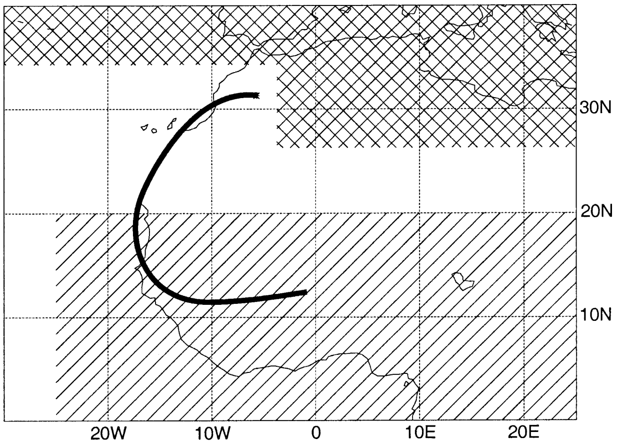

FIG. 2. Illustration of the TTA definition (for details, see section 2).

month investigation periods. For the rest of the text, the northwest African end of the backward trajectories is referred to as the ‘‘starting point’’ and the other end as the ‘‘end point.’’ The ‘‘analysis time of a backward trajectory’’ always refers to the starting point, that is, the time when the trajectory reaches northwest Africa.

Following the insight gained from the case studies, only backward trajectories that fulfill the following two preconditions will be considered:

- The end point must be located in the Tropics to the south of 20°N, to the east of 25°W (hatched area in Fig. 2), and at or below 400 hPa (no descending trajectories).
- From the starting point, the backward trajectory should not enter the area bordered by the parallel 3° latitude to the north and the line of longitude beginning 5° latitude to the south and running 2° longitude to the east of the starting point (cross-hatched area in Fig. 2).

The first prerequisite restricts the origin of the considered air masses to the middle and lower troposphere of tropical West Africa and the adjacent Atlantic Ocean, the typical moisture source region for the investigated TEI situations. The second precondition ensures that tropical air masses that originate from the hatched area in Fig. 2 but reach northwest Africa with a larger-scale flow from northerly or easterly directions are excluded from the investigation. The reason for this is that in the latter case the tropical air is evidently not transported on the eastern side of a subtropical trough, indicating that the dynamical conditions necessary for precipitation in northwest Africa are most likely not satisfied. Such cases, however, are observed on very few occasions. For simplicity's sake, the described trajectories will be termed trajectories from tropical Africa (TTAs) hereafter. For the period December 1978–November 1998, this definition yields a total number of 7391 TTAs, corresponding to 3.4% of the 215 550 trajectories calculated (14 370 analysis times, each with 15 trajectories). Figure 3 shows the density of TTAs crossing the 20° and 25°N parallels, respectively, in a longitude–height section. Although at 20°N (Fig. 3a) more than 25 trajectories per 3°-longitude–50-hPa box are counted over the area covering 3°E–30°W, 750–350 hPa, trajectories rise and concentrate at 25°N around 12°W (Fig. 3b). Figure 3 indicates that most trajectories basically follow the West African Atlantic coast on their way from the Tropics toward northwest Africa. Note that most trajectories have already reached midlevels at 20°N and consequently do not enter the Saharan PBL.

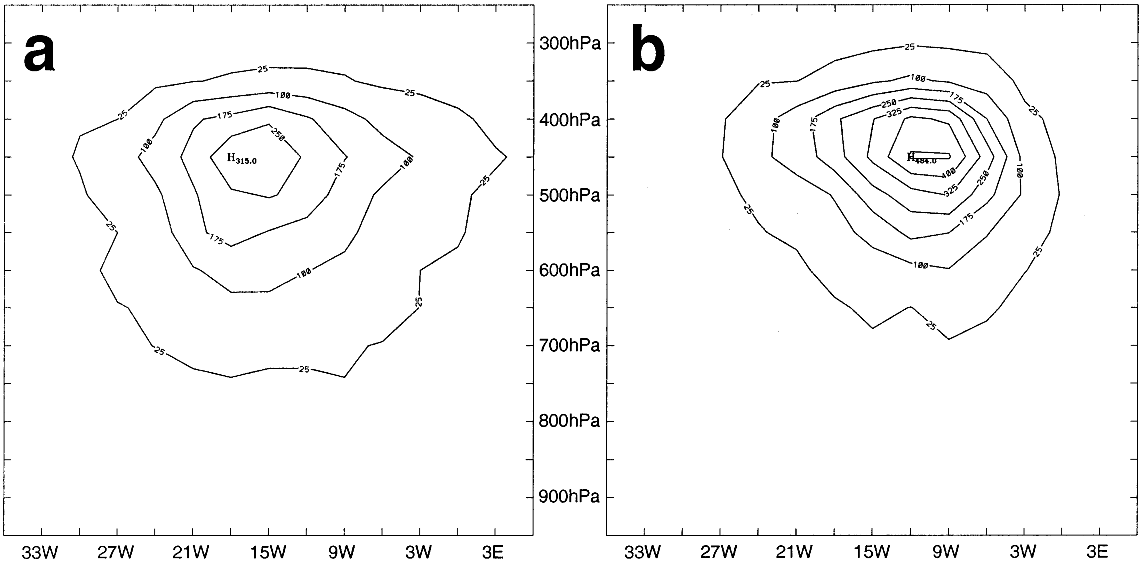

FIG. 3. Density of TTAs in a longitude–height cross section at (a) 20°N and (b) 25°N, respectively. Reference period is Dec 1978–Nov 1998. TTAs were counted in 3°-longitude–50-hPa boxes. Contours start at 25 TTAs with increments of 75. For definition of TTAs, see text.

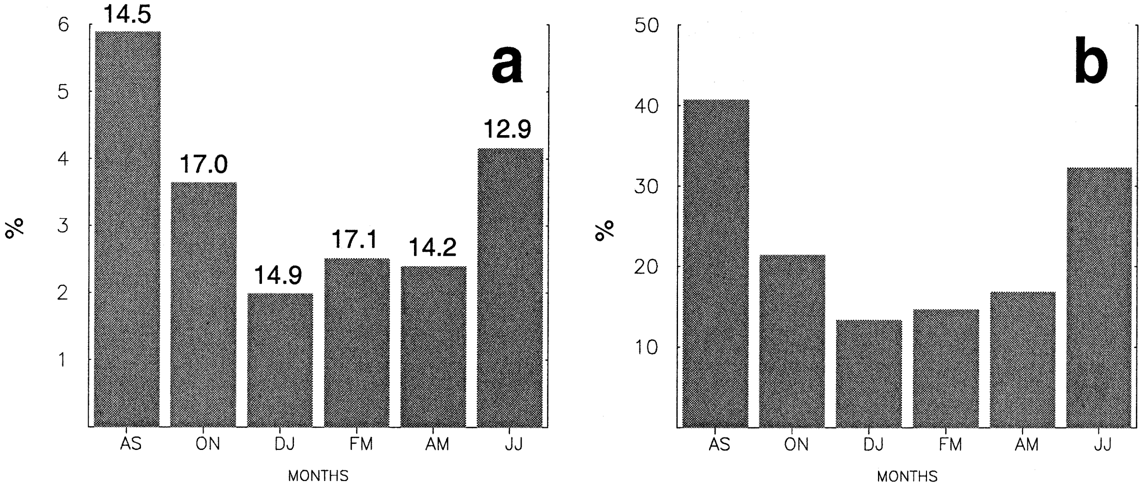

FIG. 4. (a) Percentage of trajectories identified as TTAs. The values above the bars give the same quantity, except only TTA episodes are considered. (b) Percentage of analysis times belonging to TTA episodes. Reference period is Dec 1978–Nov 1998; calculations were made for the 2-month intervals Aug–Sep (AS), Oct–Nov (ON), etc. For definitions of TTAs and TTA episodes, see text.

Inspection of single cases reveals that some TEI-related precipitation periods do not show a TTA for every consecutive analysis time. This might be due to a very slow northward propagation of the considered tropical air mass to northwest Africa (taking more than 4 days), a prolonging of the precipitation activity caused by a moistening of the PBL by previous rainfalls (see, e.g., Geb 2000), or simply uncertainties in the trajectory calculations with the ECMWF (re-) analyses. Therefore, an examination of the precipitation in northwest Africa during periods of several days' duration with a (possibly interrupted) inflow of tropical air masses appears to be more adequate than a direct attribution on the basis of single dates. This leads to the definition of *TTA episodes,* which consist of consecutive analysis times with at least one TTA plus the analysis times immediately preceding and following a TTA time. The first and last analysis time of every 2-month investigation period was not considered. In order to avoid too many short episodes or episodes with extremely few TTAs, the following extensions to the TTA episode definition were made:

- If there was only one analysis time between two TTA episodes (i.e., 24 h from the end of episode 1 to the beginning of episode 2), the respective episodes were combined to one.
- Extremely short (and weak) episodes consisting only of one analysis time with less than four TTAs (plus the preceding and following times) were not taken into account.
- Every episode was required to contain at least one analysis time for which two or more valid TTAs were analyzed.

With this definition, TTA episodes cover 23.2% of the entire 20-yr period (i.e., 3337 analysis times). Figure 4 displays the average yearly variations of TTA occurrence. As expected (see the introduction and KFRS), the largest percentage of both trajectories identified as TTAs and analysis times belonging to TTA episodes are found for August–September. With the southward shift of the ITCZ, the occurrence of TTAs is clearly decreasing toward the winter, reaching its minimum in December–January. From December to May only 13%–16% of all analysis times belong to TTA episodes. Although the yearly variations of both quantities in Fig. 4 reveal very similar characteristics, some differences are found when the calculation of the percentage of trajectories identified as TTAs is restricted to the TTA episodes (values above the bars in Fig. 4a). Being slightly above 17% in October–November and February–March, this number is considerably higher than during the summer half year from April to September, indicating that TEI situations in the transition seasons are less frequent but are characterized by a stronger inflow of tropical air. This agrees with a 36-yr climatology of upper-level cyclones (with at least one closed 60-gpm height contour around the center) by Parker et al. (1989) showing maximum frequency to the west of northwest Africa in spring and autumn.

3. Relation to precipitation in northwest Africa

For the investigation of the importance of TEI situations for the precipitation in northwest Africa during different seasons, 12-hourly precipitation reports from 36 synoptic stations in Morocco, Algeria, Mauritania, and the Spanish exclaves in northwest Africa are considered (for details, see Table 1 in KFRS). In addition to the precipitation information received from the German Weather Service (DWD) and the National Center for Atmospheric Research (NCAR; see KFRS), daily summaries from the National Climatic Data Center (NCDC) were regarded for the period from 1994–98. The dataset covers the whole investigation period December 1978–November 1998, although all station time series contain several gaps of varying duration.

In the following, precipitation that fell during a TTA episode is considered to be caused by TEIs. The inspection of single cases, however, reveals that, in the transition seasons in particular, synoptic situations occur that do not allow for an unambiguous differentiation between TEI and extratropically induced precipitation. In the beginning of such cases, a tropical air mass typically arrives at northwestern Africa on the eastern side of an upper-level trough, and precipitation is predominantly observed in the region around the Atlas chain, as in the cases described by KFRS. Subsequently, the trough propagates eastward, and northwest Africa comes under the influence of maritime cold air, which causes additional, often stronger rainfalls (cf. the end of case II in KFRS or FK). Since the time interval during which there is ambiguity concerning the competing tropical versus extratropical influences is typically brief, and since in many cases only one mechanism is active anyway, the resulting uncertainties with respect to the total precipitation are expected to be rather small.

Figure 5 shows 2-month precipitation climatologies at six stations in northwestern Africa, calculated from the accumulation of the 12-hourly station time series over the 20 yr available (December 1978–November 1998). The stations were selected because of their good data coverage, nonproximity, and considerable TEI influence. A comparison to the climatological normals for the period 1961–90 published by the World Meteorological Organization (WMO 1996) reveals overall comparable precipitation characteristics, in spite of the gaps in data coverage in the station time series. The northern stations (Figs. 5a–c; Mecheria is not available), however, show considerably smaller precipitation totals, which is probably to a large extent caused by the series of dry years in the 1980s and 1990s [see, e.g., Fig. 13 of Hurrell and van Loon (1997) or Fig. 4 of Knippertz et al. (2003a)], only partly included in the WMO normals.

The black bars in Fig. 5 indicate the portion of the precipitation that feel during TTA episodes. Averaging over the six 2-month periods yields annual contributions. As expected from the case studies, the strongest influence of TTAs on the annual precipitation is found for the southern side of the Atlas Mountains [Ouarzazate, 40%; Errachidia, 35% (not in Fig. 5); Bechar, 32%]. Elevated stations north of the High and Sahara Atlas Mountains still reveal a considerable portion of TTA precipitation (Midelt, 26%; Mecheria, 18%). Toward the northern side of the Atlas range (Meknes, 12%) and the Mediterranean coast (Oran, 10%) values further decrease. Along the Atlantic coast, TTA-induced precipitation plays a negligible role (not shown). A comparison with the proportion of the frequency of precipitation events (not shown) reveals that south of the Atlas range TTA events are on average more intense than non-TTA events (at Ouarzazate, e.g., 40% of the total precipitation amount, but only 36% of all precipitation events are connected to TEIs), while the opposite is observed on the northern side (e.g., 12% versus 19% at Fes). With respect to seasonal variations, nearly all stations show the largest TTA portion of the total precipitation for the months August–September (up to 65% at Ouarzazate). Also, the portion of the sporadic rainfalls in June/July is high. The largest absolute precipitation values at some stations (e.g., Ouarzazate, Meknes), however, are observed during the transition seasons (October–November and February–March) For these periods, the highest percentage of trajectories identified as TTAs during TTA episodes was found (see Fig. 4a). In December–January both the absolute and relative contributions are small at most stations. This justifies the concentration on extratropical synoptic disturbances in several studies on northwest African precipitation variability during winter (Lamb and Peppler 1987; Ward et al. 1999; Knippertz et al. 2003a). Most of the stations not shown in Fig. 5 (see Table 1 in KFRS) reveal an influence of TTAs on their precipitation variability consistent with the regional variations described above.

If only the precipitation observations at the seven stations most strongly affected by TTAs (Midelt, Ouarzazate, Errachidia, Mecheria, Ain Sefra, Bechar, and Beni Abbes; all within or to the south of the Atlas chain) are considered, an approximately linear relation between the total numbers of TTAs and the total number of precipitation reports (summed over all stations) is found for August–September TTA episodes (Fig. 6). Such a relation is substantially less clear for the total precipitation amount (summed over all stations; not shown), indicating a wide range of rainfall intensities per TTA episode. Figure 6 reveals that none of the above-mentioned stations reported precipitation during only eight short TTA episodes. Except for two extremely long TTA periods with an above-average frequency of rainfall events, the precipitation–TTA relation appears to be rather independent of the episode length. For the rest of the year, when precipitation is less dependent on TEI situations and when TTA episodes tend to be shorter, relations between precipitation and TTA statistics are less clear. Apart from gaps in the 12-hourly precipitation time series, a possible reason for the deviation from a linear relation is the extreme spatial inhomogeneity during the preponderantly convective precipitation events, which can be hardly met by the few observations available in the Atlas Mountains and on its southern side. As shown by KFRS, the intensity and duration of the precipitation also depends on the concrete synoptic circumstances during the respective episode. Presumably, the moisture content of the tropical air mass and the strength of the upper-level divergence over northwest Africa play an important modulating role.

4. Conclusions

This paper presents a regionally and seasonally differentiated 20-yr statistical evaluation of the importance

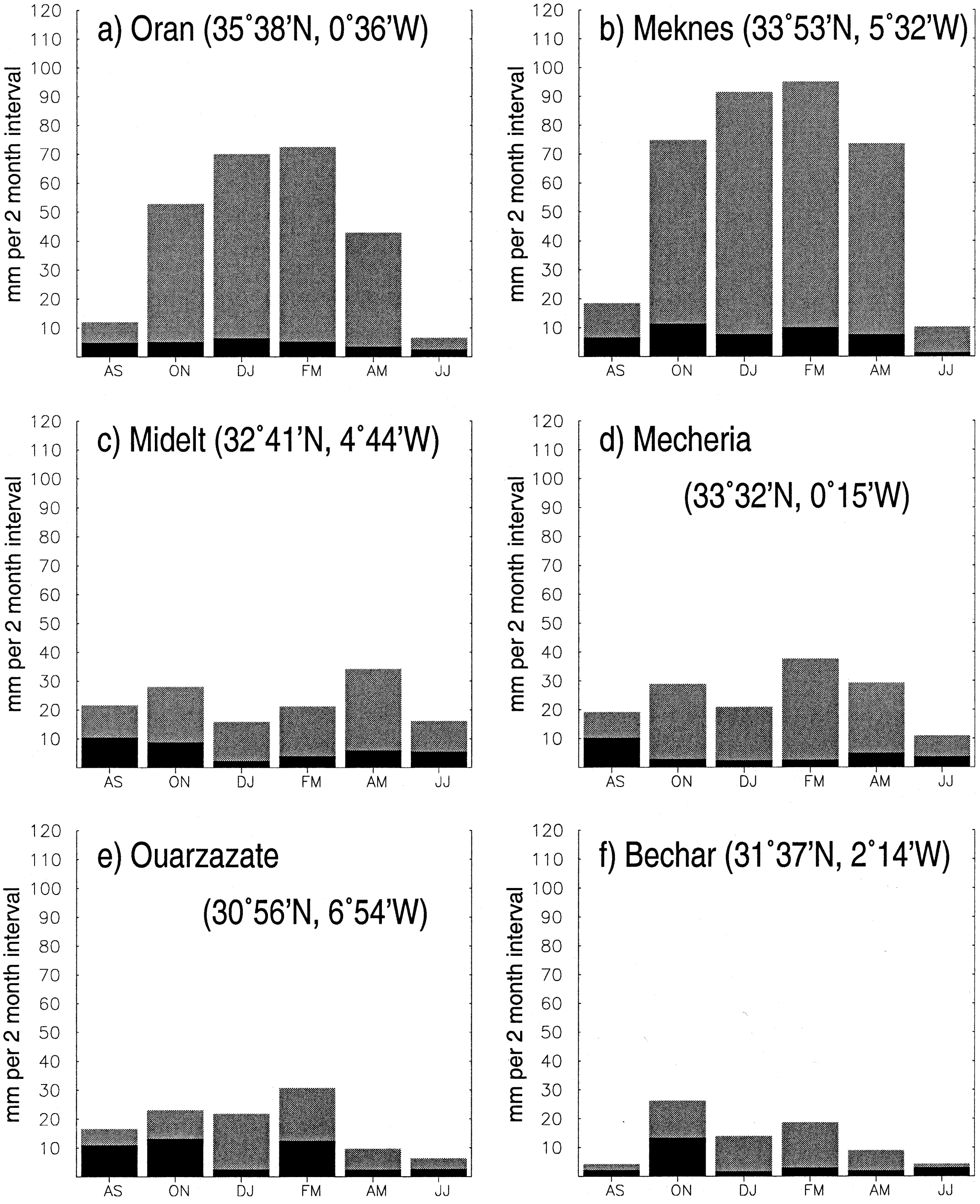

FIG. 5. Average 2-month precipitation (mm) (accumulated from all 12-hourly data available) for different stations in Morocco and Algeria. The black bars indicate the portion of the total precipitation recorded during TTA episodes (for definition, see text). Reference period and labeling of the abscissa are the same as in Fig. 4.

of TEI situations for the precipitation in northwest Africa. The developed algorithm for the automatic assignment of 12-hourly precipitation reports from synoptic stations in northwest Africa to moisture sources over tropical West Africa and the adjacent Atlantic Ocean is based on the origin and course of 4-day midtropospheric backward trajectories. Following the results of case studies by FK and KFRS, only trajectories starting to the south of 20°N and to the east of 25°W, ascending or remaining at the starting level, and reaching northwest Africa from westerly or southerly directions are considered and termed TTAs. Results show a distinct

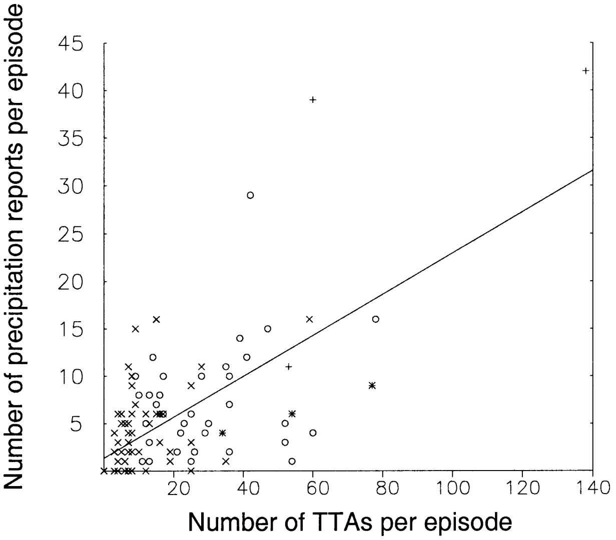

FIG. 6. Number of TTAs per episode versus number of precipitation reports per episode for Aug–Sep 1979–98. Only observations from the stations most strongly affected by TTAs (Midelt, Ouarzazate, Errachidia, Mecheria, Ain Sefra, Bechar, and Beni Abbes) are considered. The episode length is indicated by different symbols (x for 1.5–4.5 days; o for 5–9.5 days; * for 10–14.5 days; and + for 15 days or more). Linear regression was computed with the method of least squares.

decrease of the importance of tropical moisture sources from a maximum at the Saharan foothills of the High Atlas (up to 40% of the annual precipitation) toward negligible contributions along the Moroccan Atlantic coast. The greatest importance was found for August–September, when TTA episodes are most frequent and when the tropical–extratropical exchange is favored through the relatively northerly position of the ITCZ, and for October–November, when upper-level troughs to the west of West Africa are frequently observed. Also in spring, considerable precipitation in connection with TEIs is recorded at some stations. It is suggested that all precipitation that is not assigned to the TEI mechanism described in section 1 by the algorithm presented here is purely extratropical in nature.

The results of this investigation point at a climatologically nonnegligible role of TEI situations for the rainfall in northwest Africa, in particular for the region south of the Atlas Mountains. This has several far-reaching consequences for the understanding of the observed precipitation variability and for future investigations of the climate in this part of the world. First, considering the additional influence of TEIs, the spatial variations in rainfall seasonality can be better understood. In the semiarid region south of the Atlas Mountains, which is sheltered from the rain-bearing synoptic winter depressions from the Atlantic Ocean (Knippertz et al. 2003a), the TEI contributions are large enough to cause precipitation maxima in spring and autumn (Figs. 5e,f; WMO 1996), when the number of TTAs is relatively large and the TTA episodes are intense (Fig. 4). This effect is still felt directly to the north of the main watershed of the Atlas chain (Figs. 5c,d). In northern and western Morocco, however, the relative impact of TTAs is too small to modify the unimodal precipitation distribution caused by the dominant wintertime extratropical disturbances (Lamb and Peppler 1987; Knippertz et al. 2003a). Second, investigations of the meteorological reasons for the observed long-term precipitation variability including the region around the Atlas range should not be restricted to extratropical factors such as variations of the North Atlantic Oscillation (NAO) or the frequency of surface cyclones and upper-level storm track activity (see Lamb and Peppler 1987; Ward et al. 1999; Knippertz et al. 2003a). Hurrell and van Loon (1997) assigned the series of dry years north of the Atlas chain during the 1980s and 1990s to the extraordinary positive phase of the NAO. On the basis of the results of this study, it can be speculated that the opposite trend south of the Atlas chain during the same period (Nicholson et al. 2000; Knippertz et al. 2003a) is in fact connected to the different relative influence of TEIs on the respective side of the main orographic barrier. This issue cannot be addressed in detail in the present study because of the restriction to the period December 1978–November 1998 and is left for future investigations. Third, the estimation of future precipitation conditions based on the output of simulations with GCMs should take the influence of TEIs into account. Such investigations should make sure that the GCMs are able to realistically reproduce the climatological features of TEI precipitation before the climate-signal issue is addressed. This is a particularly crucial point, since some of the considered precipitation events were poorly forecasted by operational NWP models. Beyond the impacts on the modeling and forecast of precipitation, such an investigation can constitute a substantial test of the quality of the model output, since TEIs are an important part of the large-scale atmospheric circulation.

In this study, precipitation events in all seasons were classified solely on the basis of the origin and the advection paths of the involved air masses. The large variety of individual synoptic characteristics among the TTA cases within, and even more between, seasons (compare FK and KFRS), however, requires a deeper understanding of the physics and the large-scale conditions that determine the formation of TEIs in northern Africa. Given the poor data coverage in the region of interest, simulations with mesoscale models might be helpful to analyze the involved dynamics in more detail and more quantitatively than KFRS and FK did. In addition, an application of the presented method to other subtropical regions that have been reported to be affected by TEI precipitation such as, for example, Israel (Ziv 2001) and Australia (Wright 1997), might gain further insight into the TEI precipitation mechanism.

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