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Abrupt changes in rainfall during the twentieth century

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[1] Complex interactions in the climate system can give rise to strong positive feedback mechanisms that may lead to sudden climatic changes. The prolonged Sahel drought and the Dust Bowl are examples of 20th century abrupt climatic changes that had serious effects on ecosystems and societies. Here we analyze global historical rainfall observations to detect regions that have undergone large, sudden decreases in rainfall. Our results show that in the 20th century about 30 regions in the world have experienced such changes. These events are statistically significant at the 99% level, are persistent for at least ten years, and most have magnitudes of change that are 10% lower than the climatological normal (1901–2000 rainfall average). This analysis illustrates the extent and magnitude of abrupt climate changes across the globe during the 20th century and may be used for studying the dynamics of and the mechanisms behind these abrupt changes. **Citation:** Narisma, G. T., J. A. Foley, R. Licker, and N. Ramankutty (2007), Abrupt changes in rainfall during the twentieth century, *Geophys. Res. Lett.*, *34*, L06710, doi:10.1029/2006GL028628.

1. Introduction

[2] The importance of abrupt climate change, and its inclusion in the development of climate change adaptation strategies, has been increasingly emphasized in the last decade [*Overpeck and Cole*, 2006; *Higgins and Vellinga*, 2004; *Alley et al.*, 2003; *Hulme*, 2003; *National Research Council (NRC)*, 2002; *Higgins et al.*, 2002]. To date, most of the well-studied cases of abrupt climatic change are focused on paleoclimate records [*Higgins and Vellinga*, 2004; *Rial et al.*, 2004; *NRC*, 2002; *Stocker*, 1999]. The Younger Dryas event is one of the most common examples of an abrupt climate change found in paleoclimate records [*Overpeck and Cole*, 2006; *NRC*, 2002; *Stocker*, 1999]. An analysis of longer time records showed that the Younger Dryas is just one of the Dansgaard-Oeschger events, which are a series of large, widespread abrupt climate changes [*Alley et al.*, 2003; *NRC*, 2002; *Stocker*, 1999]. Moreover, studies of future climate change have indicated the potential for the collapse of the thermohaline circulation in the North Atlantic [*Vellinga and Wood*, 2002; *Cubasch and Meehl*, 2001; *Stouffer and Manabe*, 1999; *Rahmstorf*, 1995] under scenarios of global warming. Many studies have suggested that the thermohaline circulation has a role in historical abrupt changes in climate including the Dansgaard-Oeschger oscillation [*Alley et al.*, 2003; *Clark et al.*, 2002; *Broecker*, 2003].

[3] Aside from these studies of abrupt climate change in the geologic past or a simulated future, there has not yet been a systematic survey of the recent historical climate record to determine the extent of abrupt climate changes. There have been limited studies on 20th century sudden climatic shifts, which include studies on the Sahel drought and the Dust Bowl [*Schubert et al.*, 2004; *Wang et al.*, 2004; *Foley et al.*, 2003; *Taylor et al.*, 2002; *Nicholson et al.*, 1998], and a shift in the atmospheric circulation in 1977–1877 that affected temperatures over Alaska and the central and western North Pacific [*Trenberth*, 1990]. Given the potential cost of these abrupt changes to both the environment and society [*Alley et al.*, 2003; *Hulme*, 2003; *NRC*, 2002], the need for investigating historical records for evidence of other sudden climatic changes in the more recent past in different regions of the world has been highlighted in recent literature [*Alley et al.*, 2003; *Foley et al.*, 2003; *Hulme*, 2003; *Stocker*, 1999]. Here we examine global climate records for large, sudden decreases in rainfall during the 20th century. In this study, we define abrupt climate changes as large, sudden, rainfall decreases that are persistent and deviate significantly from the normal historical level (defined here as the average over 1901–2000). These abrupt changes may be indicative of a transition into another climatic/rainfall regime because of the sudden and persistent nature of these drought events [*Alley et al.*, 2003; *Higgins et al.*, 2002; *Scheffer et al.*, 2001].

2. Detecting Sudden Changes in Rainfall

[4] A flow diagram of how we detected regions of abrupt rainfall decreases based on our definition above is shown in Figure 1. Regions of abrupt change in rainfall are detected by analyzing the gridded high resolution (0.5×0.5 degrees) precipitation data, which cover the years 1901–2000, from the Climate Research Unit [*Mitchell et al.*, 2004]. We first remove any temporal trends and spatial noise in the data set by, respectively, linearly detrending the time series for each grid cell and by applying a three by three spatial Gaussian filter to the global data set. Wavelet analysis (using the algorithm developed by *Torrence and Compo*, 1998, available at http://ion.researchsystems.com/IONScript/wavelet/) is then applied to the detrended and smoothed out data set to isolate strong low-frequency events. The wavelet transform of a time series gives a time-frequency profile that shows the different climatic modes or periodicities present in the data set. Wavelet transforms have been used to study the variability of the southern oscillation index and sea surface temperatures [*Andreoli and Kayano*, 2004; *Lau and Weng*, 1999; *Torrence and Webster*, 1999], and trends and variability in temperature [*Datsenko et al.*, 2001; *Park and Mann*, 2000; *Ware and Thomson*, 2000; *Baliunas et*

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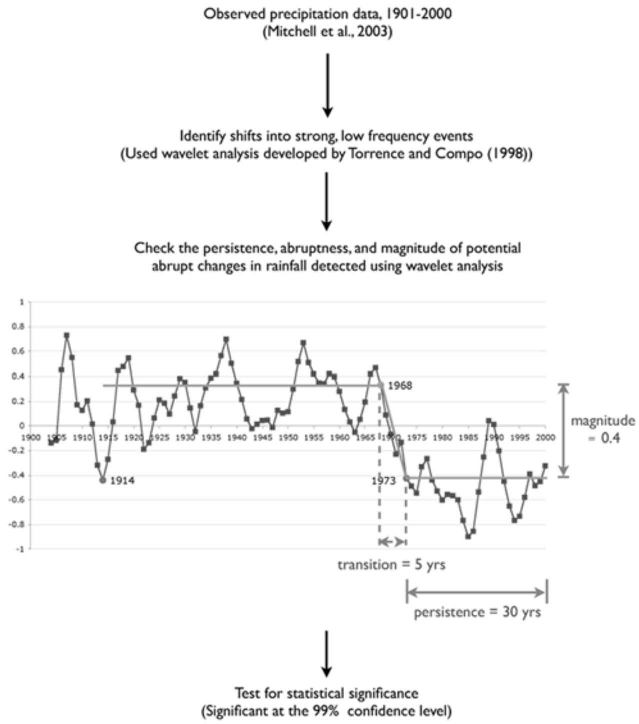

Figure 1. Flow diagram illustrating our technique for detecting abrupt changes in rainfall.

al., 1997]. A more detailed and technical description of wavelet analysis are given by *Torrence and Compo* [1998].

[5] We used wavelet analysis primarily because the time-frequency profile of the precipitation time series allows us to examine existing frequencies or climatic modes and the corresponding strength of these modes for each year in the data set. To identify potential abrupt changes in rainfall using wavelet analysis, we first isolate shifts of the strongest wavelet power from higher frequency to lower frequency modes. In the case of the Sahel, for example, the wavelet spectrum of the rainfall time series shows stronger high frequency bands in years prior to the onset of the prolonged drought in the late 1960s. From about 1970 onward, the strongest wavelet power has shifted into lower frequency modes. Hence, for this example, we identify a potential abrupt change in rainfall in the Sahel around 1970. We eliminate shifts or events that may be part of the seasonal, annual or interannual variability of the system by only considering shifts into periods greater than 36 months. This wavelet analysis is applied using the real-valued Mexican hat wavelet function for each time series in each grid cell or region in the precipitation data set. For regions where a shift into lower frequency modes has been detected, we check for anomalies in the station numbers. Any region that has a 50% change or greater in the number of stations during the approximate year of frequency shift is removed. We further impose that there should be at least five observation stations in the region. The output of this first step is a map of potential regions of abrupt rainfall changes, which is based on shifts into strong low frequency events and are not due to anomalies in the number of observation stations in the region.

[6] A three-year running mean is next applied to the original time series data of the regions identified in the first step and we test further for abruptness, persistence and magnitude of change and statistical significance. For the decrease in rainfall to be considered abrupt, we consider the length (in years) of the persistence of the event and the length (in years) of the transition period, which is the time it takes for the event to settle into the new drought regime. We impose that the transition period must be less than the persistence. Here we define persistence as the number of drought years until at least two years of more than average rainfall falls in the region. In the Sahel region, see Figure 1, rainfall steadily declined for about five years but the drought lasted for roughly 30 years. Hence, we consider this to be an abrupt change since the number of years in transition before the event settled into the drought regime is much less than the persistence of the event. We check the average magnitude of change in rainfall of the drought event and only include those that have deviated from the climatological normal, which is the average from 1901–2000, by at least 5%. Lastly, we test for statistical significance using the student's t-test and retain only those regions where the decrease in rainfall is statistically significant at the 99% level.

3. Regions of Abrupt Changes in Rainfall

[7] The detected events of abrupt decreases in rainfall during the 20th century are shown in Figure 2. These regions have experienced a change in climate that is different from the seasonal, annual, or interannual variability of precipitation. The strength of these drought events is quantified by the percent deviation of the decrease in rainfall relative to the normal (Figure 2). The detected changes are persistent with most of the drought events lasting for at least ten years (see Table 1 and auxiliary material Figure S1).[1] In terms of the abruptness of these changes, the ratios of the transition period relative to the persistence of the drought in these regions show that most regions have transition periods that are at most a quarter of the persistence, indicating that these droughts occurred abruptly (see Figure S2). Graphic illustrations of the sudden changes in rainfall in the time series data in some of the regions in Figure 2 and Table 1 are shown in Figure S3.

[8] Our results show the sudden and prolonged drought in the Sahel region in the late 1960s. Figure 2 also shows two of the strongest droughts documented in the United States, the Dust Bowl in the 1930s and the drought in the Southwest in the 1950s, which also affected Mexico. The large and sudden decrease in rainfall identified in the southwestern U.S. and Mexico during the 1950s and 1960s is consistent with tree ring records, which indicate that the region's most severe drought of the 20th century occurred in the 1950s extending in some parts into the 1960s [*Cleaveland et al.*, 2003; *Fye et al.*, 2003; *Cook*, 2000]. This period of persistent drought in Mexico triggered massive forest fires that destroyed thousands of hectares of forest [*Cleaveland et al.*, 2003] and agricultural productivity declined in parts of the region with insufficient irrigation

[1] Auxiliary materials are available in the HTML. doi:10.1029/2006GL028628.

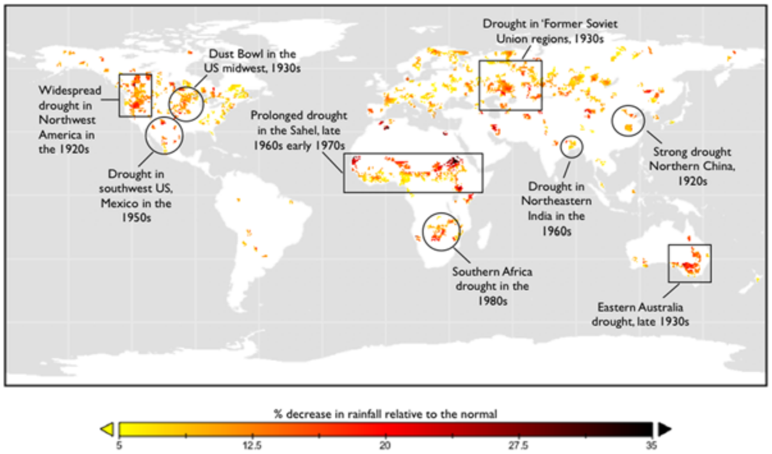

Figure 2. Regions of large, sudden decreases in rainfall. Highlighted are some of the regions where these events occurred, including the Sahel, the US Midwest, and southern Africa.

infrastructure to mitigate the impacts of the drought (D. Yetman et al., manuscript in preparation, 2006; D. Liverman, personal communication, 2006).

[9] Strong and persistent droughts are also identified in northeast China in the 1920s, in Kazakhstan and regions in the Former Soviet Union in the 1930s, in southeast Australia in the late 1930s, and southern Africa and eastern Europe in the 1980s. The severe and prolonged drought in China is also detected in tree ring reconstructions from northern China, and in the flow records of the Yellow River [*Liang et al.*, 2003; *Changming and Shifeng*, 2002]. The drought in the late 1930s to the mid 1940s in southeast Australia triggered widespread bushfires and greatly reduced flows in the Hunter and Hawkesbury Rivers (Australian Government Bureau of Meteorology, 2005, The World War II droughts 1937–45, available at http://www.bom.gov.au/lam/climate/levelthree/c20thc/drought3.htm). We also detected droughts that may not be spatially widespread but may have had strong societal impacts because of the geographical location. These events include droughts that occurred over regions in East India and Bangladesh in the 1950s. Table 1 shows the top 30 regions where the strongest and more persistent abrupt decreases in rainfall have been identified. Also shown in Table 1 are the average persistence and magnitude of change of the event in these regions. The dynamic progression of these droughts (see Animation S1 for an animated movie of the development and progression of these abrupt drought events) show that an event often begins in a specific location and then proceeds either to develop into a stronger widespread drought in the region (e.g. the Sahel drought) or move geographically into nearby regions through time (e.g., the drought in Russia in the early part of the 20th century).

[10] Interestingly, these regions of abrupt precipitation changes are mostly located in semi-arid and arid regions (with rainfall amounts of about 350–700 mm/year). We plotted (Figure 3) the frequency of finding abrupt rainfall decreases against the climatological (1901–2000) precipitation. Figure 3 shows that the rainfall probability density function for regions of abrupt changes are shifted towards lower precipitation, indicating that the sudden decrease in rainfall is most likely to occur in already relatively dry

Table 1. Thirty Regions of the World With Abrupt Decreases in Rainfall During the 20th Century[a]

No.	Region	Magnitude, %	Persistence, yrs
	1905–1920		
1	**Western North America**	**10**	**15**
2	Central North America	10	14
3	**Eastern Africa**	**13**	**15**
4	Former Soviet Union	10	14
5	**Eastern China**	**10**	**16**
6	Northeast China	12	10
7	Turkmenistan, Afghanistan	11	14
	1921–1940		
8	**Western North America**	**10**	**15**
9	**Central Canada**	**9**	**15**
10	Central North America (Dust Bowl region)	10	14
11	Kazakhstan	10	14
12	Southeast Africa	11	13
13	Eastern Australia	13	14
14	**Eastern Africa**	**15**	**15**
	1941–1960		
15	Southern US, Northern Mexico	12	13
16	Eastern Canada	9	14
17	Western Europe (inc. France, Spain, Italy)	10	12
18	Ukraine	10	13
19	Iran	11	14
20	**Eastern India, Bangladesh**	**8**	**15**
21	Central China	5	11
22	**Western Australia**	**13**	**15**
	1961–1980		
23	**Central Africa, (including the Sahel)**	**12**	**17**
24	Mongolia	10	13
25	Northern Russia	8	11
26	Northeast China	12	10
27	Algeria	14	14
	1981–1995		
28	Southern Africa	12	13
29	Central Europe (inc. Greece, Bulgaria, Yugoslavia)	11	12
30	India	9	14

[a]See Figure S1 for the regions, boxed and numbered accordingly.

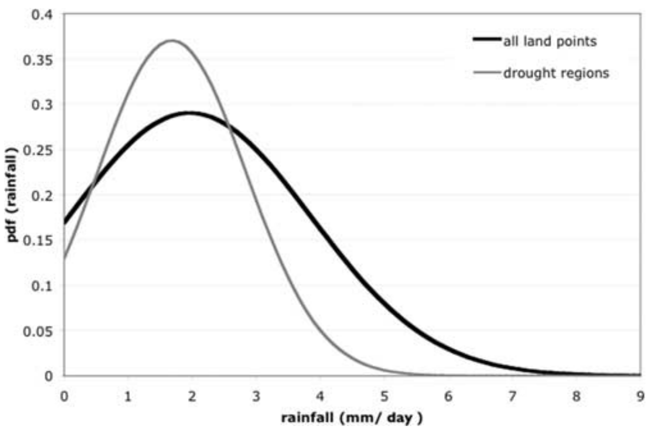

Figure 3. Probability density function (PDF) of rainfall shows that abrupt changes in rainfall are most likely to occur in arid and semi-arid regions. The black line is the PDF of rainfall over all land grid cells, while the grey line is the PDF of rainfall over just the abrupt drought-detected regions of Figure 2.

regions. Many climate modeling studies that include the effects of dynamic vegetation cover, which have explored the susceptibility of different regions of the world to shifts in climatic regimes, have also shown that arid and semi-arid regions are more likely to have multiple equilibrium states and exhibit abrupt ''regime shifts'' between states [*Scheffer et al.*, 2005; *Foley et al.*, 2003; *Kleidon et al.*, 2000; *Claussen*, 1998]. These studies have shown that certain regions of the world, such as Africa, Australia, South and East Asia may have multiple equilibrium states in precipitation (and associated patterns of vegetation), with abrupt changes between them.

4. Conclusion

[11] We have identified large and abrupt rainfall decreases in different regions of the world by analyzing historical precipitation data from the 20th century. The Sahelian droughts and the North American Dust Bowl are two abrupt changes in climate during the last century that have been analyzed in depth [*Schubert et al.*, 2004; *Wang et al.*, 2004; *Foley et al.*, 2003; *Taylor et al.*, 2002; *Nicholson et al.*, 1998]. However, despite the large impacts of these events, there has been no systematic survey of recent climate history to determine the prevalence of abrupt climatic changes. This study shows that, in addition to these two events, large and sudden changes in rainfall have occurred in about 30 other regions of the world (Table 1). This includes persistent droughts in Mexico and southwest United States, southern Africa, the former Soviet Union, east India and Bangladesh, northeast China, and eastern Europe. Our analysis also indicates that these sudden decreases in rainfall are most likely to occur in arid and semi-arid regions, a result that is consistent with climate modeling studies [*Scheffer et al.*, 2005; *Foley et al.*, 2003; *Kleidon et al.*, 2000; *Claussen*, 1998]. The susceptibility of dry regions to abrupt climate changes has been linked to a strong positive feedback between vegetation and climate interactions [*Wang and Eltahir*, 2000a; *Wang and Eltahir*, 2000b; *Zeng et al.*, 1999; *Claussen*, 1998].

[12] We recognize that the significance of these events may be dependent on geographical characteristics and location. A three to five year decrease in rainfall, although sudden, may not affect Southern Africa as much as it would affect the central region of the United States. We also note that semi-arid and arid regions are areas of high rainfall variability and hence are naturally prone to large fluctuations. The average persistence, however, of the detected abrupt drought events is at least ten years. This can be seen in Table 1 and in Figure S4 where we show the regions of abrupt rainfall changes at different persistence cutoffs. Further, Table 1 also shows that the magnitude of change in rainfall in most regions is about 10% lower than the normal. The decrease in precipitation in these regions is abrupt, persistent, and significant. Our analysis depicts the extent and magnitude of sudden climate changes across the globe in the 20th century and is indicative of what could also happen in the future. Further analysis is needed to understand the mechanisms behind these changes, their predictability, as well as their impacts on the Earth system and human societies.

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