European Hot Summers Associated with a Reduction of Cloudiness

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ABSTRACT

A pronounced summer warming is observed in Europe since the 1980s that has been accompanied by an increase in the occurrence of heat waves. Water deficit that strongly reduces surface latent cooling is a widely accepted explanation for the causes of hot summers. The authors show that the variance of European summer temperature is partly explained by changes in summer cloudiness. Using observation-based products of climate variables, satellite-derived cloud cover, and radiation products, the authors show that, during the 1984–2007 period, Europe has become less cloudy (except northeastern Europe) and the regions east of Europe have become cloudier in summer daytime. In response, the summer temperatures increased in the areas of total cloud cover decrease and stalled or declined in the areas of cloud cover increase. Trends in the surface shortwave radiation are generally positive (negative) in the regions with summer warming (cooling or stalled warming), whereas the signs of trends in top-of-atmosphere (TOA) reflected shortwave radiation are reversed. The authors' results suggest that total cloud cover is either the important local factor influencing the summer temperature changes in Europe or a major indicator of these changes.

1. Introduction

In the last decade, Europe has experienced record-breaking heat waves and temperature-related mortality (Patz et al. 2005; D'Ippoliti et al. 2010; Fischer and Schär 2010; Barriopedro et al. 2011). The heat waves are sometime considered as an example of hot summers under enhanced greenhouse gas concentrations (Klein-Tank et al. 2005; Stott et al. 2004). A number of works have investigated the factors contributing to such extreme events (Meehl and Tebaldi 2004; Sutton and Hodson 2005; Seneviratne et al. 2006) and suggested that soil moisture deficits are likely responsible for the increase in the summer temperature variability (Schär et al. 2004; Fischer et al. 2007; Zampieri et al. 2009; Hirschi et al. 2011). Although these studies partly explain the extreme weather phenomena, it is not clear how other components of the climate system have been affected and/or responded to these extremes. Being an integrated part of the climate system, cloud cover (CC) influences the surface energy and water cycles exercising strong cloud–climate feedbacks (Cess et al. 1989). CC change and associated change in cloud albedo dominate surface shortwave radiation variability on monthly to decadal time scales over Europe (Norris and Wild 2007), although impacts of changes in atmospheric aerosols (Kaufman and Koren 2006; Norris and Wild 2007), circulation patterns (Trigo et al. 2002; Cassou et al. 2005; Della-Marta et al. 2007), and soil moisture and evapotranspiration (Schär et al. 1999; Fischer et al. 2007) intertwine with CC changes, interact with it, and feed back to the regional climate dynamics. In particular, the switch from

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global-dimming to global-brightening phase during the early 1980s that was likely due to a decline in aerosol emissions may also affect decadal changes in surface solar radiation (Wild et al. 2005). We do not intend to separate the effects of CC and aerosol concentrations in our analysis, because (i) according to Norris and Wild (2007) the effect of solar dimming/brightening insignificantly contributes into the solar radiation variability (but not to long-term trends) and (ii) the aerosol load effects on cloudiness and precipitation are highly nonlinear processes (cf., Andreae and Rosenfeld 2008; Graf et al. 2009; Timmreck et al. 2010).

CC can significantly alter surface air temperature and its variations have contributed to recent climatic changes (Ramanathan et al. 1989; Wang and Key 2003). From a surface energy balance perspective, the temperature change may be influenced by changes in surface solar heating that is related to CC and surface evaporative cooling that is related to surface wetness (Wild et al. 2004). Understanding the CC interactions with surface radiation and temperatures is critical for climate modeling and prediction (Groisman et al. 2000). Therefore, the following analysis is an attempt to answer the question, how do CC changes interact with summer temperature in Europe?

2. Data and method

We used the Climatic Research Unit (CRU) temperature data derived from instrumental records (Mitchell and Jones 2005), precipitation data from the Global Precipitation Climatology Centre (GPCC) (Schneider et al. 2010), daytime cloud data (satellite ascending node at 1:30 p.m.) from the next-generation cloud climatology of the Advanced Very High Resolution Radiometer (AVHRR) Pathfinder Atmosphere (PATMOS-x) dataset (Heidinger et al. 2012), and cloud and radiation data from the National Aeronautics and Space Administration (NASA) Global Energy and Water Cycle Experiment (GEWEX) surface radiation budget (SRB) dataset in which the International Satellite Cloud Climatology Project (ISCCP) cloudiness data were used (Rossow and Schiffer 1999). The Palmer drought severity index (PDSI) is one of the most frequently used drought indices and a useful proxy of moisture conditions on the ground (Dai et al. 2004). We used the National Center for Atmospheric Research (NCAR) PDSI dataset (Dai 2011) as a complementary proxy other than precipitation for surface wetness. Satellite CC data have provided globally uniformly sampled information about cloudiness variations, and the PATMOS-x and ISCCP data are the longest available satellite CC records for surface radiation estimates (Wang and Key 2003; Pinker et al. 2005). The relatively long-term observations by the PATMOS-x and ISCCP datasets enable trend analyses. We used the updated version of the PATMOS-x record (version 5) (Heidinger et al. 2012) in which some artifacts like orbital drift (Jacobowitz et al. 2003) still exist. Because of a chance to miss a part of the natural variability, we did not implement any correction procedure to the dataset. The data have been widely used in detecting cloud and aerosol change (e.g., Clement et al. 2009; Evan et al. 2009). We chose to analyze CC in summer when the solar radiation is high and clouds tend to result in cooler temperature (Sun et al. 2000; Key et al. 2008). For the period of common data availability, we calculated linear trends of temperatures and total CC using least squares fit regression. All the datasets are available from 1984 to 2007, except for the PATMOS-x CC, which is missing in summer 1995. We distinguish two periods (1984–94 and 1996–2007) to calculate the trends due to restrictions in the data availability. The periods do not correspond to the global-dimming to global-brightening phases (Wild et al. 2005; Norris and Wild 2007); thus, the effect of dimming and brightening may not be substantial. Linear trends are used as the estimates of the decadal changes, although these changes may not be linear. However, the periods under consideration are too short for quantification of nonlinearities. The statistical significance of each trend was calculated according to the two-tailed Student's t test.

3. Results

Figure 1 shows spatial patterns of linear trends in summer (June–August) CC from PATMOS-x data and in summer mean daily maximum temperatures $T_{\max}$. Trends in the total CC during the 1984–2007 period are generally negative over west Europe and positive over east Europe (Fig. 1a). During the same period, Europe experienced significant summer warming and the east showed stalled increase or decline in summer $T_{\max}$ (Fig. 1b). To further evaluate the linkage between summer $T_{\max}$ and cloud trends, we compare the CC and $T_{\max}$ trend patterns in the 1984–94 (Figs. 1c,d) and 1996–2007 (Figs. 1e,f) periods, although we have to emphasize here the limitations of regression analysis performed on such short samples. The spatial pattern of the $T_{\max}$ trends match well with that of CC in both decade-long periods. In the 1984–94 period, the daytime CC trends are negative in west Europe and northeastern European Russia, where summer $T_{\max}$ increased, and are positive eastward and northward of Caspian Sea, where summer cooling is most evident. In the 1996–2007 period, a daytime CC increase dominated the central European Russia, in the areas where summer cooling

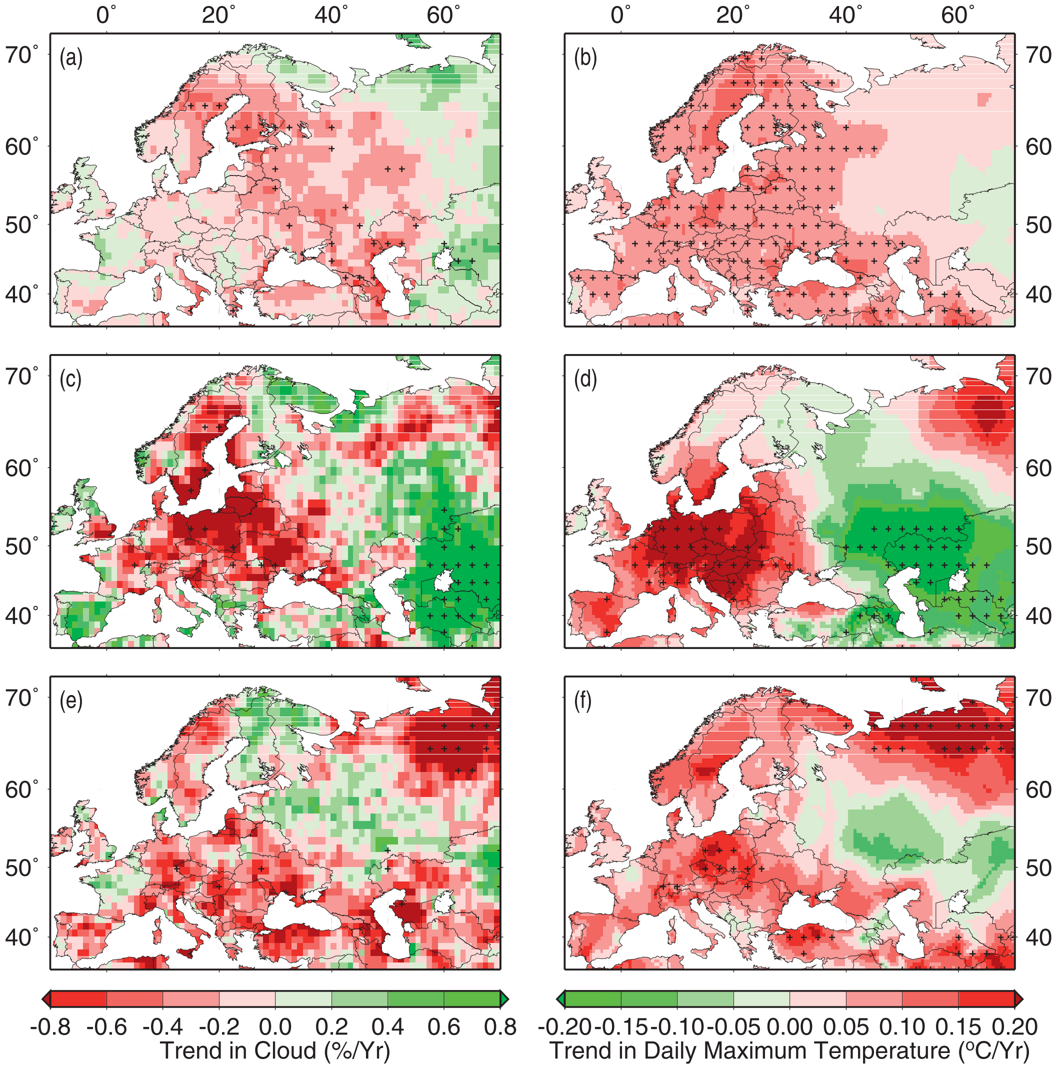

FIG. 1. Spatial distribution of summer (June–August) daytime CC changes and summer mean daily maximum surface air temperature T_{max} changes in Europe. (a) Summer daytime CC trends during the period of 1984–2007. The cloud data in 1995 are not used because PATMOS-x data are missing in that summer. (b) Summer daily T_{max} trends during the period of 1984–2007. (c) Summer daytime CC trends in the period of 1984–94. (d) Summer daily T_{max} trends in the period of 1984–94. (e) Summer daytime CC trends in the period of 1996–2007. (f) Summer daily T_{max} trends in the period of 1996–2007. The cross symbol indicates the areas where the reported trends are significant at the 90% confidence level or higher. The limitations of regression analysis on short samples must be noted.

occurred, in contrast to summer warming in the rest of Europe. Specifically, the PATMOS-x cloud trend is negative over a large area of Europe (63% area of the study area; 10% area with a significant decrease) during the 1996–2007 period (Fig. 1e). During the same period, summer warming dominated Europe (69% area of the study area; 17% area with a significant increase), with the significant increases occurring where cloud decreased (Fig. 1f). The trends in mean daily mean and minimum temperatures have similar spatial patterns as the trends in T_{max}, and the patterns of noon and mean daily CC trends from SRB data match those of daytime CC (not shown). Generally, we found that, in different periods over Europe, summer warming (cooling or stalled warming) is coherent with CC decrease (increase). The remarkably similar spatial patterns of our trend estimates suggest that CC–temperature interactions are strong enough to predefine European summer temperature variations on the decadal time scale.

A strong correlation between summer T_{max} and CC has been observed (Figs. 2a,b). The correlation is significant over most of Europe. The correlation between summer T_{max} and summer precipitation is insignificant over northern European Russia and is weaker than the

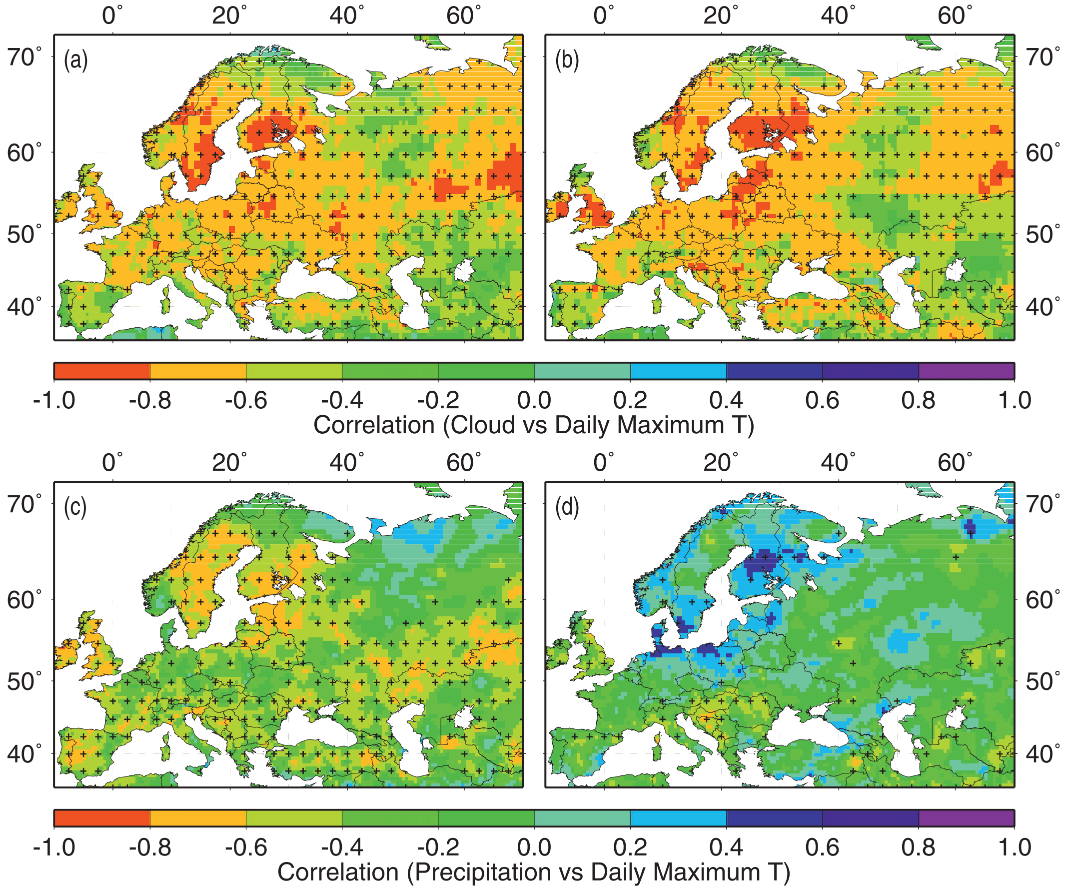

FIG. 2. Correlation between summer cloudiness, precipitation, and temperature during the period of 1984–2007 in Europe. (a) Correlation between daytime CC from PATMOS-x data and $T_{\max}$. (b) Correlation between mean daily CC from SRB data and $T_{\max}$. (c) Correlation between summer precipitation and $T_{\max}$. (d) Correlation between spring precipitation and summer $T_{\max}$. The PATMOS-x CC in summer 1995 is not used because the data are unavailable.

correlation between $T_{\max}$ and CC over Europe (Fig. 2c). Although significant correlation between summer $T_{\max}$ and spring precipitation is found in Southern Europe, the correlation is generally weak (Fig. 2d). These imply precipitation is not a dominant controlling factor for summer $T_{\max}$ at local scale. However, the dynamic effects of soil moisture–atmosphere interaction may influence summer temperatures at large distance and over a long period of time (Fischer et al. 2007; Vautard et al. 2007). We conclude that CC acts as a better indicator of European summer $T_{\max}$ change than precipitation and it may be an important local factor influencing summer temperature variations in Europe.

Several mechanisms can contribute to the recent summer temperature increase in Europe. The current most widely accepted explanation is that a lack of sufficient amount of soil moisture has reduced latent cooling and amplified the summer temperature anomalies (Seneviratne et al. 2006; Fischer et al. 2007; Zampieri et al. 2009). Results from in situ observations and analyses (Dai et al. 1999; Trenberth and Shea 2005) and regional climate models (Fischer et al. 2007; Vautard et al. 2007) have shown that correlation exists between precipitation and surface air temperature. However, decreased precipitation may not be the only driver of the summer warming. Figures 3a,b show the normalized variations of $T_{\max}$ anomalies with daytime CC and precipitation over three regions of extended Europe (Western and Central Europe, European Russia, and West Asia). Western and Central Europe refers to the continent of Europe including United Kingdom but excluding European Russia (political boundary), and West Asia refers to Asian areas in our study area. Over Europe, correlations between $T_{\max}$ and precipitation are substantially lower than those between $T_{\max}$ and total CC, indicating that change in precipitation alone has less contribution to $T_{\max}$ changes than total CC. The only significant correlation between $T_{\max}$ and precipitation is found in West Asia,

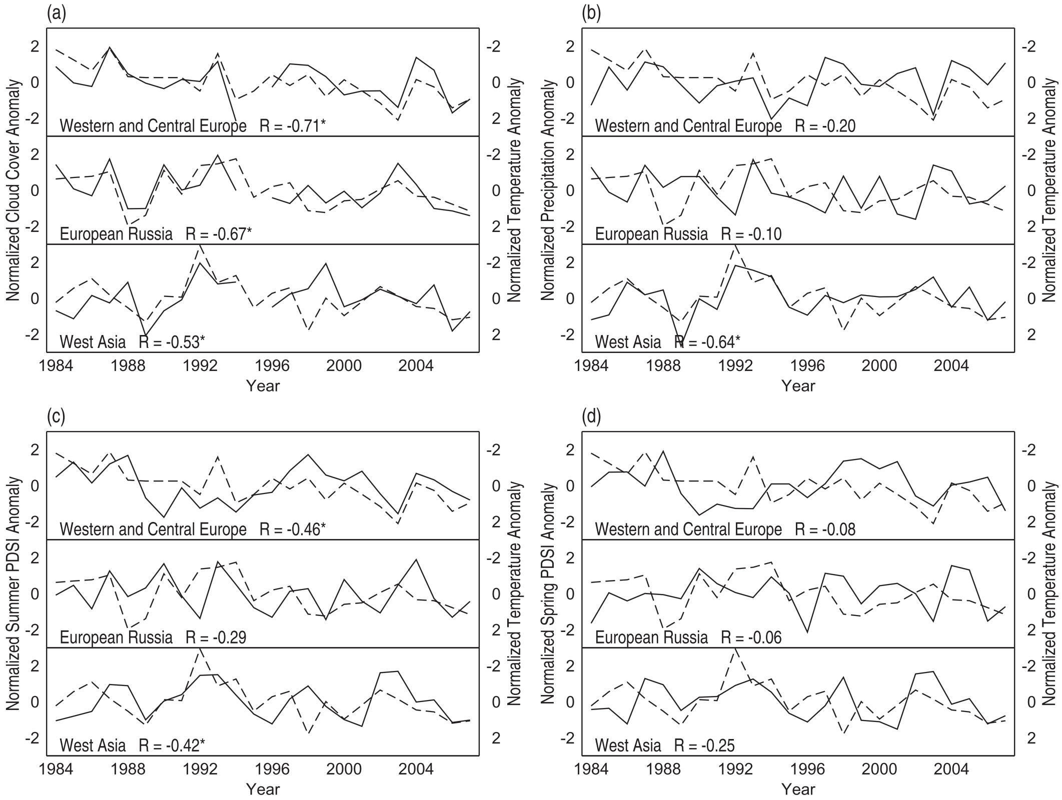

FIG. 3. Normalized variations of anomalies of summer $T_{\max}$ (dashed lines) with (a) daytime CC, (b) summer precipitation, (c) summer PDSI, and (d) spring PDSI (solid lines), over three large regions of extended Europe during the period of 1984–2007. Note that the scale for temperature anomalies on the right side decreases upward. Correlation coefficient R between the curves is given. The asterisk indicates that the correlation is significant at the 90% confidence level or higher.

where large areas are arid or semiarid. In fact, the summer precipitation decrease is more evident in the first decade of our analysis (period of 1984–94) than in the 1995–2007 period, and the three regions experienced increase in spring precipitation during the past decades. Furthermore, the correlations between spring precipitation and summer $T_{\max}$ are positive across the Baltic Sea area and western European Russia (Fig. 2d). These show that the summer warming is probably not caused by the water deficit due to a lack of antecedent precipitation in spring. The correlations between summer $T_{\max}$ and PDSI (Figs. 3c,d) are generally weaker than the correlations between cloudiness and temperature (Figs. 3a,d) over the various regions of extended Europe. It suggests the dependence of summer $T_{\max}$ on soil moisture is weak in all three regions. Therefore, soil moisture deficit may not be the major local driving factor causing recent summer warming, although it may have an amplifying effect and influence summer $T_{\max}$ through dynamic feedbacks (Fischer et al. 2007; Vautard et al. 2007).

Model studies showed that the interannual summer temperature variability was mainly driven by land–atmosphere coupling and/or radiative processes (associated with atmospheric circulation variability and cloud processes), although the relative contribution of these processes differed substantially between models (Fischer and Schär 2009). From a surface energy balance perspective, the decreased total CC may have contributed to the summer warming through the effects of decrease in top-of-atmosphere (TOA) reflected shortwave radiation and increase in surface shortwave radiation (Ramanathan et al. 1989; Pinker et al. 2005; Sun et al. 2000; Wielicki et al. 2005). Figure 4 shows the normalized variations of anomalies of temperature with surface and TOA reflected shortwave radiation over the various regions. Summer $T_{\max}$ closely correlate with both surface shortwave radiation (positive) and TOA reflected shortwave radiation (negative) in all regions. Trends in the surface shortwave radiation are generally positive (negative) in the regions with summer warming (cooling or stalled warming), whereas the signs of trends

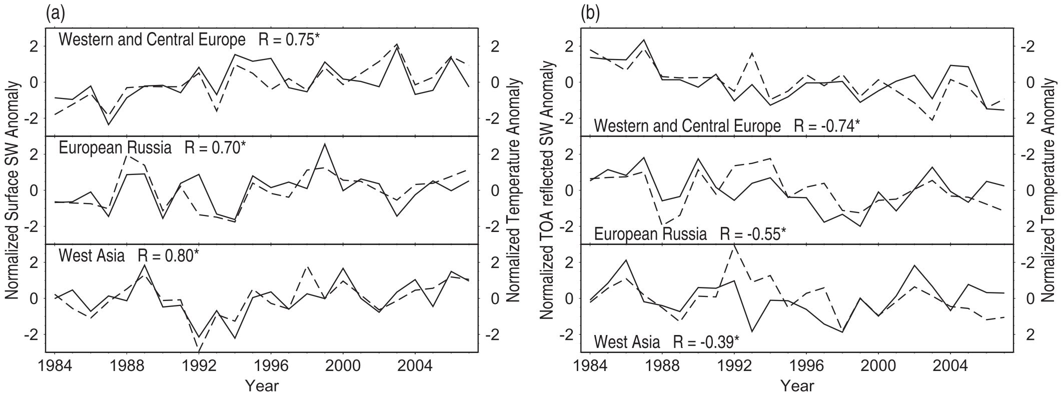

FIG. 4. Normalized variations of anomalies of summer $T_{\max}$ (dashed lines) with (a) surface shortwave radiation and (b) TOA reflected shortwave radiation (solid lines), over three large regions of extended Europe during the period of 1984–2007. Note that the scale for temperature anomalies on the right side decreases upward in (b). Correlation coefficient R between the curves is given. The asterisk indicates that the correlation is significant at the 90% confidence level or higher.

in TOA reflected shortwave radiation are reversed. The uncertainties of the SRB cloud and radiation retrievals are generally large in the east side of our study area because of a lack of coverage from geostationary satellites, known as ''Indian Ocean gap'' (Wielicki et al. 2009). However, the AVHRR provided continuous observations over the gap area. The change directions of the PATMOS-x CC trends are consistent with those of the trends in TOA reflected shortwave radiation and reversely consistent with those of the trends in surface shortwave radiation in the various regions (Figs. 3, 4). Because the satellite retrievals of radiative fluxes are closely related to the retrieval of the total CC, we can have confidence in those trends as well.

4. Conclusions and discussion

Our results demonstrate that the European summer temperature has experienced a pronounced increase in association with decreased CC and increased surface solar radiation. This implies that, in addition to land–atmosphere coupling emphasized in the previous studies (Seneviratne et al. 2006; Fischer et al. 2007; Zampieri et al. 2009), radiative processes characterized by decrease in CC and increase in surface solar radiation may also contribute to the incidence of hot summers in Europe. It should be noted that our analysis shows the simultaneousness and coherent spatial distribution of reduction in CC and increase in summer $T_{\max}$ in Europe, but not the direct causality. There are known plausible mechanisms relating soil moisture, precipitation, cloud, and temperature. A dry soil may inhibit cloudiness and precipitation, increase daytime shortwave radiation, and further increase daytime temperature (Schär et al. 1999; Vautard et al. 2007). The positive soil moisture–cloud feedbacks may make contribution to the strong negative correlation between CC and daytime temperature. Although soil moisture and CC interact with one another and it is difficult to assess their respective independent contributions to temperature change, numerical experiments have suggested that the changes of European summer temperature was mainly due to CC changes caused by the large-scale forcing while soil moisture had an amplifying effect (Jaeger and Seneviratne 2010). Our observational analysis suggests that in Europe, CC is a better indicator (although we emphasize not necessarily the climate driver) of summer $T_{\max}$ changes than the proxies for soil moisture anomalies (i.e., precipitation and PDSI). An extended study further suggests that CC was an important local factor influencing the summer $T_{\max}$ variations over northern Eurasia, including Europe and Siberia, whereas precipitation plays an important role at the middle latitudes (Tang and Leng 2012). More studies are needed to explain the relationship between CC and summer temperature in Europe. Furthermore, the observed strong CC–temperature interactions may be also used for evaluation of the ability of contemporary climate models to reproduce these interactions (e.g., repeating the assessment of Groisman et al. 2000).

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