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Drought episodes in the climatological sinks of the Mediterranean moisture source: The role of moisture transport

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It is well known from previous work that the regions most affected by moisture transport from the Mediterranean Sea (MED) are central-eastern Europe and the eastern Mediterranean. We apply a Lagrangian approach to investigate whether severe drought episodes observed in these areas, hereafter referred to as the climatological moisture sinks of the MED source, are associated with changes in moisture transport from the basin. The drought events were identified for both hydrological summer and winter using the Standardised Precipitation Evapotranspiration Index (SPEI). The analyses were complemented with fields of precipitation and potential evapotranspiration (PET) over the sinks, together with evaporation over MED and the vertically integrated moisture flux. According to our results, a significant reduction in the moisture contribution from MED is evident in events for both summer and winter, as evidenced by the values accumulated over the episodes concerned. Anomalies in MED evaporation presented seasonal contrasts, i.e., a reduction in winter and an increase in summer episodes. In terms of interannual variability, linear correlation analyses show that in winter, the SPEI over the sinks is more associated with moisture transport from the MED than with MED evaporation. The correlation between moisture contribution from MED and the sink SPEI/precipitation is stronger in winter than summer.

1. Introduction

The analysis of the hydrological cycle has become one of the most important themes in the geosciences given its multidisciplinary nature and its association with considerable societal impacts (e.g., droughts, floods, agriculture, hydro-electric power). It is also clear that further in-depth research of the various components of the hydrological cycle may help us to clarify questions concerning the variability of past and future trends in climate change (Gimeno et al., 2012). Here we focus on changes in moisture transport during drought years in those areas that are climatological receptors or sinks for moisture transported by air masses travelling from the Mediterranean Sea (MED). Previous authors (e.g., Trenberth and Guillemot, 1998) point to the importance of moisture transport and its convergence at low tropospheric levels, leading to intense precipitation. The identification of moisture sources is therefore necessary for a better understanding of precipitation over a given region.

A detailed review and comparison of the different approaches used to study moisture transport may be found in Gimeno et al. (2012). According to these authors, all the various methods provide useful information in support of the analysis; however, the results are subject to the assumptions made and to the type and accuracy of the data used. The assessment of moisture sources can be conducted using a wide range of methods, including "analytical and box models", "physical water vapour tracers" (isotopes) and "numerical water vapour tracers". The last method includes both Lagrangian and Eulerian approaches. While in the Lagrangian frame of reference the observer follows an individual fluid parcel as it moves through space and time, in the Eulerian frame of reference the focus is on specific locations in the space through which fluid flows as time passes (Gimeno et al., 2012). Consequently, because the Lagrangian approach provides more realistic traces of air parcels, enabling the trajectories to be followed and source–sink relationships to be established, it is extensively applied to evaluate the origin of the water that precipitates over a given region (e.g., Stohl and James, 2004, 2005; Dirmeyer and Brubaker, 2007; Sodemann et al., 2008; Gimeno et al., 2013; Knippertz et al., 2013; Nieto et al., 2014).

The sophisticated Lagrangian diagnostic scheme developed by Stohl and James (2004, 2005) was recently used to identify those continental regions affected by moisture transport from the major oceanic sources (Gimeno et al., 2010, 2012, 2013), MED among them. It is worth stressing that despite its relatively small size,

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evaporation provides the largest contribution to the Mediterranean freshwater budget (Mariotti et al., 2002). Being an important source of atmospheric moisture, the local water budget influences the moisture transport towards southern Europe, northeast Africa and the Middle East (Peixoto et al., 1982; Ward, 1998; Gimeno et al., 2013 and references therein). Nevertheless, the increase in MED evaporation and decrease in regional precipitation both on land and over the sea as observed over the last 60 years (e.g., Mariotti, 2010; Allan and Zveryaev, 2011) is predicted to continue for the next few decades (Seager and Vecchi, 2010; Hoerling et al., 2012). As a consequence, it may trigger regional climate changes through variations in the moisture transport.

Previous authors have investigated the moisture transport over the MED using different methodologies, mostly based on Eulerian techniques (e.g., Mariotti et al., 2002; Fernández et al., 2003). Some exceptions are found in studies based on the Lagrangian methods proposed by Stohl and James (2004, 2005) and Sodemann et al. (2008). Both these methods are based on the analysis of changes in specific humidity at 6-h intervals along the trajectories. It is assumed that moisture changes in an air parcel at this time scale correspond to the net difference between evaporation and precipitation. Following the approach of Sodemann et al. (2008), the cumulative moisture changes along the trajectory are also considered together with the net gain or loss at each grid point, and the impact of each of these moisture gains and losses along the trajectory on the precipitation is assessed in terms of the precipitation in the target region. The identification of the moisture sources and sinks based purely on the net evaporation or precipitation as proposed by Stohl and James may lead to a failure to identify evaporation sources where precipitation dominates en route. We acknowledge that the approach of Sodemann et al. (2008) appears to be more sound and accurate for quantifying the moisture contribution from the remote regions to the precipitation in a target region. However, the original method of Stohl and James seems reasonable for those studies investigating the sources and sinks of moisture along trajectories approaching a region of interest, regardless of the occurrence of precipitation there.

Two examples of the application of the approach of Sodemann et al. (2008) for MED are given in Sodemann and Zubler (2010) and Winschall et al. (2014). Sodemann and Zubler (2010) identified the moisture sources for precipitation in the Alps, mainly the North Atlantic, the Mediterranean, and continental evapotranspiration. The moisture sources for heavy precipitation events in the northwestern Mediterranean for 1989–2009 were investigated by Winschall et al. (2014). Their results indicate that during precipitation extremes not only does the Mediterranean Sea provide moisture; the North Atlantic is also important in autumn and winter as is land evapotranspiration in summer.

Other studies have also made use of the Lagrangian approach of Stohl and James (2004, 2005). Unfortunately, the computing demand of these Lagrangian methods meant that the first studies were restricted to short datasets. Thus, the pioneering analysis of Nieto et al. (2010) and Schicker et al. (2010) investigated the main sources and sinks of moisture over the MED based on a 5-year period (from 2000 to 2004), providing an overview of the annual mean source patterns for different regions surrounding the basin. Drumond et al. (2011) analysed the seasonal variations in moisture sources during drier and wetter years for different Mediterranean target regions for the same 5-yr period. Although this only represents a relatively short period, the results showed that in most of the years chosen, the moisture sources were more extensive and/or more intense during wetter periods. In particularly, the Mediterranean Sea is the predominant source for Eastern North Africa, and for the Italian and Balkan Peninsulas. Gomez-Hernandez et al. (2013) extended these previous studies for a 21-year period in order to accommodate both the seasonal and interannual variability analysis of the main climatological moisture sources for eight target regions in the Mediterranean basin. Exploring changes in the intensity of the moisture sources, Gimeno et al. (2013) identified for the winter season (DJF) that southern and eastern Europe areas are particularly affected by a decreasing precipitation trend during periods of strong intensity of Mediterranean moisture sources.

All the works cited in the previous paragraph have contributed to a deeper understanding of the climatological role of the MED as a source of moisture in the regional hydrological budget. However, to date the role of the anomalies of moisture transport from the basin during drought episodes has not been explored in any detail using a Lagrangian approach. It is well known that the Mediterranean has a strong influence on European precipitation; nevertheless, it is crucial to investigate the role of the basin in expected climate change impacts over southern Europe, i.e., more frequent droughts and summer heat waves (IPCC, 2013).

Drought is a natural phenomenon that occurs whenever water availability is significantly below normal levels over a long period and existing demand cannot be met (Redmond, 2002). Due to its long-term development and duration, and the progressive character of its impacts and its diffuse spatial limits, drought is perhaps the most complex natural hazard to be identified, analysed, monitored and managed (Wilhite, 1993). Much effort has been devoted to developing drought indicators for risk analysis and drought monitoring. At present, the two most widely used drought indicators are the Palmer Drought Severity Index (PDSI) (Palmer, 1965) and the Standardised Precipitation Index (SPI) (McKee et al., 1993). The PDSI is based on the supply and demand concept of the water balance equation, and incorporates precipitation, moisture supply, runoff and evaporation demand at the surface level. The main shortcoming of the PDSI is its fixed temporal scale, which is critical to the analysis of drought impacts given the differences in characteristic drought resilience times between different natural and economic systems. On the other hand, the SPI can be calculated at different time scales (i.e., accumulated over given time spans) to monitor drought conditions affecting systems with different resilience times. Nevertheless, the calculation of the SPI is based solely on precipitation. The Standardised Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010) was developed more recently, and combines the sensitivity of PDSI to changes in the atmospheric evaporative demand with the multi-temporal nature of the SPI, thereby addressing the limitations of the two previous indices.

Most meteorological analyses of droughts focus on Sea Surface Temperature (SST), which can modulate both atmospheric circulation and atmospheric stability (e.g., Feng et al., 2010; Sousa et al., 2011). However, a few authors have focused on the anomalies of moisture transport (e.g., Kam et al., 2014; Dirmeyer et al., 2014). Thus, a further reason for understanding the source-sink relationships in the atmospheric water cycle lies in the role they might play during extreme hydrometeorological events. Previous authors have suggested that the absence of moisture transport from the sources towards the continents may contribute to the persistence of droughts (Seneviratne et al., 2006; Trigo et al., 2013).

The present study applies a Lagrangian approach to investigate whether the intense drought episodes observed in the summer and winter climatological moisture sinks of MED during the period 1980–2012 were associated with changes in the moisture transport from the Mediterranean. Drumond et al. (2016) applied a very similar Lagrangian approach to investigate the anomalous moisture transport that occurred during the 2012 drought episode in central USA. In the present study, we made some modifications to the methodology applied recently in another case, in order to make it more suitable for the climatological analysis of drought periods configured in a given region. The Lagrangian approach and selection criteria of the episodes using the SPEI index are explained in Section 2. The analysis of the drought periods of the hydrological winter and summer is presented in Section 3. The main findings of the present study are then summarised in Section 4.