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Trend analysis of a new MODIS drought severity index with emphasis on the Carpathian Basin

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Abstract—Recently, *Mu et al*. (2013) have compiled an open access data base of a remotely sensed global drought severity index (DSI) based on MODIS satellite measurements. Observations cover a continuous period of 12 years between January 1, 2000 and December 31, 2011 with a temporal resolution of 8 days. The highest spatial resolution is around 5 km in the geographic band between 60°S and 80°N latitudes (more than 4.9 million locations over land). Here we extend the global trend analysis by *Orvos et al*. (2014) of these satellite based DSI time series in order to locate geographic areas where either positive or negative trends are statistically significant. Significance is established by a standard perturbation test, where each individual record is cut into annual pieces, and the statistics of 1000 randomly shuffled and glued time series is compared with the original record. We exhibit three regions of significant wetting and/or drying trends over extended geographic ranges and try to correlate them with recent reports of local climate shifts. We are fully aware of the fact that 12 years are too short for linking the findings to global climate change. Most probably, the identified significant trends can be considered as a component of natural climate variability on decadal time scales, however, a full explanation will require to identify a couple of explanatory variables.

We demonstrate that drying and wetting trends are weakly significant in the Carpathian Basin. Nevertheless, the observations can serve as benchmark for regional climate simulations, projections can be accepted when the test period is properly reproduced considering also high resolution DSI data.

Key-words: drought indices, linear trend analysis, high resolution mapping, statistical significance tests, remote sensing

1. Introduction

Severe droughts or floods are devastating events for both ecosystems and human society. There are several indices used widely for drought assessment integrating large amounts of data (precipitation, snowpack, stream-flow, etc.). Probably, the best known is the Palmer drought severity index (PDSI) (*Palmer*, 1968; *Alley*, 1984) determined by monthly water supply (precipitation), water outputs (evaporation and runoff), and preceding soil water status. New variants of the original approach have been emerged in order to overcome some limitations of the Palmer model (*Alley*, 1984; *Keyantas* and *Dracup*, 2002), such as the self-calibrating PDSI by *Wells et al*. (2004) or PDSI incorporating improved formulations for potential evapotranspiration (*Heim*, 2002). Remote sensing data from the Moderate Resolution Imaging Spectroradiometer (MODIS) combined with NCEP reanalysis records and statistical procedures together have supported to develop an evaporative drought index (EDI) by *Yao et al.* (2010, 2014) with 4 km spatial and 1 month temporal resolutions. Nevertheless, the development and improvement of drought indices are incomplete tasks, and numerous challenges remain for the future (*Vicente-Serrano et al.*, 2011).

In order to better exploit the strengths of continuous satellite observations, *Mu et al.* (2013) have recently developed a remotely sensed global drought severity index (DSI), and compiled an open access data base spanning 12 years between 2000 and 2011 at a temporal resolution of 8 days. The highest spatial resolution is around 5 km (0.05°× 0.05°) with an almost global coverage. Permanently unvegetated locations such as deserts, high mountains, lakes, or large cities cannot provide input for DSI data, because the computation algorithm incorporates the following MODIS products (*Parkinson* and *Greenstone*, 2000):

1. The normalized difference vegetation index (MOD 13) determined as (NIR-VIS)/(NIR+VIS), where NIR and VIS denote the spectral reflectances in the near-infrared and visible (practically red) regions.
2. The surface resistance and evapotranspiration (MOD 16) calculated using land surface temperature data (MOD 11), the previously mentioned NDVI index (MOD 13) and incident radiation. For details, see *Mu et al.* (2011, 2013).

To our best knowledge, the most comprehensive and longest PDSI trend analysis has been provided by *Dai et al.* (2004). A monthly PDSI dataset from 1870 to 2002 has been derived using historical precipitation and temperature data for global land areas on a grid of 2.5°× 2.5°. An empirical orthogonal function (EOF) analysis resulted in a linear trend in the twentieth century, with drying over northern and southern Africa, the Middle East, Mongolia, and eastern Australia, and moistening over the United States, Argentina, and parts of Eurasia (*Dai et al.,* 2004). A follow-up study by *Dai* (2011) compared the original and three other variants of PDSI records, but the main conclusion remained the same: warming in the second half of the last century is responsible for much of the drying trend over several land areas. Increased heating itself from global climate change may not cause droughts, but it is expected that when droughts occur they are likely to set in quicker and be more intense (*Trenberth et al.*, 2014). However, similarly to the open questions on an optimal definition of a drought index, debates on the trends are also not entirely closed (*Sheffield et al.*, 2012; *Damberg* and *AghaKouchak*, 2013; *Spinoni et al.*, 2013).

2. Locations of significant DSI trends

Here we extend the global trend analysis by *Orvos et al.* (2014) of the remotely sensed DSI data base by *Mu et al.* (2013). Records at 4 914 440 geographic locations are evaluated in order to identify linear trends. Each individual record consists of 552 points covering 12 years from January 1, 2000 to December 31, 2011. The basic time-step is 8 days, apart from the necessary cuts at the end of each year. Statistical significance of slopes is verified by the standard permutation test (*Manly*, 2007). Since most of the DSI signals exhibit marked seasonality, the basic unit of data shuffling was one whole calendar year. We cut a given record into 12 pieces, and built a test set from randomly shuffled and glued years. The mean slope and standard deviation were determined, and we accepted a fitted slope of a measured record to be significant when its distance from zero was larger than 2σ of its own test set. *Orvos et al.* (2014) demonstrated that a test set of 100 samples provides essentially the same statistics as 100 000 random samples, however, for the sake of minimizing errors, we fixed the size of test sets at 1000 samples. The larger the test sample size the closer the histogram of obtained slopes to a pure Gaussian, however, the mean and standard deviation do not show detectable sensitivity to the size of the test sets (*Orvos et al.* 2014). Statistically significant slopes are obtained for 852 373 data points (17.34%) at 2σ level, the numbers for 2.5σ and 3σ thresholds are 269 900 (5.49%) and 16 321 (0.33 %), respectively.

The main result of the global trend analysis is illustrated in *Fig. 1*. There are several geographically connected areas exhibiting drying (South America, Middle Asia, or Sub-Equatorial Africa) or wetting (Middle and North Africa, Indian Peninsula, or eastern Spain) tendencies. We emphasize that the remotely sensed DSI is a standardized variable (12-year mean value is removed and normalized by the standard deviation), thus values and trends provide local information: the same numerical value can be connected to very different local circumstances. In order to demonstrate the power of high resolution mapping, we illustrate zooms in three different regions where extended changes are clearly observable.

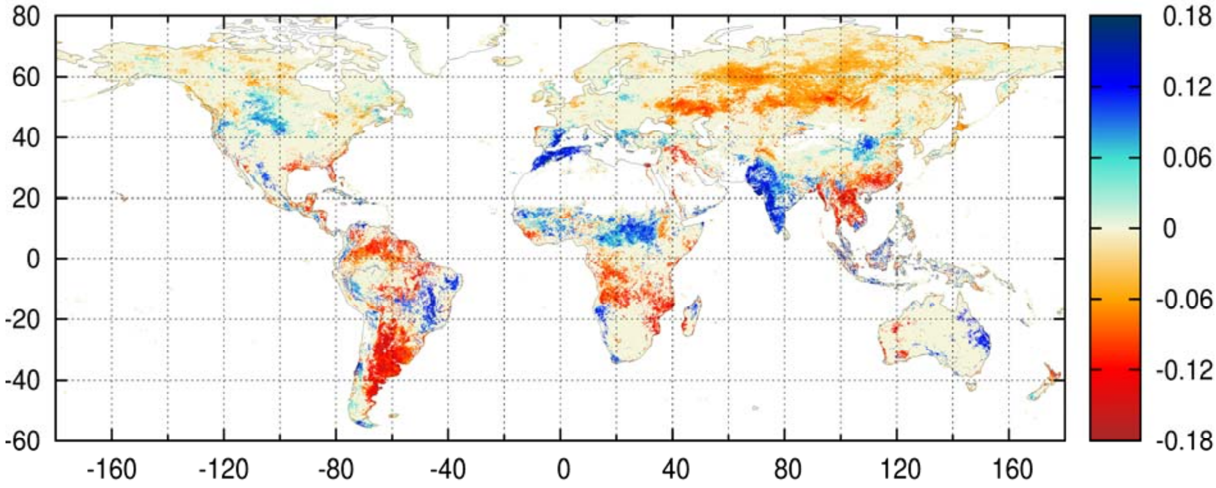

Fig. 1. Geographic locations of statistically significant drying (red) or wetting (blue) trends. Slopes are color coded in units of DSI/year. White color indicates missing data. (*Orvos et al.*, 2014)

Fig. 2 illustrates a detailed map of the southern part of the Asian subcontinent. As for climate shifts in India, *Kothyari* and *Singh* (1996) studied long-term time series of summer monsoon rainfall and identified decadal departures above and below the long-time average alternatively for three consecutive decades. *Singh* and *Sontakke* (2002) reported on an increase in extreme rainfall events over northwest India during the summer monsoon and a decline of the number of rainy days along east coastal stations in the past decades, resulting in a westward shift in rainfall activities. Similarly, *Murumkar* and *Arya* (2014) demonstrated by means of wavelet analysis that prominent annual rainfall periods exist ranging from 2 to 8 years at all the studied stations after 1960s. Large-scale spatial and temporal correlations between the trends of rainfall and temperature are found by *Subash* and *Sikka* (2013), without a direct relationship between increasing rainfall and increasing temperature of monthly or seasonal patterns over meteorological subdivisions of India. As for the particular area, even glaciers can be listed as candidate explanatory factors, since they influence runoff into lowland rivers, and recharge river-fed aquifers (*Bolch et al.*, 2012). In order to illustrate the difficulties of interpreting DSI trends, *Panda* and *Kumar* (2014) also found increasing trends of extreme rainfall indices based on the percentile and absolute values, simultaneously with a significantly increased length of dry spells over northern and central regions of India, suggesting a serious threat to the Indian agriculture.

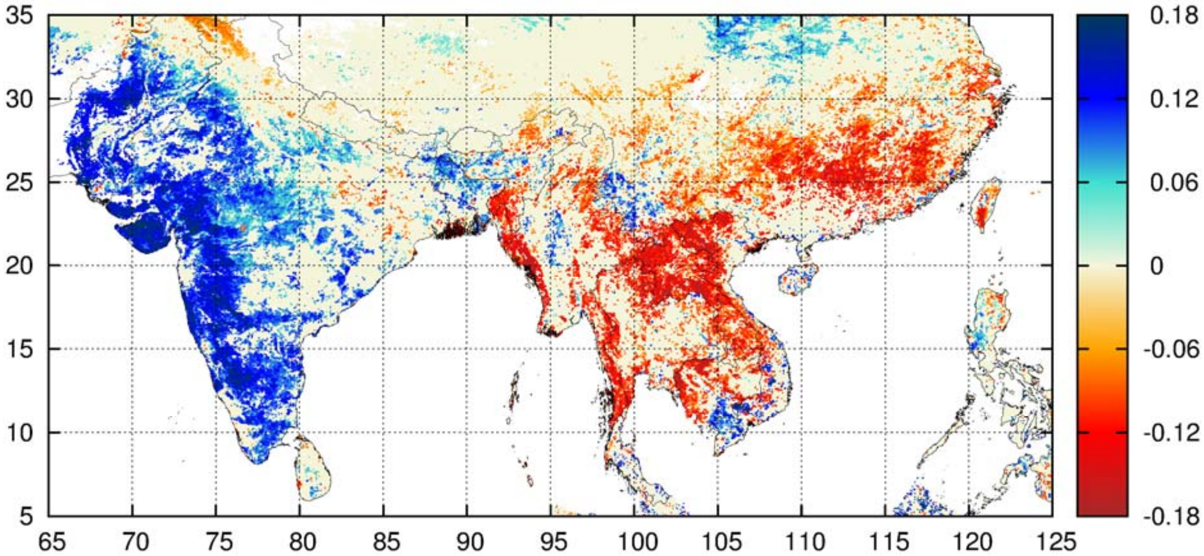

Fig. 2. Geographic locations of statistically significant drying (red) or wetting (blue) trends in Southern Asia. Slopes are color coded in units of DSI/year.

At the other side of the Bay of Bengal, the largest part of Laos, Northern Vietnam, and extended territories in South China are affected by an opposite, drying trend. *Nguyen et al.* (2014) studied a total of 40 years of data from 60 stations around Vietnam. They concluded that dominant trends for annual rainfall are declines, but not in a statistically significant way (they used the Mann-Kendall test). Among the eight climate regions, five of them in Northern Vietnam show decreasing trends, but only the sub-region around Ha Noi has statistically significant decreases. Note that DSI is not a direct measure of precipitation, however, the spatial and temporal coincidences indicate a strong relationship between them. *Hsu et al.* (2014) reviewed the variability of East Asian, Indochina, and Western North Pacific Summer Monsoon on time scales ranging from diurnal to interannual and interdecadal. They concluded that one of the largest challenges is to understand the observed long-term changes and regime shifts in terms of global monsoon. Regional climate model runs by *Zhou et al.* (2013) suggest that the high-speed emission of SO_2 and its uneven distribution over eastern China can contribute to the change in the May-August rainfall over eastern China between the two decades of 1999–2008 and 1989–1998, especially to the decrease of rainfall in the Yangtze River valley.

As a next example, *Fig. 3* demonstrates also an interesting large-scale pattern in DSI trends at the opposite sides of the equator. Large regions in Sudan and in the Central African Republic exhibit positive (wetting), while Eastern Congo, Angola, and Mozambique suffer from negative (drying) tendencies. Various regions in Africa are commonly accepted to be among the most vulnerable territories considering global climate change, the climatological literature is quite controversial and uneven. One reason is that Africa has the lowest density and quality observational network, therefore, most of the studies are based on reanalysis data or numerical modeling. Since the DSI strongly depends on NDVI data, a proper interpretation would require reliable information on local circumstances such as land use changes, shepherding, large-scale migrations, etc.

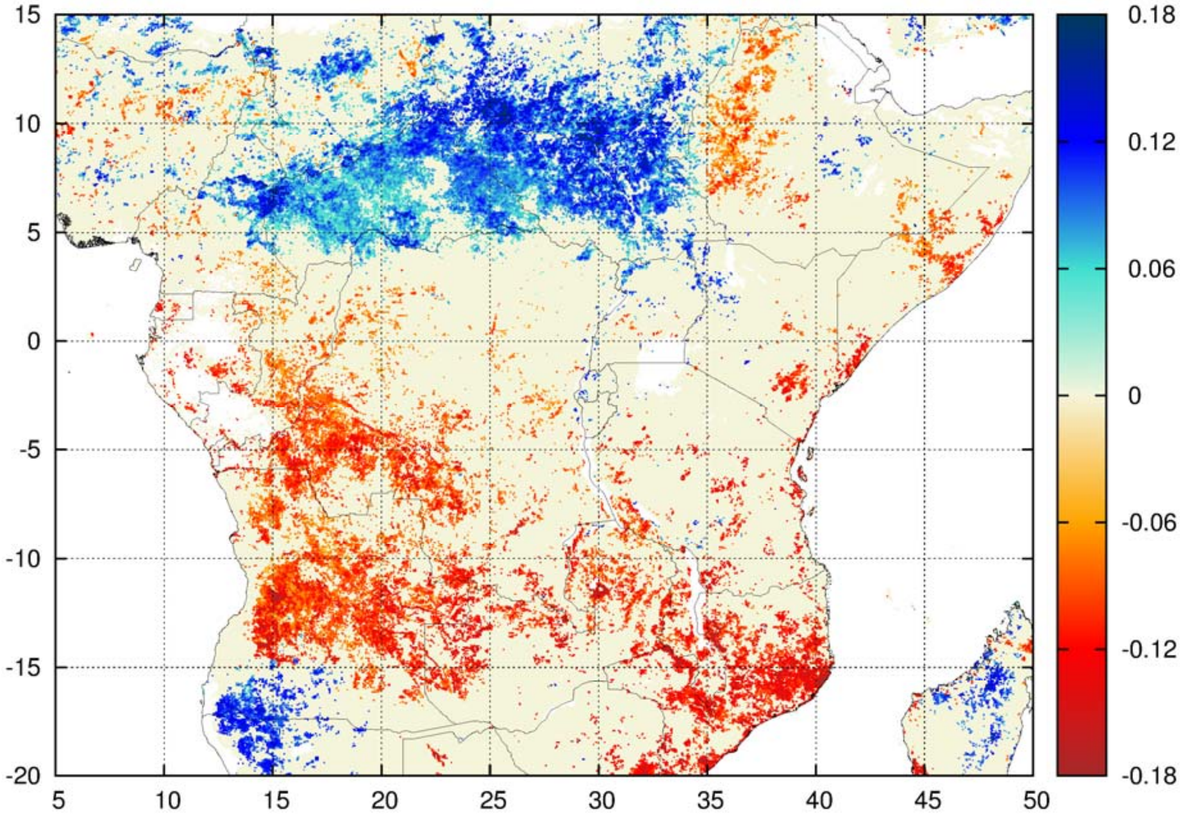

Fig. 3. Geographic locations of statistically significant drying (red) or wetting (blue) trends in Middle Africa. Slopes are color coded in units of DSI/year.

Fig. 4 demonstrates remarkable tendencies around the western Mediterranean basin: northern Morocco, Algeria, and Eastern Spain exhibit strong and significant wetting trends. The main characteristic of the region is the strong gradient between two large-scale systems, namely the North Atlantic (Azores) anticyclone and the low pressure monsoon system over the Indian Ocean and Middle East. This strong gradient establishes a flow from north to south during all seasons that is enhanced by the differential heating between the land of North Africa and South Europe with the Mediterranean waters. It is interesting to note that a recent collaborative assessment on regional climate change (see: *Navarra* and *Tubiana*, 2013) concluded that no basin-wide trends in precipitation and droughts are detectable for the second half of the twentieth century.

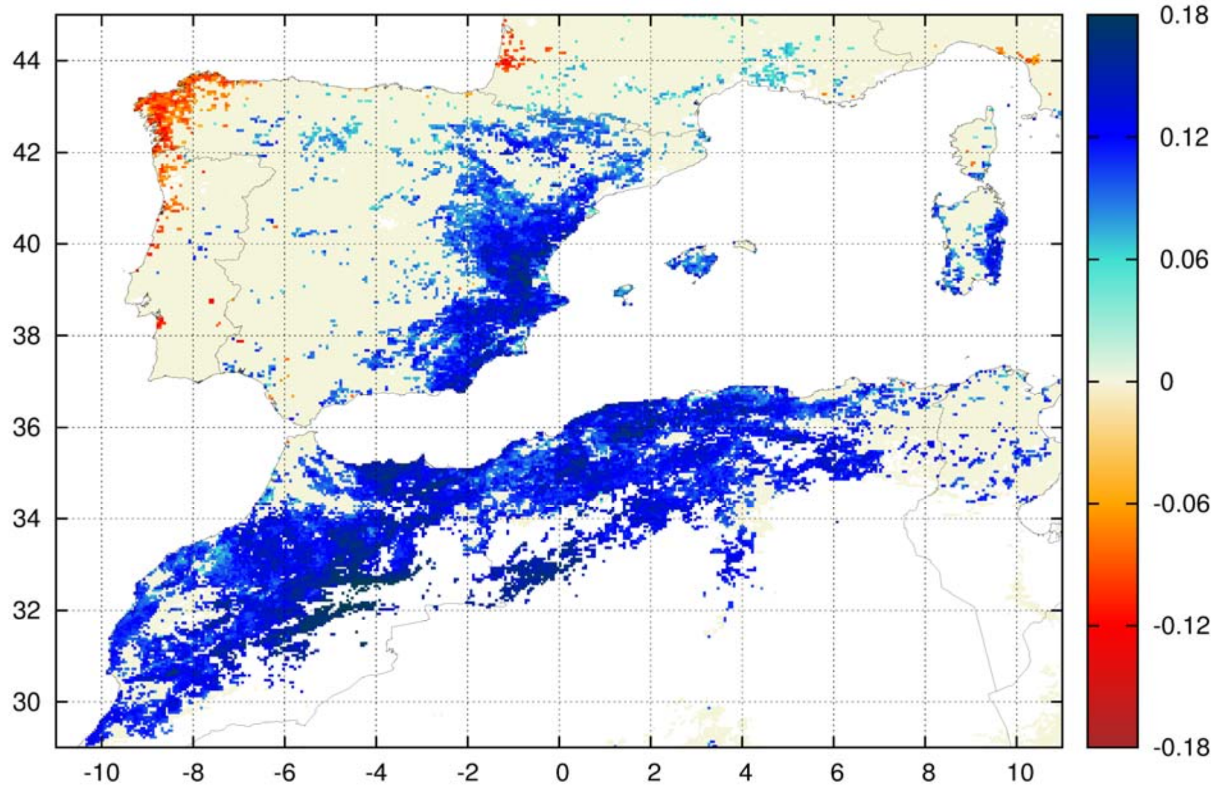

Fig. 4. Geographic locations of statistically significant drying (red) or wetting (blue) trends around the western Mediterranean region. Slopes are color coded in units of DSI/year.

3. Weak DSI trends in the Carpathian basin

Since the drought severity index basically conveys local information, it is worth to check regions where trends are not such significant as in the examples in the previous Section. As a case study, *Fig. 5* shows the geographic distribution of DSI trends in the Carpathian Basin, Central Europe. Locations are plotted where measured slopes passed the significance test by at least 1σ level (the number of sites obeying 2σ significance is not more than 1.1%). While an isolated point of weak DSI trend can easily be a consequence of statistical uncertainties, larger connected regions of similar tendencies support the existence of real effects in the background.

Representative locations are indicated in *Fig. 5*. Sites around České Budějovice (Czech Republik), Szombathely (Hungary), or Pula (Croatia) obey weak wetting, while weak drying is characteristic in the surroundings of Doboj (Bosnia and Herzegovina) or the diagonal band between 49°N–23.5°E and 48°N–25°E (see *Fig. 5*). The latter band coincides with a by and large unpopulated region of Carpathian Mountains in Ukraine, where the observed tendencies are probably consequences of forest cover loss (*Dezső et al.*, 2005).

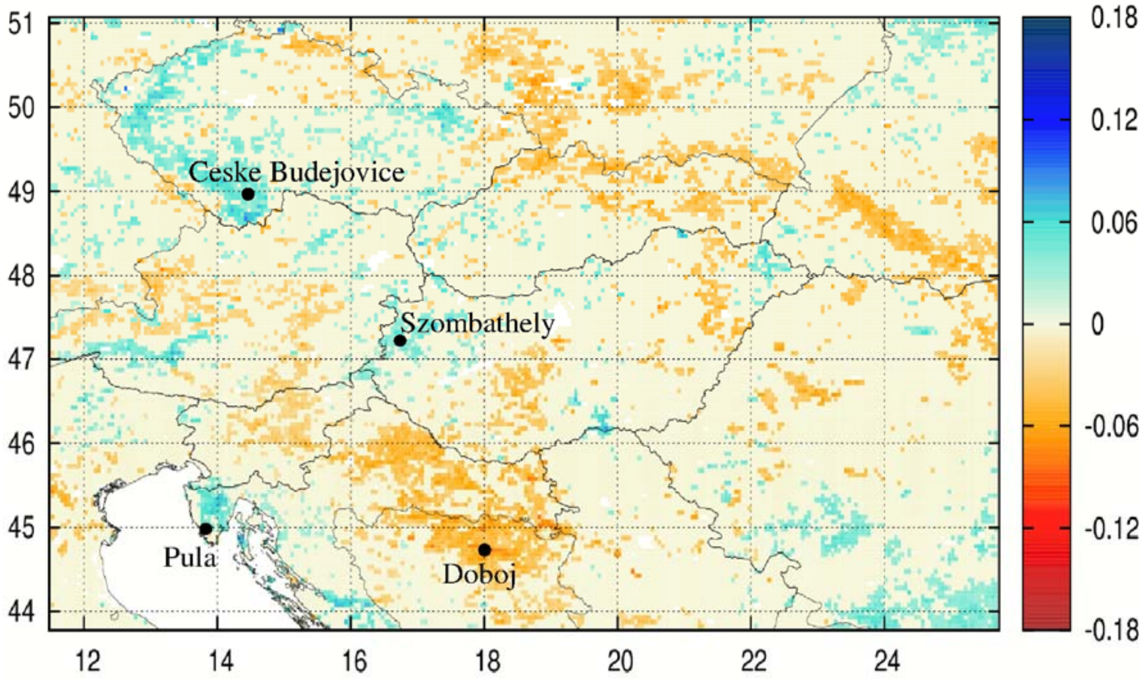

Fig. 5. Geographic locations of weakly significant drying (red) or wetting (blue) trends at 1σ level in the Carpathian Basin. Slopes are color coded in units of DSI/year (note that the range of the color scales is identical for all maps). Locations of a few cities are indicated for an easier orientation.

Repeated analyses and projections of regional climate change are in focus of several research projects also in the Carpathian Basin (*Gálos* and *Jacob*, 2007; *Szépszó* and *Horányi*, 2008; *Krüzselyi et al.*, 2011; *Torma et al.*, 2011; *Bartholy et al.*, 2012; *Bartholy et al.*, 2013; *Mezősi et al.,* 2013). The results are somewhat controversial similarly to other efforts in regional climate modeling: warming and drying tendencies are often identified with various intensities for different geographic sub-regions. However, it should be emphasized that a direct comparison of numerical simulation with empirical results such as illustrated in *Fig. 5* is not really possible, simply because the models cannot determine the very drought severity index analyzed in this work (*Rummukainen,* 2010).

4. Discussion

We have shortly described the way of obtaining DSI records in Section 1. Clearly, any drought severity index is related to precipitation in some way, however, we have illustrated in *Orvos et al.* (2014) that several other local factors, most importantly changing land-use, contribute to a given index value. As a further illustration we show in *Fig. 6* that precipitation trends are not directly related to local DSI trends. Two locations from the map of *Fig. 5* are chosen, where the weakly significant DSI trends of opposite signs are not related to daily precipitation time series at all.

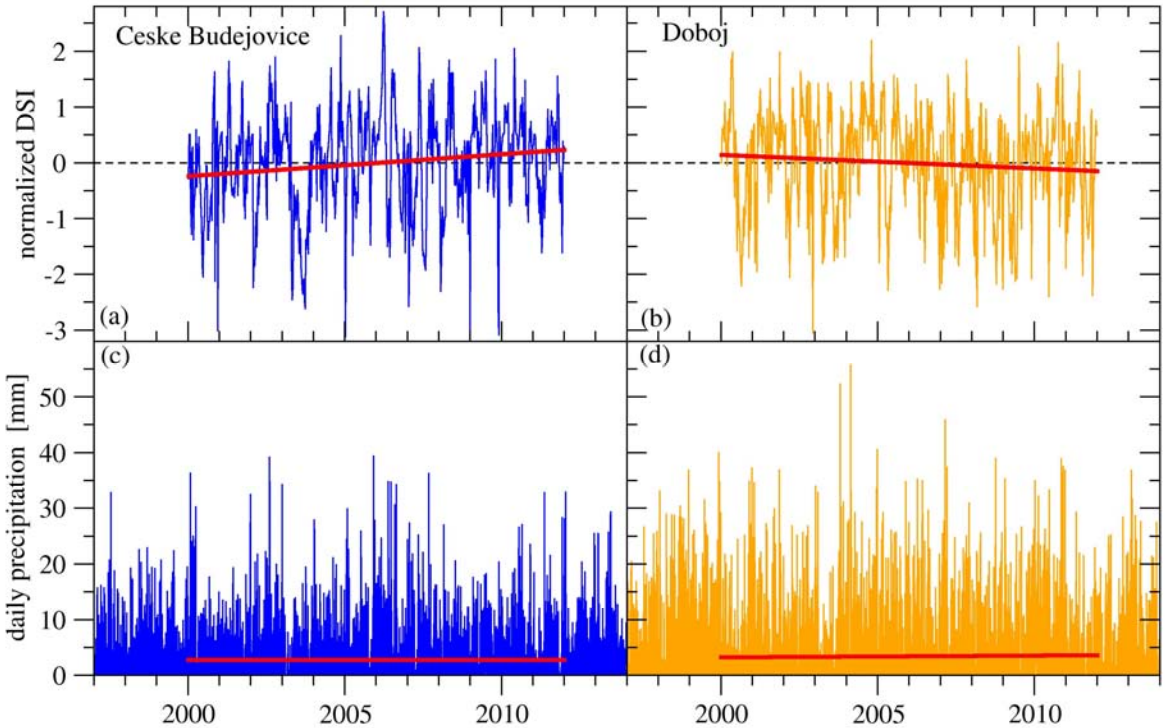

Fig. 6. Weakly significant wetting/drying trends at 1σ level at (a) České Budějovice (49.5°N, 14.5°E) and (b) Doboj (44.5°N, 18.5°E). Red lines indicate slopes of +0.0394 and -0.0243 DSI/year, respectively. (c) and (d) show daily precipitation time series in units of mm for the same geographic locations. Note that fitted trends for the same 12-year period (red lines) are statistically not significant, however the slopes are opposite: –0.0042 mm/year for České Budějovice (c) and +0.0317 mm/year for Doboj (d).

As for the Carpathian Basin, our findings are in agreement with a high spatial resolution trend analysis of monthly self-calibrating PDSI records by *van der Schrier et al.* (2005). Trends in summer moisture availability over Europe for the 1901–2002 period failed to be statistically significant, both in terms of spatial means of the drought index and the area affected by drought. While the time interval of our analysis has a negligible overlap with the cited study (*van der Schrier et al.,* 2005), we also found that the MODIS DSI time series have non-significant local trends in the middle of the European continent.

Nevertheless, we think that the DSI defined by *Mu et al.* (2013) can be implemented in numerical models. Considering the high temporal and spatial resolutions of the data set, it can serve as an exceptional tool for model parameterization and benchmarking.

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