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Re-evaluation of moisture sources for the August 2002 extreme rainfall episode in central Europe: Evaporation from falling precipitation included in a mesoscale modeling system

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SUMMARY

Discriminating moisture sources with precision is an important requirement to better understand the processes involved in extreme rainfall episodes. In a previous contribution by Gangoiti et al. (2011b), an innovative technique was presented to assess surface moisture sources contributing to a target precipitation within a Lagrangian framework. The technique was based in transporting parcels of vapor, representing the target precipitation, across a set of nested grids covering a large area at different resolutions. A mesoscale model estimated the meteorological variables to transport and redistribute the vapor back into its original sources, all of them assumed to be at the surface. The sequence of extreme rainfall events, which occurred over central Europe on August 11–13, 2002, was chosen to put the methodology to test. An important innovation has now been introduced. This new advance allows discriminating not only the terrestrial and oceanic sources but also the evaporation from precipitation occurring below the clouds and falling either on land or on the open sea. It is also able to detect with greater precision the relative importance of remote versus local sources, together with the sequence of evaporation of a rainfall event. After its application to the same episode and targets, our results confirm a similar distribution and strength of surface terrestrial and marine sources. Furthermore, the estimated direct evaporation from precipitation columns contributes to the precipitation episode with a significant amount of moisture which averages around 18% of the total sources, with a main fraction evaporated over land and close to the target regions in central Europe. This contribution adds to the surface sources, and it is consistent with the existence of an important mechanism of positive feedback for the inland transport efficiency of moisture and precipitation, operating at the regional level for this type of episodes. Significant regional differences are found in the contribution to different rainfall targets, with a lower fraction of 14% for the southern target (Upper Austria), and 22% for the northern one (Bohemia).

1. Introduction

The water holding capacity of air increases at higher temperatures, and in a global warming climate scenario there must be an increase in precipitation totals to compensate for the enhanced evaporation. It seems that the distribution of relative humidity in the troposphere would remain approximately constant (Allen and Ingram, 2002), and consequently we should expect, following the Clausius–Clapeyron relation, that precipitation should increase roughly exponentially with temperature (7% per Kelvin), at least for heavy rainfalls, which are likely to occur when all the moisture in a volume of air is effectively precipitated out (Trenberth et al., 2003; Allen and Ingram, 2002). Hence, whenever the lifting mechanism results in saturation, thunderstorms, orographic rainfall, extratropical depressions and tropical cyclones, while being fed with increased moisture, will produce more precipitation. Indeed, observed changes in daily precipitation extremes seem to be consistent with Clausius–Clapeyron related 7% increase per degree of warming, although Lenderink and Meijgaard (2008) have found that hourly precipitation extremes could even be beyond that percentage.

However, observations of global precipitation do not show such a general increase of 7% per Kelvin. Instead, large regional

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differences are observed, with a clear decrease of rainfall in the subtropics and tropics outside of the monsoon trough, and increases in land precipitation at higher latitudes, notably over North America and Eurasia (Trenberth et al., 2007). These changes are in accordance with a poleward shift of the mid-latitude low tracks, with the tropics becoming wider and the convergence zones narrower (Trenberth, 2011). A decrease in the annual totals is especially evident in the Mediterranean; this is associated not only with the increase in the frequency and persistence of sub-tropical anticyclones, but also with increases in surface temperature and the atmospheric demand for moisture. In addition, even where total precipitation is decreasing, more intense precipitation events are observed to be occurring widely (Trenberth, 2011).

Synoptic variations related to changes in mid-latitude low tracks and the occurrence and persistence of blocking anticyclones can change the water budget of a region, highly dependent on rainfall recycling, which is most significant in summer conditions, as shown by Van der Ent and Savenije (2011): the northern Mediterranean is shown to be the region of Europe with the strongest soil-atmosphere feedback and the lowest time and length scales of atmospheric moisture recycling. This mechanism is sensitive to the land use modifications and even to the increased levels of air pollution (Millán et al., 2005; Millán, 2014), which have been operating in the Mediterranean region at different time scales from decades to centuries (Millán et al., 2005), resulting in a trend towards the loss of summer precipitations.

Drought in the Mediterranean is accompanied by stronger rainfall events despite a clear reduction in the number of rainy days (Brunetti et al., 2001; Alpert et al., 2002), which confirms the existence of a substantial change in the rainfall distribution. The successive floods and droughts in this region are making flood control and water resources management more challenging: widespread floods in the summer of 2002 in southern and central Europe were followed by heat waves and droughts in 2003. A list of the most significant summer floods in central Europe during the last five decades can be found in Müller et al. (2009), where a series of common synoptic patterns are found to characterize these types of episodes. In this respect, after the torrential rainfall episodes in the Alpine region during the last decades (Brunetti et al., 2001), the scientific community has put the focus on this region, located at the boundary between the Atlantic temperate climate of Western Europe and that of the Mediterranean. One of the main concerns is the role of the Mediterranean Sea and the Atlantic Ocean as primary sources of vapor for these heavy rain episodes (Turato et al., 2004; Ulbrich et al., 2003; James et al., 2004; Sodemann and Zubler, 2010; Winschall et al., 2011), as well as the search for changes in land use and sea surface temperatures which could be behind the observed trends in the frequency and intensity of the episodes (Millán et al., 2005).

In this context, the capability of discriminating moisture sources with precision is an important requirement to better understand the mechanisms of extreme rainfalls and droughts. A summary and comparison of different approaches to identify sources and sinks of atmospheric moisture is found in Gimeno et al. (2012), where particular consideration is given to a range of recently developed Lagrangian techniques suitable for evaluating the origin of rainfall during extreme events. This type of studies could help to understand the changes in the source regions affecting the occurrence and intensity of the episodes as discussed in Gimeno (2014), the relative role of marine and terrestrial sources to selected episodes (Dirmeyer and Brubaker, 1999), the characteristic distances and timescales of evaporation/precipitation processes, changes with sea surface temperature and land coverage, among other issues, which could have an impact in hydrology, climatology and weather forecasting. In a previous contribution (Gangoiti et al., 2011b), referred to as G11-b, we presented a new mesoscale modeling system (hereafter *MesoWat_Source*) designed to map evaporative regions of a precipitation event, which was based in a Lagrangian approach for diagnosing the origin of moisture that precipitates in a particular region. The paper also included the main differences with other Lagrangian approaches and showed the results after its application to the August 2002 flooding episode in the Alpine region and central Europe. There, we showed both the relative importance of the marine source in the Western Mediterranean during the initiation of the episode, and the recycling of rainfall through land evaporation in vast areas of the European continental landmass throughout the episode, which illustrated the highly changing nature and distribution of the moisture sources contributing to the episode. However, there is a component of the water balance which was not included in our modeling system: the direct evaporation of rain during its trajectory from cloud to ground. To our knowledge, this component has never been explicitly included in a modeling system devoted to moisture source estimations. Nevertheless, Worden et al. (2007) have shown the importance of its contribution in the tropical water cycle: using the Tropospheric Emission Spectrometer on NASA's Aura satellite, they found that rainfall evaporation adds significant moisture to the lower troposphere, with typically 20% and up to 50% of the rain evaporating before it reaches the ground. This mechanism, together with evapotranspiration from the tropical forest, allows the temporal storage of some water in the lower troposphere, which can later be used to both maintain and propagate the cloud and rain production. Consequently, rain evaporation is an added positive feedback to land evapotranspiration; they work together for the propagation of rains into the continental landmass of the summer hemisphere. Direct evaporation of falling rain also contributes significantly to the heat and moisture budgets of clouds, cooling the air and generating downdrafts which redistribute heat and moisture (Braun and Houze, 1995); however, few observations of these processes are available (Gamache et al., 1993).

The question to be answered here is whether this mechanism is also operating in the Mediterranean summer and, if so, to evaluate its role in the inland propagation of precipitation. Thus, the main objective of this manuscript is to enlarge the capabilities of our modeling system MesoWat_Source, in order to cope not only with surface moisture sources but also with direct rain evaporation, and then to apply it to the central Europe flood episode of August 2002. The results will give us an estimation of the relative importance of this mechanism during the episode, and help us to evaluate its possible use for other types of rain episodes and regions. The paper is organized as follows: in the next section we will describe the modification introduced to the version of the modeling system presented in G11-b. Then, in Section 3, the results of the new version are shown after its application to the evaluation of the evaporative sources for the August 2002 episode. Differences with the evaluations made with the old version are also discussed in this section as well as a model sensitivity analysis and the estimation of the time scale at which the rain evaporation operates in the moisture feeding of this episode. Finally, Section 4 provides a brief summary of the results and the main conclusions.

2. The modified modeling system

The modeling system *MesoWat_Source* is based in a series of software modules, which share meteorological and positional information on water vapor parcels to evaluate and draw maps of evaporative moisture sources associated with selected precipitation targets. The details of the methodology were published in G11-b, and here we are showing the modifications introduced in order to add a new capability to the modeling system: the evaluation of rain