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Do large-scale models capture reported drought events?

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Abstract Large-scale hydrological models are used to determine drought on a global scale. However, it is important to know how well these large-scale models can reproduce major drought events in the past before projections can be made. This study presents a comparison between a multi-model ensemble and reported drought events in the literature to assess the performance of large-scale models. Major drought events in the selected period (1963–2000) were reproduced by the model ensemble median, although the duration and spatial extent differed substantially from reported events. The major drought events are caused by precipitation deficits linked to oscillations in climatic patterns, such as ENSO. This implies that major drought events were simulated if these were included in the forcing data. Spatial extent and duration of simulated drought events differed from extent and duration of reported ones due to a fast runoff response in some models.

Key words hydrological drought; large-scale models; global; runoff

INTRODUCTION

Drought is one of the natural hazards with the most impact. In the future, impacts of drought are expected to increase in large parts of the world due to climate change (Romm, 2011). To investigate the impacts of drought, long time series are needed for several hydro-meteorological variables, which are usually not available on a global scale. To overcome this lack of data, large-scale models are used to estimate the values of hydro-meteorological variables, e.g. soil moisture, runoff. However, before these large-scale model results are used for projections, it is important to know how well they reproduce major drought events in the past. Some studies have been reported, however, they are either mainly focused on mean discharge (e.g. Haddeland *et al.*, 2011), or focused on drought using a single model (e.g. Sheffield *et al.*, 2009), or focused on drought on a regional scale rather than a global scale (e.g. Wang *et al.*, 2009; Prudhomme *et al.*, 2011; Wang *et al.*, 2011; Gudmundsson *et al.*, 2012; Stahl *et al.*, 2012).

The lack of observed time series on a global scale makes it difficult to evaluate large-scale model results. Comparison between observed discharges and gridded runoff values from the models is not possible. Therefore, in this study a qualitative comparison was made between a multi-model ensemble and drought events reported in the literature during the second part of the 20th century to assess the performance of large-scale models for drought analysis.

LARGE-SCALE MODELS AND FORCING DATA

For the identification of hydrological drought, model results from 10 different large-scale models were used from the European project WATCH (Water and Global Change, *www.eu-watch.org*). The multi-model analysis in this study comprises the following models: GWAVA, H08, HTESSEL, JULES, LPJml, Mac-PDM, MATSIRO, MPI-HM, Orchidee and WaterGAP. Associated model references can be found in Haddeland *et al.* (2011). All models were run at the same 0.5° × 0.5° resolution with the same forcing data, the WATCH Forcing Data (WFD). The WFD originate from modification (bias-correction and downscaling) of the ECMWF ERA-40 re-analysis data (Weedon *et al.*, 2011). Individual models differ in factors such as the model time step, the number of meteorological variables used, solving of the energy balance, evapotranspiration scheme, runoff scheme and snow scheme. More information about the WFD, models' set-up and structure can be found in Haddeland *et al.* (2011).

Time series of daily total runoff (sum of surface runoff and subsurface runoff) were aggregated to monthly total runoff time series that were used to analyse hydrological drought for the period 1963–2000 following 5 years of model spin up. Since this study does not intend to evaluate individual models, the ensemble median runoff, calculated from the monthly runoff time series of all models, was used for the drought analysis.

DROUGHT ANALYSIS

Drought events have been derived with the combined drought identification method (Van Huijgevoort *et al.*, 2012), which combines the characteristics of the threshold level method (Yevjevich, 1967) and the consecutive dry period method (Vincent & Mekis, 2006). This method allows a drought in periods with runoff to continue in a following period without runoff and thus provides a robust drought indicator for all climates. The threshold used in this study is the 20th percentile (Q20), which is defined as the value that is equalled or exceeded 80% of the time.

Time series of area in drought were calculated for several regions, as in Giorgi & Francisco (2000) and as adapted by Sheffield & Wood (2007). For each region, drought events were divided into short events of 2–6 months and long events of 7 months or longer to find the most extreme drought events, as simulated by the model ensemble median, and to filter out short drought events (duration of 1 month). The variability in the percentages of area in drought across the regions is a function of scale, since the regions have different areas. Occurrence of drought events in each region was compared with the literature as a qualitative assessment of the results. Additional information about the main literature sources used is given in Table 1. For the investigation of synchronicity of drought events across the different regions, the largest spatial events of duration longer than 6 months (above the 90th percentile to investigate a representative number of events) have been selected. The percentages of area in drought for each region (this includes droughts with all durations again) at the time of these most severe events were determined.

Table 1 Overview of main literature sources used for comparison.

Authors	Year	Drought type	Data
Dai *et al.*	2004	Meteorological	Observed data
Sheffield & Wood	2007	Soil moisture	Model data
Sheffield *et al.*	2009	Soil moisture	Model data
Sheffield & Wood	2011	Soil moisture & Hydrological	Observed & Model data
Stahl	2001	Hydrological	Observed data
Vicente-Serrano *et al.*	2011	Meteorological	Reanalysis data
Wang *et al.*	2011	Soil moisture	Model data
Wu *et al.*	2011	Soil moisture	Model data
Zaidman *et al.*	2002	Hydrological	Observed data

IDENTIFICATION OF MAJOR DROUGHT EVENTS

Drought in Europe

In the period 1975–1977, drought events occurred in northern Europe. During 1976, around 30% of northern Europe was in drought for longer than 6 months, according to the ensemble median (Fig. 1). This drought event in Europe is well-known and described in the literature (e.g. Zaidman & Rees, 2000; Stahl, 2001). Other events were found from the ensemble median, both short and long duration droughts in 1964, around 1990 and 1995–1996. These drought events are also listed by Bradford (2000) and Stahl (2001). The drought in 1989 and the beginning of 1990 spread over large areas of Europe and also affected the Mediterranean (Bradford, 2000). That region showed a large increase in area in drought from 1989 until the mid-1990s (Fig. 1).

Drought in North America

In North America, several drought events occurred that covered large areas and were most extreme in multiple regions in this study. In 1976, a long duration drought event (Fig. 1) occurred in three

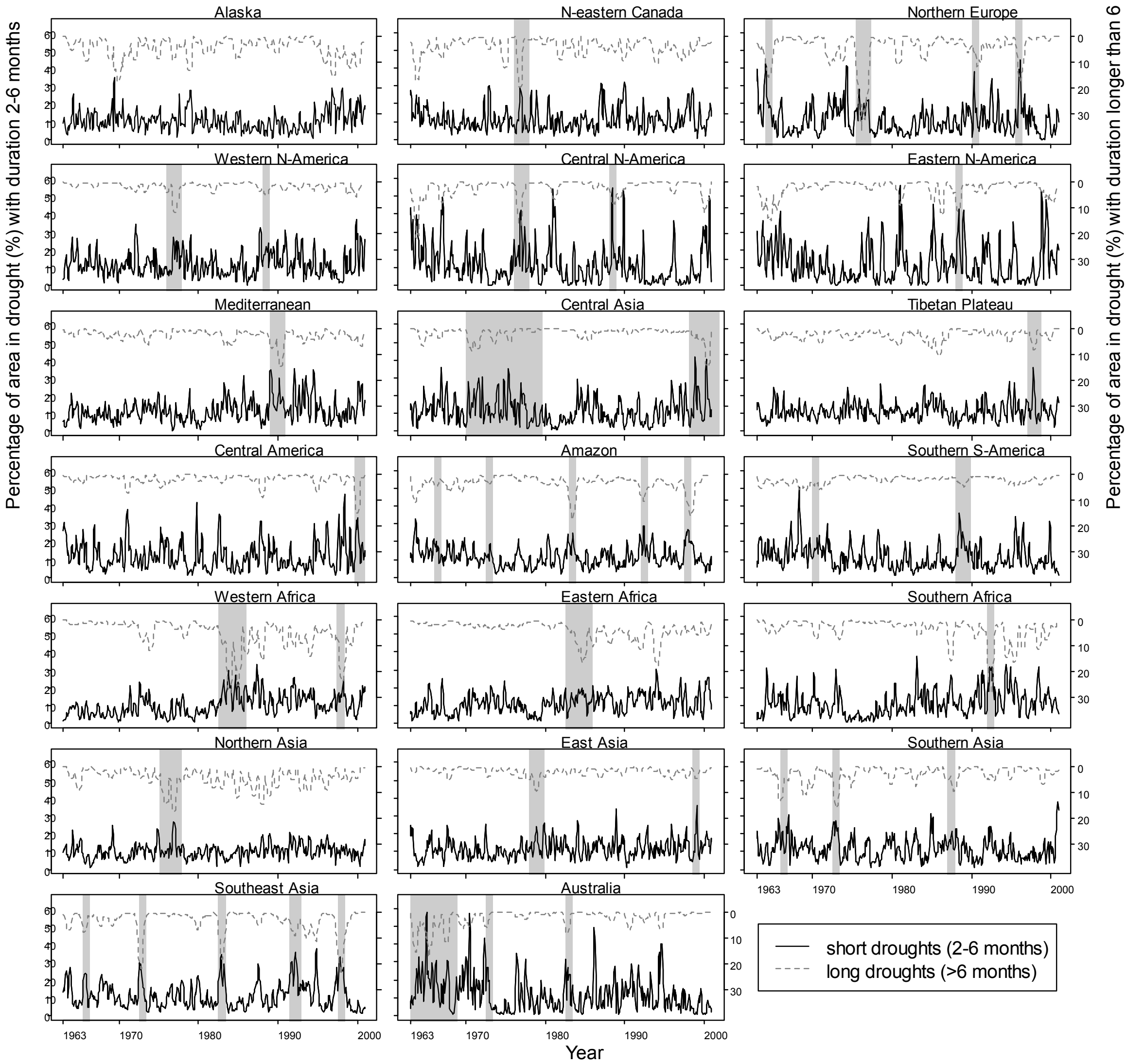

Fig. 1 Fraction in drought of the ensemble median for different drought duration classes. Drought events discussed here are indicated in grey.

regions (Northeastern Canada, Western North America, and Central North America). This winter drought was one of the most spatially extensive droughts in the period 1950–2000 (Sheffield *et al.*, 2009). Another extreme event was found in Western North America, Central North America and Eastern North America in 1988 (Figs 1 and 2). This was a major drought in the US and Canada (Trenberth & Branstator, 1992; Sheffield & Wood, 2011). In Alaska, the timing of the high percentages of area in drought longer than 6 months and the overall pattern agreed with time series of soil moisture drought reported by Sheffield & Wood (2007). The lack of extreme drought events in Central America (hardly any higher percentages of area with long duration droughts) was also consistent with the findings of Sheffield *et al.* (2004), although the large area in drought in 2000 was different.

Drought in Asia

Droughts in China have been investigated in several studies (e.g. Wang *et al.*, 2011; Wu *et al.*, 2011). They found an increase in area in drought in China since the 1990s. In this study, the Tibetan plateau region showed a high percentage of area in drought, with short durations around 1997 (Fig. 1) and the Eastern Asia region in 1999, but a clear increase in area in drought or duration of droughts has not been found. Drying, according to the literature, has been mostly limited to North and Northeast China, which cannot be identified by the large regions used in the current study. Other extreme events have been simulated. For example, the event ranked as most severe in East China by Wu *et al.* (2011) and as severe by Wang *et al.* (2011) in 1978–1979, has been identified in the current study in the long duration droughts in East Asia. In the 1970s and towards the end of the 1990s most of the central Asia region experienced short duration droughts. This is consistent with soil moisture drought time series found by Sheffield & Wood (2007) for this region. Northern Asia exhibited events in long duration droughts in 1975–1977 in the ensemble median, corresponding with a drought mentioned by Sheffield & Wood (2011) in Russia in 1975, which caused severe crop failures. However, other years with known crop failures were not reproduced in the model time series.

Drought in regions related to ENSO

Since drought events often affect large areas, single events typically occur in several regions at the same time (Fig. 2). For example, teleconnections may exist for multiple regions affected by the El Niño-Southern Oscillation (ENSO). ENSO has a large influence on the occurrence of drought on large scales in both precipitation (e.g. Ropelewski & Halpert, 1987) and streamflow (e.g. Chiew & McMahon, 2002). Figure 2 provides information on whether extreme events occurred simultaneously in different regions. Although there were several drought events that covered multiple regions (Fig. 2), the model outcome did not reveal any clear synchronicity pattern, besides that related to ENSO. Drought events linked to ENSO were most clearly identified in strong El Niño years (the warm phase of ENSO): 1966, 1972, 1983, 1992, 1998 (e.g. Smith & Sardeshmukh, 2000; Wolter & Timlin, 2011; NCEP, 2012). In these years, the regions mainly affected were Australia, Southeast Asia, Amazon and Southern Asia (Fig. 2), which is consistent with the regions under influence of ENSO mentioned by Vicente-Serrano *et al.* (2011). When including the dates with the highest percentage in drought for all drought durations (not shown here), Southern Africa was also affected in these years. Drought events in these El Niño years were caused by lack of precipitation and strongly linked to the timing of the meteorological droughts. The influence of ENSO was very strong in 1997–1998, leading to very low water levels in the Amazon region and large forest fires in Indonesia (Bell & Halpert, 1998; Tomasella *et al.*, 2011). Droughts mentioned by Sheffield & Wood (2011) as most widespread and damaging in Southern Asia occurred in 1966, 1972 and 1987, which were all identified as extreme events by the ensemble median of this study (Fig. 2). In Australia almost no large spatial drought events of long duration could be identified from the ensemble median in the period with available model data. The most extreme events for both duration classes (Fig. 1) were found in 1963–1968, corresponding with literature (BoM, 1997). The model ensemble median showed long drought events with large percentages of area in drought in Western Africa and Eastern Africa in the mid-1980s (Figs 1 and 2). In the 1980s large parts of Africa suffered from drought, including the well-known drought in the Sahel in 1983–1984 (Dai *et al.*, 2004; Sheffield *et al.*, 2009; Dai, 2011). This event was caused by very low rainfall in the Sahel following a major El Niño event (Dai *et al.*, 2004). Overall, it can be concluded that the model ensemble median reproduced major drought events linked to El Niño well.

La Niña years (the cold phase of ENSO) have also been linked to drought events in some regions, but these events generally tend to be less widespread (Ropelewski & Halpert, 1987). Southern USA and Northern Mexico (Central North America and western North America region), Southern Russia and Eastern Europe (Northern Asia, Central Asia and Northern Europe regions) and parts of southern South America have been identified by Vicente-Serrano *et al.* (2011) as areas with drought events influenced by La Niña. Strong La Niña years were 1971, 1974, 1976, 1989, 2000 (e.g. Smith & Sardeshmukh, 2000; Wolter & Timlin, 2011; NCEP, 2012). Some drought events in these years were found in the model outcome in the regions mentioned (e.g. the Northern Asia region in 1976 and the Central America region in 2000, Fig. 1). In Southern South America,

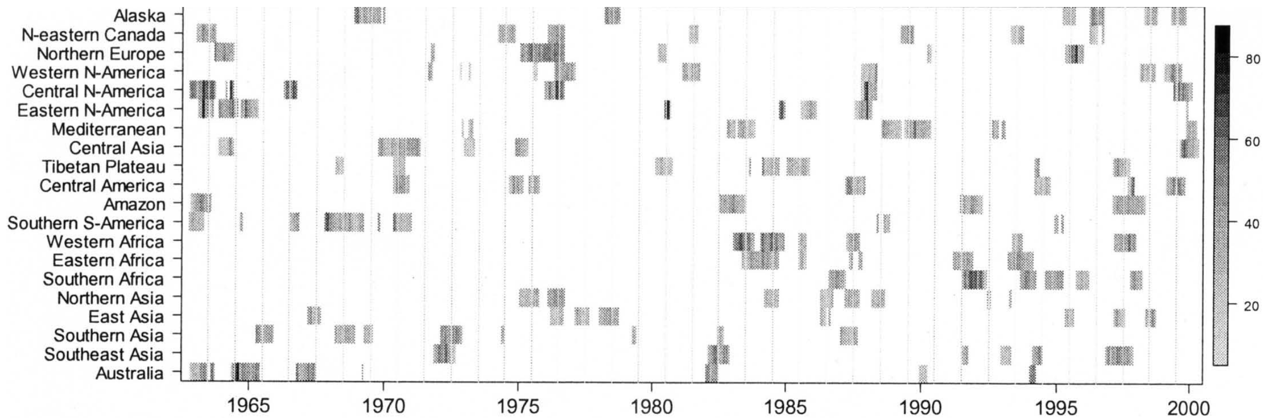

Fig. 2 Total fraction in drought per region for large spatial events (top 10% of events with duration longer than 6 months).

years with extreme events mainly corresponded to La Niña years (1970, 1989), but the highest percentages of area in drought in the long duration class in this region were relatively low and peaks were almost non-existent. Overall, the connection between drought events and La Niña is not as strong as for El Niño. This can be explained by the relatively small areas that are affected by La Niña, as compared to the size of the regions used in this study.

DISCUSSION AND CONCLUSIONS

The major drought events in the second part of the 20th century were reproduced by the model ensemble median, although the duration and spatial extent differed substantially between the models as well as with reported events. The major drought events are caused by precipitation deficits linked to oscillations in climatic patterns, like ENSO. When comparing the runoff of the models with the precipitation forcing, a fast reaction of some models was observed (Van Huijgevoort *et al.*, 2013). This implies that the models simulate major drought events if these are included in the forcing data. When compared to other model studies (e.g. Sheffield & Wood, 2007), differences in the forcing data could account for some of the differences in spatial extent and duration of droughts that were found in the model results in this study. In the same way, similarities could be caused by the use of the same forcing data. Another reason for the differences could be the drought identification method and the variables used. The outcome from a drought analysis is in most cases dependent on the definition used and this should be considered for an adequate intercomparison of the outcome from different studies. Due to the lack of observed data and the limited number of independent drought studies at global scale for runoff or streamflow, in this study droughts in runoff (hydrological drought) were compared to droughts in other variables (soil moisture) and results from single model studies. This will influence the comparison; however, major drought events are expected to propagate through the hydrological cycle, so should be identifiable in the different variables although with somewhat different characteristics. Overall, the large-scale models are able to reproduce extreme drought events, but spatial extent and duration differ from reported events.

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