EXCEPTIONAL WARMING IN THE WESTERN PACIFIC–INDIAN OCEAN WARM POOL HAS CONTRIBUTED TO MORE FREQUENT DROUGHTS IN EASTERN AFRICA

Chris Funk—U.S. Geological Survey, and University of California, Santa Barbara, Climate Hazard Group, Santa Barbara, California

In 2011, East Africa faced a tragic food crisis that led to famine conditions in parts of Somalia and severe food shortages in parts of Ethiopia and Somalia. While many nonclimatic factors contributed to this crisis (high global food prices, political instability, and chronic poverty, among others) failed rains in both the boreal winter of 2010/11 and the boreal spring of 2011 played a critical role. The back-to-back failures of these rains, which were linked to the dominant La Niña climate and warm SSTs in the central and southeastern Indian Ocean, were particularly problematic since they followed poor rainfall during the spring and summer of 2008 and 2009. In fact, in parts of East Africa, in recent years, there has been a substantial increase in the number of below-normal rainy seasons, which may

be related to the warming of the western Pacific and Indian Oceans (for more details, see Funk et al. 2008; Williams and Funk 2011; Williams et al. 2011; Lyon and DeWitt 2012). The basic argument of this work is that recent warming in the Indian–Pacific warm pool (IPWP) enhances the export of geopotential height energy from the warm pool, which tends to produce subsidence across eastern Africa and reduce onshore moisture transports. The general pattern of this disruption has been supported by canonical correlation analyzes and numerical experiments with the Community Atmosphere Model (Funk et al. 2008), diagnostic evaluations of reanalysis data (Williams and Funk 2011; Williams et al. 2011), and SST-driven experiments with ECHAM4.5, ECHAM5, and the Community Climate Model version 3 (CCM3.6) (Lyon and DeWitt 2012).

An increased frequency of East African droughts. Here we present 1979–2010 GPCP data (Adler et al. 2003), augmented by 2011 estimates based on the Climate Prediction Center's RFE2 (Xie and Arkin 1997) dataset (the RFE2 data were regressed against the GPCP data and used to fill in 2011, which is not included in the current GPCP archive).

Dry areas, based in the 1999–2011 anomalies, were identified for the March–June and June–September seasons. These regions are shown with brown (March–June) and blue (June–September) polygons in Fig. 6a. The background shading in Fig. 6a shows 2005 Gridded Population of the World population densities. The region impacted is one of the most densely populated areas of Africa. The population density and population for the March–June region shown in Fig. 6a are 44 people km^{-2} and 28.5 million people. The population density and population of the June–September dry region is 49 people km^{-2} and 30.5 million people. These regions also have large chronically undernourished and food-insecure populations. As Fig. 6b shows, these highly vulnerable regions have experienced a large number of below-normal rainfall seasons, especially since 1999.

Has ocean warming led to decreased East African rainfall during La Niña episodes? While the La Niña event of 2010/11 played a central role in triggering the 2010/11 food crisis, it is impossible to unambiguously attribute a single event to anthropogenic climate change. There has been recent research, however, that has emphasized that the long-term trend in IPWP SSTs (Williams and Funk 2011), rainfall, and winds could interact dangerously with interannual La Niña climate events. The latter observation helped trigger effective early warning of the 2011 East African food crisis (Ververs 2012; Funk 2011). More recent SST-driven climate simulations have emphasized the important role of post-1999 warming in the Pacific in driving the 2011 drought (Lyon and DeWitt 2012).

How much has the IPWP been warming? Figure 7 shows the recent IPWP warming, as measured by SSTs and an air temperature index. Also shown is a new CMIP5 multimodel ensemble IPWP SST average, based on 55 simulations from five models running the historical climate experiment (Taylor et al. 2011). In the historical experiment models are initialized in

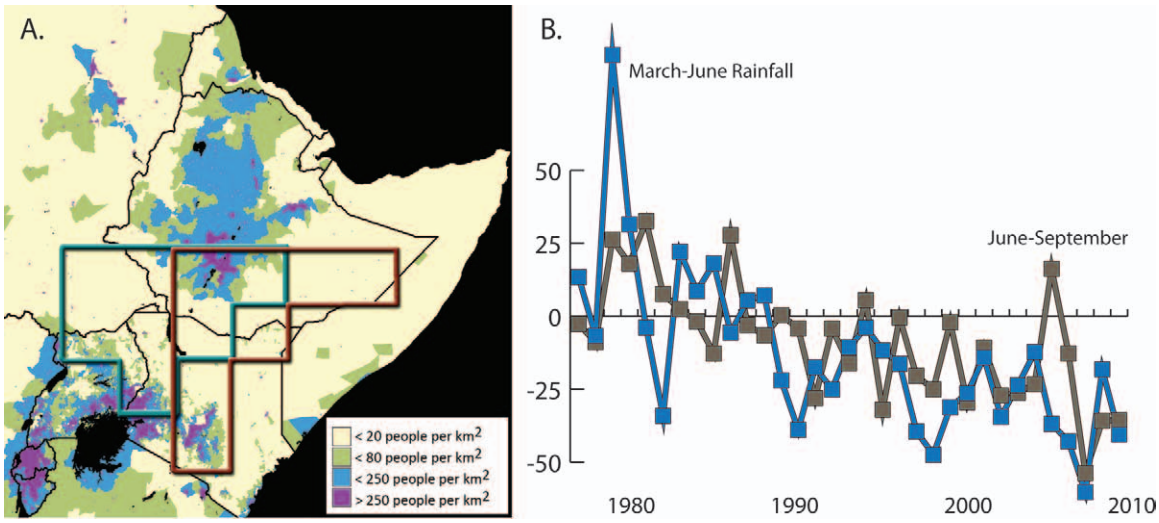

Fig. 6. (a) 2005 gridded population of the world overlain with polygons showing locations where recent GPCP rainfall values have declined substantially. (b) Time series of GPCP March–June and June–September rainfall anomalies (%) for these locations.

1850, and the coupled ocean–atmosphere models run through 2005, with the primary forcing being changes in greenhouse gases and aerosols. Annual 2001–11 IPWP SSTs have been very warm (Fig. 7), 28.4°C, which is 0.7°C greater than their 1900–50 mean. The interannual variability in the IPWP SST time series is very low (0.25°C). A 0.7°C increase represents a large change, vis-à-vis the IPWPs historic variability, as measured by the 1890–1970 standard deviation of decadal SSTs (0.10°C).

We can confirm the exceptional warming in the IPWP with an independent index we computed by averaging selected long-running GHCN v3 (Lawrimore et al. 2011) air temperature stations.[3] The 2001–11 air temperature index recorded a 0.5°C increase since 1950, a large increase when compared with the 1890–1970 standard deviation of decadal averages of the air temperature index. Both SSTs and terrestrial station data converge on substantial warming.

Between 1864 and 2011, 10-yr running averages of the IPWP SSTs are highly correlated with global National Aeronautics and Space Administration (NASA) Goddard Institute for Space Studies (GISS) (Hansen et al. 2010) temperatures (r = 0.99; Fig. 7). Over the past 160 years, the simulated IPWP SSTs have also covaried strongly with the simulated global temperatures in the CMIP5 archive. While formal attribution studies have been made for the southern and northern Indian and Pacific Oceans (Barnett et al. 2005; Pierce et al. 2006), specific attribution of the IPWP has not been made. It is interesting, however, to note how closely the magnitude of warming in the 12-member CMIP5 ensemble matches the observations (Fig. 7).

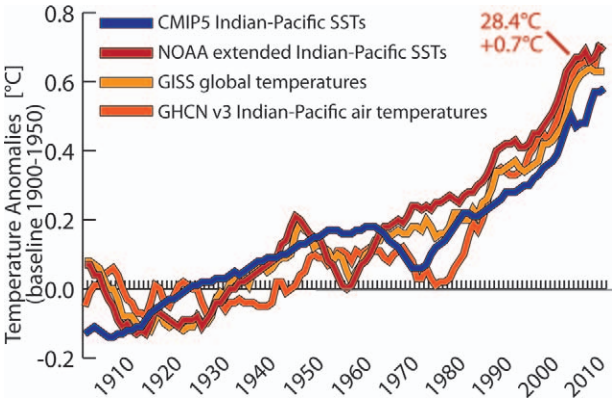

Fig. 7. Long time series of smoothed temperature indices for the IPWP CMIP5 SSTs, IPWP National Oceanic and Atmospheric Administration (NOAA) extended v3 SSTs, NASA GISS global air temperatures, Wilson tropical coral SST reconstruction, and a GHCN IPWP air temperature index.

Conclusions. The ~0.7°C IPWP warming, given the already warm state of the region, is likely to have had substantial dynamic impacts, as supported by recent modeling experiments (Lyon and DeWitt 2012). The relationship between rainfall and SSTs is nonlinear. Between 26° and 29°C average rainfall rates increase by a factor of 5, and observational studies based on GPCP data suggest that a change from mean SSTs of 27.7°–28.4°C might be associated with a change of rainfall rates from 3.4 to 5.5 mm day^{-1} (Folkins and Braun 2002); and this rate of change is similar to recent analyzes of GPCP data within the rising portion of the Pacific Walker circulation, which identified an increase of ~1 mm day^{-1} decade^{-1} (Zhou et al. 2011).

It is interesting to note that while SST-driven simulations of the 2011 March–May (MAM) season clearly show the important role played by the warm western Pacific (Lyon and DeWitt 2012), and while the new CMIP5 SSTs exhibit substantial warming during the 1990s and 2000s, these increasing SSTs do not appear to produce corresponding large changes in evaporation or rainfall over eastern Africa or the IPWP oceans. While Held and Soden (2006) suggested that the coupled models' weak hydrologic response to warming could help explain their predictions of a weakening of Walker circulation and more El Niño–like weather, recent observations indicate increases in evaporation and rainfall (Yu and Weller 2006; Zhou et al. 2011). An intensification of these hydrologic responses and the southeast trade winds across the Pacific, potentially associated with more La Niña-like climate, might help explain the differences between the observations and model projections. In any event, recent research has suggested that continued warming in the IPWP will likely contribute to more frequent East African droughts during the boreal spring and summer (Funk et al. 2008; Williams et al. 2011).

[3] Bombay/Mombassa, Madras, Port Blair, Mannar, Trincomalee, Puttalam, Colombo, Nuwara Eliya, and Sandaka.

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