Three Late Summer/Early Autumn Cases of Tropical–Extratropical Interactions Causing Precipitation in Northwest Africa

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ABSTRACT

In contrast to the winter rain-dominated region along the Atlantic and Mediterranean coasts in northwest Africa, the semiarid to arid southern foothills of the Atlas Mountains receive significant contributions to their annual rainfall amounts from rainy episodes in late summer/early autumn. Three such cases (September 1988, September 1990, August–September 1999) are studied with respect to the sources and the vertical and horizontal transports of moisture, as well as local factors for precipitation generation. Besides station reports of precipitation, the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalyses and Meteosat water vapor images are considered.

All three cases presented reveal similar tropical–extratropical interactions. Convective cloud clusters or squall lines over tropical West Africa and the adjacent tropical Atlantic Ocean, several of them associated with low-level African easterly waves, could be identified as midlevel moisture source regions by the use of trajectory analysis. The moisture is transported northward to the east of an upper-level subtropical trough, which extends anomalously deep into the Tropics. Most of the transport occurs above the dry Saharan planetary boundary layer. The moisture converges at midlevels (700–400 hPa) over northwestern Africa underneath a strong upper-level divergence center at the inflection point of the trough. The dynamically forced ascent in connection with orographic lifting at the Atlas Mountains in the southerly flow and surface heating over the elevated terrain triggers convective rainfalls, which occur preferably close to and downwind of the mountain chain.

The three cases differ with respect to the synoptic evolution of the upper-level subtropical trough and the paths of the moisture export from the Tropics. At the end of the episode in September 1988, the tropical air over northwest Africa is displaced by polar air connected with some heavy rainfall events. The presented cases are compared to studies of tropical plumes and Soudano-Saharan depressions.

1. Introduction

Most studies about northwestern African climate focus on the winter half year, since the more populated regions north of the Atlas Mountains and along the Atlantic and Mediterranean coasts receive most precipitation from wintertime extratropical synoptic disturbances, whose frequency strongly depends on the phase and strength of the North Atlantic Oscillation (e.g., Lamb and Peppler 1987; Ward et al. 1999). The episodic and often weak rainfalls of the summer half year have been studied very little. Nevertheless, several stations in northwestern Africa receive significant contributions to their annual rainfall amounts from rainy episodes in late summer/early autumn. In particular in the semiarid to arid zones between the Atlas Mountains and about 22°N, the wettest quarter of the year is during the months August to October (southern parts) or September to November (northern parts), with September and October generally being the wettest months (Griffiths and Soliman 1972; Nicholson 2000). For example, 56% of the annual mean rainfall in Bir Moghrein and 44% in Tindouf (for location see Table 1) is recorded in the period from August to October, while 40% (37%) of the annual total falls between September and November in Ouarzazate (Bechar). Since polar frontal winter rains, which regularly affect the northern and western parts of Morocco and the Mediterranean coast of Algeria, usually do not reach south of the Atlas Mountains, the contribution of the summer rains is not negligible and helps to sustain the water supply in the oases in northern Mauritania, southern Morocco, and western Algeria. Occasionally, localized strong convective showers or thunderstorms occur during the summer half year, which lead to flash floods in the dried-out riverbeds. In a climatological study, Nicholson (1981) found a similar decadal variability north and south of the Sahara for the twentieth century before 1975. During the 1980s and 1990s, however, the region at the southern foothills of the Atlas Mountains was rather wet, while the Sahel and the area north of the Atlas Mountains experienced drought conditions (Nicholson et al. 2000), which has

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not been explained so far. The quasi-stationary orographic ridge–trough over the Atlas–Ahaggar mountain complex described by Semazzi and Sun (1997) could, at least in part, provide an explanation for this out-of-phase relationship. Thus, a better understanding of the large-scale atmospheric conditions and local factors that cause late summer/early autumn rainfall events is needed to assess reasons for the extremely high interannual and decadal precipitation variability observed south of the Atlas chain and to obtain a better forecast of extreme rainfall and river discharge situations. In a detailed investigation of three such 1–2-week rainy episodes, characteristic parameters and synoptic patterns are presented, which might be used for a more statistical evaluation of the considered phenomena.

Rainy events during late summer/early autumn in northwestern Africa appear to be connected to outbreaks of tropical air into the subtropics. As long as the upper-level subtropical highs over Africa and the Atlantic build a high pressure belt, as is often seen during the time from June to August, tropical–extratropical exchange is suppressed and very few rain events are observed in northwestern Africa. In September, this high pressure belt is intersected more often by subtropical troughs that penetrate into the Tropics [see the climatology by Sadler (1975)]. The fact that the intertropical convergence zone (ITCZ) is at its northernmost position at this time of the year further favors the export of moist tropical air masses into the subtropics.

This study investigates the synoptic situation of three such late summer/early autumn rainy episodes in northwestern Africa that reveal tropical–extratropical interactions. In the analysis, emphasis is put on the moisture sources in the Tropics, the mechanisms of vertical and horizontal moisture transports into the subtropics, and the local factors and synoptic conditions that determine the precipitation generation in northwestern Africa during the episodes, in particular the role of the Atlas Mountains. Section 2 summarizes results of previous studies dealing with the characteristics, the climatology, the dynamics, and the importance for precipitation generation of a common appearance of tropical–extratropi-
ical interactions, the so-called tropical plumes. Section 3 contains a description of the data and the methods used for the analysis. In sections 4, 5, and 6, a detailed description of each of the three selected cases is presented. Where appropriate, identical parameters are employed for the analysis of the three cases to facilitate comparisons. Section 7 contains a short summary and discussion of the results, a comparison to the classic “tropical plume,” and future research perspectives.

2. Previous studies on tropical–extratropical interactions

Among the common features of tropical–extratropical interactions that are observed in the entire tropical belt are the so-called cloud bands, tropical plumes, tropical intrusions, cloud surges, or moisture bursts [termed tropical plume (TP) hereafter]. According to a definition offered in McGuirk et al. (1987), TPs are continuous bands of upper- and midtropospheric clouds that extend poleward and eastward from the Tropics into the subtropics and midlatitudes. These bands usually have a length of several thousand kilometers and can be easily identified from infrared (IR) satellite imagery. They often originate from the upper-level outflow from tropical cyclones or synoptic-scale deep tropical convection and form on the downwind side of a synoptic-scale midlatitude trough penetrating to low latitudes. In the subtropics, the cloud band typically recurs anticyclo-}


activity from May to September. McGuirk and Ulsh (1990) observed that TPs over the eastern Pacific do not form when there is a very active Hadley cell, which possibly explains the low numbers of TPs during summer.

In order to investigate the dynamics of TP formation, Blackwell (2000) forced a divergent barotropic model with subsidence-induced tropical upper-tropospheric convergence and found an equatorward amplification and zonal contraction of a preexisting subtropical trough connected to concentrated convergence–divergence couplets and jet exit–entrance regions, which define the actual TPs. The importance of the right-entrance divergence center in the southeastern portion of the trough in accelerating the STJ and in triggering tropical convection that moistens the middle and upper troposphere was also stressed by Ziv (2001). Mecikalski and Tripoli (1998) present a different dynamical concept for TP formation based on the behavior of the upper-level convective outflow. Although Nicholson (1981) does not refer to the term TP, but to “Soudano–Saharan depressions” (SSDs), she sketches a synoptic situation of tropical–extratropical interaction over West Africa (Fig. 3 of Nicholson 1981) that shows similarities to TP evolution. The basic mechanism of SSD formation involves the coupling of a wave disturbance in the low-level easterly flow with an upper-level trough in the subtropical westerlies. According to Nicholson (1981), SSDs occur mainly during the transition seasons, when they frequently bring rain to North and West Africa.

The importance of TPs for precipitation in the subtropics is assessed in a climatological study by Wright (1997), who shows that 40%–80% of subtropical Australian cool season precipitation is related to TPs and their interactions with extratropical fronts and disturbances. Case studies of heavy precipitation events on the Sinai Peninsula (Dayan and Abramski 1983) and in Israel (Ziv 2001) also reveal connections to TPs. Ziv (2001) points out that the observed intense precipitation was connected to enhanced upper-level divergence associated with positive vorticity advection at the inflection point downstream of the upper-level trough that initiated the TP. Due to a quadratic dependence of divergence on wind speed, the strongly intensified STJ appears crucial to the precipitation generation in connection with TPs (Ziv 2001).

3. Data and methods

Three late summer/early autumn episodes of 1–2 weeks have been chosen to demonstrate tropical–extratropical interactions that are related to precipitation in northwestern Africa: case I (9–20 September 1990), case II (10–16 September 1988), and case III (22 August–5 September 1999). The two longer episodes (cases I and III) are interrupted by a short drier period and have been subdivided into two rainy phases (see sections 4 and 6).
For cases I and II, 12-hourly precipitation reports (at 0600 and 1800 UTC) from 36 stations in northwestern Africa (Morocco, Algeria, Mauritania; for details see Table 1) are taken from a combined dataset, which was generated at the Institute of Geophysics and Meteorology of the University of Cologne, containing synoptic observations received from the German Weather Service (DWD, Seewetteramt Hamburg) and daily station summaries from the National Center for Atmospheric Research (NCAR). The data were checked for errors and inconsistencies before the datasets were merged. For case III, synoptic observations distributed by the World Meteorological Organization (WMO) via the Global Telecommunication System (GTS) were available and they were converted into a temporal resolution of 12 h. The station report time series contain sporadic gaps; for single stations and episodes (or rainy phases) data convergence can be as low as 50%.

For the synoptic-scale fields of atmospheric moisture and wind, European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis data for the 15-yr period 1979–93 (ERA-15) were used. This dataset includes uninitialized analyses of several variables at the 10 standard pressure levels, plus three additional levels, 925, 775, and 600 hPa, which were transformed from spherical harmonics space (T106) onto a $1^\circ \times 1^\circ$ grid for the time of the first two episodes and onto a $2.5^\circ \times 2.5^\circ$ grid for the whole 15-yr period in order to have a background climatology for comparison. For the post-ERA time (case III), uninitialized operational ECMWF analyses at $1^\circ \times 1^\circ$ horizontal resolution were considered. The additional levels, 925, 775, and 600 hPa, were not available for this case. Temporal resolution for both datasets is 6 h.

Sources of humidity observations in ERA-15 are radiosondes and satellite-derived moisture profiles based on the cloud-free retrievals of radiance from the Television and Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS) water vapor channels (McNally and Vesperini 1996). Over the nearly unpopulated Sahara and the adjacent Atlantic Ocean, however, very few radiosonde stations are operating. Satellite retrievals were used only over sea areas and below 300 hPa. They significantly corrected the ERA-15 model first guess (Uppala 1997). Temperature profiles up to 100 hPa were also assimilated from TOVS multispectral radiances, and Meteosat cloud track winds were used for lower- and upper-level winds in data-sparse regions over the Atlantic. Over the African continent, only upper-level cloud track winds were considered. Further details concerning the ERA-15 dataset can be found in Gibson et al. (1997) and Uppala (1997). In the operational analysis for 1999 (case III), additional information from Special Sensor Microwave Imager (SSM/I) total column water vapor and more TOVS channels over land were considered.

For the analysis of cloud developments and midlevel moisture transports during the three episodes, rectified, inverted, and unenhanced infrared (IR, 10.5–12.5 μm) and water vapor (WV, 5.7–7.1 μm) channel Meteosat satellite images in 3-hourly resolution for the area between 5° and 50°N and 30°W and 20°E were provided from the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT). In contrast to most studies on tropical plumes, both IR and WV imagery are used, since additional information on plume formation like midlevel moisture transports in cloud-free regions, and the subsidence and drying west of the TP are not visible in IR images (cf. McGuirk and Ulsh 1990; Blackwell 2000).

In order to identify the source regions and advection paths of the air masses involved in the considered precipitation events in northwestern Africa, backward trajectories were calculated. After some testing with several concrete synoptic situations, a duration of 4 days was found to be a reasonable time span for the transport from a tropical moisture source to northwestern Africa. Since most precipitation fell in the vicinity of the Atlas chain during all three episodes (see Figs. 1, 7, and 14), 15 points close to and south of the Atlas range were chosen as starting locations for the backward trajectories in order to have an ensemble of tracks of different air parcels that affect the area of interest (for an example, see Fig. 4). The starting level depends on the episode considered. The backward trajectories were computed using an algorithm developed by the Irish Meteorological Service (McGrath 1989). Basically, analyzed winds at spectral resolution T106 are used to trace the Lagrangian movement of an air parcel. The three-dimensional wind field is interpolated linearly in time between the 6-h (re-) analysis intervals to 1-hourly increments. The algorithm then uses a simple predictor/corrector method to estimate the new position of the air parcel at the next time step.

African easterly waves (AEWs) play an important role in triggering convection over tropical Africa and the adjacent Atlantic during July through September (e.g., Carlson 1969; Burpee 1972; Reed et al. 1977). AEW trough lines have been manually identified and tracked using Hovmöller diagrams of the unfiltered meridional wind component at 700 and 850 hPa and horizontal distributions of streamlines of the 2–6-day band-pass-filtered wind at 850- and 700-hPa vorticity. This identification technique basically follows the approach used in Reed et al. (1977).


a. Synoptic situation and precipitation

The temporal evolution of the rainfalls during case I suggests a subdivision into two rainy phases. Although several stations reported rainfall during two or three 12-h periods within the 2 days of phase I (0600 UTC 10 September–0600 UTC 12 September), accumulated precipitation amounts were generally rather small (Fig. 1a).
Fig. 1. Total precipitation amount in mm per number of 12-h rainy intervals for several synoptic stations in northwestern Africa. Considered periods are at (a) 0600 UTC 10 Sep 1990–0600 UTC 12 Sep 1990 (case I, phase 1) and (b) 1800 UTC 14 Sep 1990–1800 UTC 19 Sep 1990 (case I, phase 2). Gray shading represents orography. Here, 0.0 mm stands for precipitation observed, but not measurable; no entry indicates no precipitation at all. Station locations are marked by stars; for detailed information about the stations see Table 1.

Maximum values of 7 and 6 mm were recorded in Fes and Oujda, located on the northern margin of the Atlas chain. The IR satellite images reveal that precipitation fell in connection with convective cells that formed during the afternoon over the Atlas range in a SW–NE-orientated, broken band of cirrus and altocumulus that slowly moved in from the south (Fig. 2). Since the convection was advected north-northeastward, it is not surprising that considerable precipitation fell only in the vicinity or north of the Atlas Mountains, whereas the coastal stations had no (Atlantic) or very little rain (Mediterranean). At the beginning of the second phase (1800 UTC 14 September–1800 UTC 19 September), another broken band of middle and high clouds is visible over Morocco with an often varying length and texture, which became more and more disrupted and shortened on the following days (not shown). During the entire phase 2, convective cells formed during the afternoon, usually over the Atlas range, spread, and were advected toward the Mediterranean coast. This explains why frequent (up to nine 12-h observation periods with precipitation in Midelt) and considerable (up to 23 mm in Fes) rainfalls were only observed at stations close to and north of the Atlas chain, while, except for a local 20-mm shower in Larache on 18 September, no rain fell along the Atlantic coast (Fig. 1b). This is similar to what was observed for phase 1 (Fig. 1a). During the 2.5 days between the two phases, precipitation was restricted to local afternoon showers or thunderstorms in the Atlas Mountains, which are clearly visible in the IR satellite images (not shown) with rainfall recorded only in Midelt, Ouazarzate, Errachidia, Mecheria, and Ain Sefra. No precipitation at all fell at the Saharan stations in the southeastern part of the considered region.

Since the upper-level synoptic situation during case I is rather stationary in the subtropics, we examine episode means (9–20 September 1990) of different atmospheric parameters instead of the characteristic single dates as for the other cases (sections 5 and 6). Figure 3a shows the averaged 250-hPa streamlines. A pronounced upper-level subtropical trough remained quasi-stationary over the Atlantic west of North Africa throughout the episode. Average wind speeds reach 25 m s$^{-1}$ on the eastern side of the trough just to the west of the Moroccan coast. A comparison with the climatological situation (Fig. 3b) reveals that the trough is amplified equatorward and zonally contracted with a more than 50% enhancement of wind speeds in the jet
maximum with respect to the climatology. The trough is marked throughout the upper and middle troposphere, but weak at 850 hPa and below, where trade winds are prevailing over most of northern Africa and the adjacent Atlantic (not shown). At the beginning of the episode, the trough moves southward reaching its most southerly position at 15°N on 1200 UTC 10 September. The precipitation observed during phase 1 is likely to be related to this southward excursion. After 12 September, the trough retreated into the subtropics and a more zonal flow prevailed. At 0000 UTC 15 September, the trough started another southward extension a bit farther west over the Atlantic than the first time, initiating the second rainy phase. The episode ended when an anticyclonic center formed around 15°N and 25°W, which blocked tropical–extratropical exchange and forced the trough to retreat northward again.

b. Moisture transports

In order to trace back the air masses involved in the two rainy phases of the considered episode, 4-day backward trajectories were calculated and are displayed for a selected day of each phase (1800 UTC 11 September and 1200 UTC 19 September, respectively) in Fig. 4. As moisture transports appear to have occurred mainly at midlevels (see below and Fig. 5), 400 hPa was selected as the starting level for the backward trajectories. In order to demonstrate the moisture content of the regions, where the backward trajectories ended, WV satellite images of the beginning of the 4-day periods that span the trajectory calculation (i.e., 1800 UTC 7 September and 1200 UTC 15 September, respectively) were underlaid. Note that, dependent on the moisture content of the atmosphere, the maximum of the weighting function for WV images in cloud-free regions is around 350–550 hPa (Brimacombe 1981) and thus corresponds with the starting level of the backward trajectories.

For phase 1, Fig. 4a shows that the southward movement of the trough described in section 4a forced midlevel tropical air to leave the area of easterly flow east of the Greenwich meridian and to recurve anticyclonically east of the trough into northwestern Africa. The westernmost trajectories originate in the subtropics and recurve cyclonically, probably transporting rather dry air into the region. Most air parcels remained between 500 and 300 hPa throughout their 4-day travel. Only the southernmost trajectory ascended from 600 to 400 hPa. Several backward trajectories end close to a cloud cluster near 0° longitude that belongs to a long-lived squall line that formed over the Jos Plateau around 13°N and 8°E at 0000 UTC 7 September and traveled westward, where the convection collapsed early on 9 September (not shown). The course of the trajectories and the movement of the squall line strongly suggest that one important moisture source for the precipitation of phase 1 was the midlevel (600–400 hPa) outflow in the squall-line region (15°–20°N and 0°–5°E). In fact, the ERA-15 vertical profile of divergence for this region reveals dual peaks of divergence in the middle (600–500 hPa) and upper troposphere (~150 hPa) and convergence maxima below (~925 and ~300 hPa, respectively). This pattern strongly resembles the profile shown in Fig. 5 of Thompson et al. (1979) for the eastern tropical Atlantic. Midlevel divergent outflow at and above the axis of the African easterly jet (600 hPa) is a characteristic feature at and north of its mean latitudinal position (~15°N), both over land and ocean (Burpee 1972; Druyan et al. 1997).

For phase 2, two convective centers around 16°N west
Fig. 4. Four-day backward trajectories starting at 400 hPa from 15 different points over the southern margin of the Atlas Mountains (a) at 1800 UTC 7 Sep 1990–1800 UTC 11 Sep 1990 (case I, phase 1) and (b) 1200 UTC 15 Sep 1990–1200 UTC 19 Sep 1990 (case I, phase 2). Different colors indicate the height of the trajectory (see figure legend); the numbers 2, 3, and 4 mark the beginning of the second, third, and fourth 24-h period backward in time. The Meteosat WV image corresponding to the end of the backward trajectories (i.e., the earliest date) is underlaid. In (b), AEW trough lines are marked by dashed lines.
and east of the African coast could be identified as moisture sources in the WV image for 1200 UTC 15 September (Fig. 4b). On 13 September, the former emerged on the eastern side of a low-level AEW that had crossed West Africa during the previous days (dashed line in Fig. 2), while the latter formed on the western side of the following wave on 14 September (dashed lines in Fig. 4b). North of 12.5°N, convective activity is often observed in the region of strong humidity advection in the southerly winds east of an AEW trough. Convection ahead of the AEW trough due to dynamic uplift is generally more important farther south (Burpee 1974; Duvel 1990). The course of the trajectories suggests that midlevel moisture from the two convective centers was advected toward northwestern Africa east of the upper-level trough, whose eastern edge is also visible in the WV image. Note that the anticyclonic outflow of the eastern convection center is clearly displayed in the course of the trajectories.

Figure 5 shows the episode-averaged (9–20 September 1990) moisture flux and moisture flux convergence between 700 and 400 hPa for the period 0000 UTC 9 Sep 1990–1200 UTC 20 Sep 1990 (case 1). Absolute values of moisture flux greater than 50 kg m⁻² s⁻¹ are shaded; convergence isolines are at 30, 50 and 70 mm (12 days)⁻¹; maxima are labeled $Q_x$ for moisture flux and $D_x$ for moisture flux convergence.

`>50.0` `>75.0` `>100.0`

**Fig. 5.** Mean moisture flux [kg (m s)⁻¹] (vectors and shading) and moisture flux convergence [mm (12 day)⁻¹] (isolines) integrated between 700 and 400 hPa for the period 0000 UTC 9 Sep 1990–1200 UTC 20 Sep 1990 (case 1). Absolute values of moisture flux greater than 50 kg m⁻² s⁻¹ are shaded; convergence isolines are at 30, 50 and 70 mm (12 days)⁻¹; maxima are labeled $Q_x$ for moisture flux and $D_x$ for moisture flux convergence.

which can extend up to 500 hPa in summer (Karyampudi and Carlson 1988). The SI unit for flux convergence (kg m⁻² s⁻¹) was converted into mm (12 days)⁻¹ to get a more expressive idea of how much water could possibly precipitate over the whole length of the episode. The averaged moisture fluxes clearly reveal the humidity band of the ITCZ between 7° and 15°N over tropical Africa. The two branches of moisture transport into the subtropics, the more easterly over the continent during phase 1 and the more westerly over the Atlantic during phase 2, are clearly displayed in the episode average. Over Morocco, slightly southeast of the upper-level wind maximum (Fig. 3a), the moisture flux reaches a maximum of 136 kg m⁻² s⁻¹. At about the same location, a midlevel moisture flux convergence maximum of 107 mm (12 days)⁻¹ is observed. The dry areas in the western portion of the upper-level trough and to the southeast of the upper-level anticyclone over North Africa correspond to the dark regions in the WV imagery (Fig. 4).

c. Precipitation generation

Figures 3a and 5 reveal that the precipitation area in northwestern Africa is located close to the inflection point of the trough, where the curvature of the flow changes from cyclonic to anticyclonic. It can be expected that advection of positive vorticity together with the anomalously high wind speeds (see Fig. 3) lead to enhanced upper-tropospheric divergence in this region (Ziv 2001). In fact, an episode mean of the vertical profile of divergence averaged over 16 grid points around the Atlas range (30°–33°N and 4°–7°W) clearly reveals a deep layer of anomalously strong divergence between 150 and 400 hPa with a maximum at 200 hPa (Fig. 6a). In the midtroposphere, between 700 and 400 hPa, anomalously strong convergence is observed corresponding to the moisture flux convergence maximum seen in Fig. 5. Below, weak divergence is observed. Note that the levels 850, 925, and 1000 hPa are below ground for some of the considered grid points. The middle-/upper-tropospheric convergence/divergence pattern is connected to strong ascent between 700 hPa and the tropopause, thus spanning the entire free troposphere (Fig. 6b). The moisture transports into the region (section 4b) together with the dynamically induced ascent allows the formation of deep convective clouds that caused the observed precipitation (Fig. 1). The fact that only small portions of the water vapor converging at midlevels (see Fig. 5) reach the ground as precipitation might be due to low-level divergence or errors in the reanalysis data, but also evaporation in the dry planetary boundary layer (PBL) is a likely reason (Geb 2000). Note that the weak upper-level trough seen in the climatology (Fig. 3b) causes a similar but much weaker divergence/convergence/ascent pattern (Fig. 6, dashed curve) than observed during this episode.

In addition to that, the precipitation distribution (Fig.
1) and the inspection of IR images (see section 4a and Fig. 2) suggest an important role of the Atlas Mountains in precipitation generation. Two mechanisms might be responsible for that. First, orographic lifting at the southern side of the Atlas range in the southerly flow, which prevails throughout the whole episode, leads to ascent that might destabilize the atmosphere or even release potential instabilities. The fact that convection mainly formed during the afternoon indicates a strong connection to surface heating, which is still very pronounced in the subtropics in late summer/early autumn. The elevated areas of the Atlas range, where heating occurs above the subsidence inversion, are particularly favorable for convection.

5. Case II (10–16 September 1988)

a. Synoptic situation and precipitation

The geographical distribution of precipitation amounts and frequency during case II (Fig. 7) shows several similarities to the two phases of case I (Fig. 1). Most precipitation fell in the vicinity and to the north of the Atlas chain, while Atlantic coastal stations received little or no precipitation (except of 4 mm in Tan Tan). In contrast to case I, the largest precipitation amounts, however, were recorded at stations in northwestern Algeria with maxima at Mecheria (28.4 mm) and Beni Saf (28.0 mm), where the largest number of rainy periods also was observed (four at Mecheria and Bechar).

At the beginning of the episode, IR imagery shows a SW–NE-orientated cloud band reaching from the ITCCZ to the Mediterranean Sea that formed from the poleward stretching of a patchy ensemble of mainly altocumulus clouds over the central Sahara on 10 and 11 September (not shown). To the northwest of the cloud band local convection can be seen over the Atlas Mountains during the afternoon of 11 September that caused light rains at stations on their northern side. In contrast to the typical TP cases described in section 2, the cloud band moved westward and northward, and reached the
southern parts of Morocco on 13 September (Fig. 8), when precipitation was recorded at stations south of the Atlas range (Ouarzazate, Errachidia), in northern Mauritania (Bir Moghrein), and at the southern Moroccan Atlantic coast (Agadir, Tan Tan). On 14 September, the cloud band started to move in the opposite zonal direction (i.e., eastward) and precipitation was recorded north of the Atlas chain and along the central Moroccan Atlantic coast. By the beginning of 15 September, the cloud band had passed over Morocco and merged with the clouds of an extratropical front over the Mediterranean that moved rapidly eastward. Behind the band, local convection occurred in the northeastern part of the considered region on 15 and early 16 September causing precipitation on the order of magnitude of 100%–200% of the long-term September average (Oran, 21 mm; Beni Saf, 28 mm; Tlemcen, 18 mm; Mecheria, 28 mm).

Figure 9a shows 250-hPa streamlines and isotachs for 1200 UTC 11 September. A narrow and elongated trough that extends from the Mediterranean over North Africa into the Tropics at 15°N, 10°W is indicated by a thick black line that basically follows the axis of strongest cyclonic curvature and minimum wind speeds. The two separated segments of the STJ and the high wind speed in the jet (up to 45 m s\(^{-1}\)) east of the trough show similarities to the TP case study by Ziv (2001). In Fig. 9b the temporal evolution of this trough is displayed. During the beginning of the episode, the trough moved steadily westward until it split up into a tropical and a subtropical part on 14 September (see also Fig. 8). The latter merged with a midlatitude trough on 15 September that split up again on 16 September and propagated into the western Mediterranean. The cloud band described above remained east of the trough in the region of southerly flow throughout the period (e.g., Fig. 8). The dashed lines in Fig. 9b indicate the trough line of a low-level AEW that formed around 18°E on 5 September and moved westward, circa 7°–8° longitude ahead of the subtropical trough during 10–12 September.

**b. Moisture transports**

The IR satellite imagery shows that convection occurred on the eastern side of the above-described AEW during its passage over tropical Africa (not shown). On 10 September a convective cluster formed around 15°N between 0° and 5°E, which then traveled westward with the low-level wave and the upper-level trough until it broke up over the course of 12 September. At 1200 UTC 11 September, the anticyclonic outflow center of the
convection can be clearly identified in 250-hPa streamlines just to the southeast of the upper-level trough (Fig. 9a). The strong divergence in the southern entrance region of the jet (not shown) is likely to have triggered and/or maintained convection in agreement with the mechanism proposed by Ziv (2001), which is explained in section 2.

In analogy to Fig. 4, 4-day backward trajectories were calculated starting at 400 hPa over the Atlas range at 0600 UTC 14 September (Fig. 10). The underlaid WV image from 0600 UTC 10 September shows the beginning convection around 15°N and 5°E and a broad area of high midlevel moisture connected with the cloud band over the Sahara. The evolution of WV images reveals that this moisture was advected northward east of the upper-level trough (solid line in Fig. 10) in the course of the preceding days. The western side of the trough appears as a dark (i.e., dry) band. Most of the considered air parcels affecting Morocco and western Algeria originated from this moist area and traveled northwestward at midlevels (400 or 500 hPa). On 13 September, when the cloud band had reached the south of Morocco (Fig. 8), their trajectories recurved anticyclonically toward the northeast. In contrast to that, the three westernmost air parcels started at low levels (900 or 800 hPa); ascended cyclonically to 600 hPa during the following 2 days, as the convection of the AEW approached; and subsequently followed the anticyclonic midlevel flow into northwest Africa showing a more direct influence of the AEW's convection than the other air parcels. The strong midlevel humidity advection from tropical convection between 5° and 15°W toward northwestern Africa is also clearly demonstrated by the 700-400-hPa moisture flux at 0000 UTC 13 September (Fig. 11). Maximum moisture flux and moisture flux convergence (up to 28.8 mm day⁻¹) were found south of the Atlas chain at the northern edge of the cloud band described in section 5a. Midlevel moisture flux convergence in a tropical air mass of the same order of magnitude was found by Zangvil and Isakson (1995) in association with a rainstorm over Israel.

c. Precipitation generation

As demonstrated for case I, the precipitation generation during case II also appears to be connected to upper-level divergence, as revealed by the inspection of data for single dates. By the end of 12 September, when the cloud band approached southern Morocco, light precipitation was observed at Agadir (Moroccan Atlantic coast), which is generally not affected by the kind of precipitation events described above (see, e.g., Fig. 1). The vertical profile of divergence averaged over the 16 grid points around Agadir (28°–31°N and 7°–10°W) for
FIG. 11. Moisture flux (kg m$^{-2}$ s$^{-1}$; vectors and shading) and moisture flux convergence (mm day$^{-1}$; isolines) integrated between 700 and 400 hPa for 0000 UTC 13 Sep 1988 (case II). Absolute values of moisture flux greater than 100 kg m$^{-2}$ s$^{-1}$ are shaded; convergence isolines are at 10, 15, 20, and 25 mm day$^{-1}$; maxima are labeled $Q_x$ for moisture flux and $D_x$ for moisture flux convergence.

0000 UTC 13 September (Fig. 12) shows that the precipitation is indeed connected to extreme upper-level divergence and (moisture) convergence at middle levels (see also Fig. 11). Below 600 hPa another divergence–convergence couplet is found, which is presumably associated with the formation of shallow cumulus clouds at the trade wind inversion. The vertical pattern of divergence–convergence shown in Fig. 12a resembles the schematic picture of an upper-level subtropical cyclone presented by Ramage (1962). The presented case suggests that extreme upper-level divergence and midlevel convergence are needed to trigger precipitating convection in late summer/early autumn at coastal stations, where orographic lifting and surface heating of elevated areas is absent.

Precipitation generation through afternoon convection over the Atlas Mountains as described for case I is seen only on 11 and 14 September. Presumably, more convection has occurred during the passage of the cloud band. The strong rains recorded on 15 and early 16 September (see section 5a) are connected to the midlatitude trough that moved into the Mediterranean from the Iberian Peninsula (Fig. 9b). Four-day backward trajectories starting at 400 hPa at 0600 UTC 16 September (Fig. 13a) demonstrate that this trough transported polar air masses into western Algeria, which then propagated southwestward along the polar front from 80°N during the preceding 1.5 days (corresponding to wind speeds of roughly 150 km h$^{-1}$). Meanwhile, the region south of the Atlas range was affected by dry subtropical air upstream of the tropical cloud band. The convective rains formed at the margin between the tropical and polar air masses as localized showers or thunderstorms. In contrast to the tropical air masses (sections 4b and 5b), the southward moving polar air over the North African coast was moist at lower levels as shown by the relative humidity and wind vectors at 850 hPa at 0000 UTC 15 September (Fig. 13b). This presumably suppressed evaporation of the convective rains in the

a) Divergence [1/s*10$^{-6}$]  
b) Omega [Pa/s*10$^{-2}$]

FIG. 12. Vertical profiles of (a) divergence and (b) vertical pressure velocity, omega. Solid lines represent 0000 UTC 13 Sep 1988 (case II) and dashed lines the twice-daily (0000 and 1200 UTC) ERA-15 climatology for the period 10–16 Sep 1979–93. The considered regions (28°–31°N and 7°–10°W for case II and 27.5°–30°N and 7.5°–10°W for the climatology) cover the region around Agadir (30.3°N, 9.4°W).
6. Case III (22 August–5 September 1999)

a. Synoptic situation and precipitation

As in case I, the rainfall evolution during case III suggests a subdivision into two rainy phases. The accumulated precipitation amounts and frequencies for each phase are shown in Fig. 14. Again, the largest and most frequent precipitation events were observed in the vicinity and north of the Atlas chain. A maximum of 12 rainy events (6 in each phase) with a total precipitation of 48.1 mm was recorded at Midelt. With the exception of the extraordinary rains of 15 mm in Sidi Ifni and 4 mm in Agadir on 26 and 27 August (compared to 1 mm in the long-term August average at both stations), the Atlantic coast remained mainly dry during both phases. In contrast to cases I and II, several hyperarid Saharan stations also received considerable amounts of rain, reaching from only slightly more than the August average at Tindouf (2 mm) and Beni Abbes (3.3 mm) to 25% (Bechar), 75% (Timimoun, central Algeria), or even 107% (Adrar) of an average annual

PBL and/or enhanced convection. This result agrees with a study of Wright (1997) who found that precipitation is generally stronger when a TP interacts with an extratropical front over Australia.
Precipitation is generally stronger in phase 1 than in phase 2. During the 2.5 days between the rainy phases, no precipitation was recorded. The IR images show westward moving scattered altocumulus, cirrus, and convective clouds over the central and southern Sahara during the first 2 days of the episode. In the course of the afternoon of 24 August, an elongated and narrow band of convective cells formed between the High Atlas Mountains and the northern part of the western Sahara, when 23 mm of precipitation was recorded in Ouarzazate (south of the High Atlas Mountains). On 25 August, a broken cloud band stretched northward from a convective cluster over southern Mauritania that merged on 26 August with an extratropical cold frontal cloud band moving from the Atlantic over the Iberian Peninsula into the Mediterranean ahead of a short-wave upper-level trough (Fig. 15). The band tilted clockwise until it nearly reached a W–E orientation over Morocco and broke up early on 28 August. Numerous convective cells formed within and to the southeast of the cloud band over northwestern Africa and the adjacent Sahara that caused most of the precipitation recorded during phase 1. Anomalous southerly and sometimes even westerly low-level winds are occasionally observed during this period at synoptic stations in the Sahara, which are also visible in the reanalysis data, but no surface depression could be identified. In the following 2.5 days most of northwestern Africa is cloud free except for some afternoon cumuli over the Atlas chain. The rainfalls of phase 2 (31 August–4 September) are mainly due to afternoon convection that formed over the Atlas chain and was advected northeastward.

Like for the other cases, the synoptic evolution of the episode can be followed most easily by examining the upper-level flow. The 250-hPa streamlines and isotachs (shading in m s$^{-1}$) for 1200 UTC 24 Aug 1999. High (low) labels indicate maximum (minimum) wind speeds in m s$^{-1}$. The cyclonic (C) and anticyclonic (A) centers from (b) are marked. (b) The 1200 UTC positions of the upper-level trough (black solid lines) and the low-level AEW trough (black dashed lines), as well as tracks of the upper-level cyclonic (gray dashed line) and anticyclonic centers (gray solid line) for Aug–Sep 1999 (case III). Dates are indicated by numbers. The upper-level features were subjectively identified from streamlines of the unfiltered 250-hPa wind; the AEW trough line from streamlines of the 2–6-day bandpass-filtered wind at 850 hPa. 

at 1200 UTC 24 August (Fig. 16a) reveal a marked upper-level anticyclone over North Africa and a cyclonic center located in a trough over the Atlantic with a strong southerly flow in between. The tracks of these features are presented in Fig. 16b. The cyclonic center emerged from an upper-level wave on the poleward flank of the tropical easterly jet (TEJ) on 19 August, which was located anomalously north at this time. The wave moved westward with the jet until it merged with a weak subtropical trough off the African west coast on
24 August (see Fig. 16a). Over the following 3 days the cyclonic center moved farther to the west, petering out over the Atlantic on 27 August. Being only visible at upper levels in the beginning, the trough penetrated into the midtroposphere down to 700 hPa in the course of its evolution (not shown). The anticyclone evolved on 22 August and followed the cyclonic center to the west maintaining the southerly flow between the two centers. On 28 August, the anticyclone moved over the Atlantic steering dry northerly flow toward northwest Africa, which caused the break between the two rainy periods. When the anticyclone finally retreated to the east again, a subtropical trough approached northwest Africa from the northwest (solid lines in Fig. 16b). The dashed lines in Fig. 16b indicate the trough line of a low-level AEW that moved westward, circa 6° longitude ahead of the upper-level cyclonic center between 22 and 26 August, similar to the situation of case II.

b. Moisture transports

A large convective cluster formed on the eastern side of the AEW (see Fig. 16b) between 0° and 5°E on 22 August and moved to around 7°W by 0000 UTC 23 August (Fig. 17a). Four of the 4-day backward trajectories that started at 300 hPa over northwestern Africa at 0000 UTC 27 August end directly in the outflow of this large cluster around 400 hPa. Farther northeast, moist air from the Tropics had been advected northward between the upper-level trough (dark region around 8°W) and the anticyclone. From this moist region, several of the considered air parcels moved westward and ascended from 600 to 300 hPa while recurving anticyclonically into western Algeria. The westernmost backward trajectories reveal the advection of presumably drier subtropical air at 300 hPa. All trajectories pass through the region of southerly flow between the cyclone and the anticyclone shown in Fig. 16. At 1200 UTC 24 August another convective cluster formed farther to the east, probably triggered by upper-level divergence at the right entrance of the southerly flow (see Fig. 16a). Moisture from this cluster was also advected northward (not shown). One day before the trajectories of Fig. 17a reach the Atlas chain (i.e., 0000 UTC 26 August), the large midlevel moisture flux from the tropical convection into the subtropics and farther north into the midlatitude cloud band (see section 5a) is clearly visible in the ERA-15 data (Fig. 18). A moisture flux convergence maximum of 46 mm day$^{-1}$ appears over the Atlas range close to Midelt, where large precipitation was observed (Fig. 14a). In the WV image for 0600 UTC 27 August (Fig. 17b), the moisture band extended from the Atlantic into the Mediterranean parallel to the Atlas Mountains.

For the second rainy phase, the trajectory analysis demonstrates that a large convective cluster over southern Mauritania, which formed on 25 August and decayed on the following day at the same location (Fig. 15), served as a tropical moisture source (Fig. 17b). In the course of the following days, this moisture is transported northward over the Atlantic on the eastern side of the upper-level cyclone (C) and then eastward on the northern side of the upper-level anticyclone (A) and ahead of the subtropical trough (Fig. 16b). The second rainy phase began when this moisture reached northwest Africa on 31 August.

c. Precipitation generation

During both rainy phases, upper-level divergence is frequently observed over northwestern Africa at the inflection region to the northwest of the upper-level anticyclone and east of the different subtropical troughs involved (not shown). As in case II, single precipitation events like, for example, the extraordinary 23 mm that fell in Ouarzazate during the afternoon of 24 August, can be attributed to divergence maxima that favored or triggered the formation of deep convection. For the case of 1200 UTC 24 August, the divergence is clearly displayed in the divergent streamlines at the exit of the region of strong southerly flow (Fig. 16a). The vertical profile of divergence averaged over the 16 grid points around and south of Ouarzazate (28°–31°N and 5°–8°W) for the same date (Fig. 19) shows very pronounced divergence between 150 and 400 hPa and strong convergence below. The resulting nearly troposphere-wide ascent is particularly strong above 700 hPa and reaches a minimum of $-0.31 \text{ Pa s}^{-1}$ at 400 hPa corresponding to a large-scale uplift of about 1.2 km in 6 h at midlevels (Fig. 19b). A comparison to the low values of the climatology for this time of year and this location demonstrates the extreme nature of the presented case. Note that values from 850 and 1000 hPa might not be realistic, because these level extend under the orography for some of the considered grid points. Also during case III (in particular during the second rainy phase), afternoon convection over the Atlas Mountains played an important role in precipitation generation.

7. Conclusions and discussion

a. Summary of the three cases

The synoptic evolution of three late summer/early autumn rainy episodes in northwestern Africa was studied on the basis of precipitation station reports, ECMWF (re-)analysis data, and Meteosat IR and WV images. The most important conclusions can be summarized as follows. Tropical West Africa and the adjacent tropical Atlantic could be identified as moisture source regions for the considered cases by the use of trajectory and vertically integrated moisture flux analysis. Convective clusters or squall lines in the Tropics transport moisture vertically from the monsoon layer into midtropospheric levels (600–400 hPa), where an outflow moisture is present in agreement with earlier studies (Thompson et al. 1979;
Fig. 17. As in Fig. 4 but for (a) 0000 UTC 23 Aug 1999–0000 UTC 27 Aug 1999 (case III, phase 1) and (b) 0600 UTC 27 Aug 1999–0600 UTC 31 Aug 1999 (case III, phase 2). Differing from Fig. 4, the backward trajectories were started at 300 hPa in (a). The positions of the cyclonic (C) and anticyclonic (A) centers and the AEW trough line (dashed line) from Fig. 16b are indicated.
An upper-level subtropical trough extends deep enough into the Tropics to induce a northerly advection of this moisture on its eastern side into the subtropics, often in connection with high wind speeds. The moisture transports are clearly reflected in WV imagery and are strongest between 700 and 400 hPa, thus mostly above the dry Saharan PBL, as in a case described by Ziv (2001). No surface cyclonic or frontal disturbances have been observed over northwestern Africa during the three cases on surface weather charts produced by the DWD. Over northwestern Africa, convection is triggered by upper-level divergence most likely caused by the strong advection of positive vorticity at the inflection point, where the curvature of the flow changes from cyclonic to anticyclonic (Ziv 2001). As in a case described by Zangvil and Isakson (1995), strong moisture convergence at midlevels and large-scale ascent between the PBL and the tropopause are observed. Due to orographically induced ascent in the prevailing southerly flow and surface heating of elevated areas above the subsidence inversion, the Atlas Mountains are a preferred region of convective activity that is often advected north or northeastward with the mean flow. Consequently, most precipitation is recorded in the vicinity of the Atlas chain and toward the Mediterranean with the Atlantic coast being almost dry. Most frequent and most abundant rainfalls are observed at Midelt, the highest available synoptic station. Most of the described precipitation events, especially at lowland stations, yield little rainfall amounts, presumably due to the high evaporation in the deep and dry PBL. Nevertheless, several events of more than 10 mm in 12 h are observed. In particular, for the stations at the semiarid southern margin of the Atlas chain, late summer/early autumn rainfalls constitute a considerable contribution to the annual precipitation.

Several differences between the three episodes have been demonstrated. In most, but not in all cases, the moisture source was associated with AEW-related convection. In particular in the northern Tropics (i.e., north of 12.5°N), AEWs play an important role, both dynam-
ically and advectively, in triggering convection over Africa (e.g., Carlson 1969; Burpee 1972; Reed et al. 1977). In some cases, upper-level divergence at the entrance region of the STJ east of the subtropical trough appears to have contributed to the release or enhancement of moist convection. The presented results, however, suggest that details of the formation of the tropical moisture source are not important for the precipitation generation, as long as enough moisture is transported at midlevels southeast of the subtropical trough.

The behavior of the upper-level disturbance also varies between the cases. While in case I, a subtropical trough remained quasi-stationary west of North Africa, a westward propagation of the trough parallel to a low-level AEW is observed in case II. In case III, the rainy episode was initiated by a westward moving upper-level wave in the TEJ that merged with a subtropical trough over the Atlantic. In this case, the low-level trade wind regime was disturbed over Africa and rains spread northward over the hyperarid part of the central Sahara as described by Nicholson (1981) and Geb (2000) for other cases. On some occasions, the tropical air links up with an extratropical cloud band over the Mediterranean. An unusual, interesting feature is the concurrence of polar and tropical air masses that caused heavy precipitation in western Algeria at the end of case II.

b. Comparison to the “classic” tropical plume

Although basic characteristics of “classic” TPs as described in section 2 (tropical moisture source, formation on the eastern side of a subtropical trough, anticyclonic recurving in the subtropics, etc.) are fulfilled by the presented cases, they hardly meet the requirements of the TP definition by McGuirk et al. (1987), which is based on the TPs’ appearance in IR satellite imagery (see section 2). With the exception of the initial phase of case II, the bands of clouds that result from the described tropical–extratropical interactions are too broken or scattered to be called continuous, are partly shorter than the required 2000 km, or consist only of convective clouds over northwestern Africa. The connection to the tropical moisture source and the transport into the subtropics is therefore merely visible, except in WV imagery or, indirectly, through trajectory analysis. It therefore appears more appropriate to designate the presented cases “moisture bursts,” a term that was already used by McGuirk et al. (1987). The discrepancy between TP definition and the presented cases might explain why few “classic” TPs are observed during August and September over the Sahara (Kuhnel 1989). Without referring to the term TP, Geb (2000) described an event in September 1996 with a cloud pattern similar to our cases.

Nevertheless, several features of the presented cases have also been mentioned in classic TP studies. For example, the merging of a westward propagating equatorial wave with a subtropical trough (our case III) has been observed for other cases (McGuirk et al. 1988). Agreement is also found with the study of Blackwell (2000) who points out that TP formation is tied to an equatorward amplification and zonal contraction of the trough (our case I). McGuirk and Ulsh (1990) point out that the position and movement of the trough is not systematic with respect to the nearly stationary plume, which is underlined by our analysis through the different behavior of the upper-level disturbances in the three cases. An inclusion of a midlatitude trough and/or a merging of the polar jet with the STJ (Ziv 2001), however, was not instrumental in initiating the moisture advection toward the sub tropics in our cases. Similar to TPs over the eastern Pacific, the described moisture bursts often, but not always, formed when a low-level wave in the tropical easterlies moved west of the TP/moisture burst origin region (McGuirk et al. 1988; McGuirk 1993). The superposition of such a low-level AEW with upper-level divergence at the right entrance region of the STJ southeast of the upper-level trough (as indicated in Fig. 3 of Nicholson 1981) will enhance both convection and horizontal moisture transport (see also Ziv 2001) and might be important to initiate SSDs (Nicholson 1981). However, neither the formation of an SSD nor the presence of an AEW is necessary to induce the tropical–extratropical interactions described in this study.

c. Outlook

Regarding the same set of parameters used in this study, additional cases should be investigated to get a better idea of which of the described features are typical/atypical of this kind of tropical–extratropical interaction. A larger statistical ensemble will certainly help to further elaborate upon the physical model developed on the basis of the results of this study. In addition to that, the question of the importance of the presented mechanism for other seasons could be addressed. Eventually, it would be interesting to investigate if the two moist decades (1980s and 1990s) at the Saharan foothills of the Atlas Mountains (Nicholson et al. 2000) are related to an anomalous frequency or duration of the tropical–extratropical interactions described in this study. Moreover, dynamical aspects of TP formation as proposed by Blackwell (2000) or Mecikalski and Tripoli (1998) could be investigated for cases affecting northwestern Africa. Another interesting aspect is the question to what extent a better understanding of tropical–extratropical interactions could be of any benefit for weather forecasting. Possible ways to infer this are the calculation of forward trajectories from operational forecasts or a precursor analysis of TPs affecting northwest Africa similar to the one put forth by McGuirk and Ulsh (1990).

Finally, it remains an open question as to how much precipitation actually falls in connection with the presented cases in elevated areas of the Atlas chain, where no observations are available. The relatively high fre-
quency of formation of convective clouds over the
mountains compared to the surroundings and the shorter
passage of raindrops through the dry boundary layer
probably favor significantly higher precipitation
amounts. Since no precipitation observations from
above 1600 m are yet available, the only way of ad-
ressing this question will be regarding discharge mea-
surements of rivers draining from the Atlas Mountains
or using measurements from the Integrated Approach
to the Efficient Management of Scarce Water Resources
in West Africa (IMPETUS) climate station network that
has been recently installed in the Drâa catchment in
southern Morocco.

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