# 15. ASSESSING THE CONTRIBUTIONS OF LOCAL AND EAST PACIFIC WARMING TO THE 2015 DROUGHTS IN ETHIOPIA AND SOUTHERN AFRICA

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*Anthropogenic warming contributed to the 2015 Ethiopian and southern African droughts by increasing El Niño SSTs and local air temperatures, causing reduced rainfall and runoff, and contributing to severe food insecurity.*

*Introduction.* In northern Ethiopia (7°–14°N, 36.5°–40.5°E, NE) during June–September (JJAS) of 2015 and in southern Africa (13.5°–27°S, 26.5°–36°E, SA) during December–February (DJF) of 2015/16, main growing seasons rains were extremely poor. In Ethiopia, Climate Hazards Group Infrared Precipitation with Stations (CHIRPS) (Funk et al. 2015c) and Centennial Trends (Funk et al. 2015b) data indicated one of the worst droughts in more than 50 years (FEWSNET 2015). More than ten million people currently require humanitarian relief (FEWSNET 2016a). SA rains were also extremely poor (FEWSNET 2016b); in Mozambique and Malawi, February maize prices were more than twice the five-year average, and in Zimbabwe the president has declared a national disaster in view of the El Niño–induced poor rains and the escalating food insecurity situation.

NE has been experiencing long-term rainfall declines (Funk et al. 2008; Funk et al. 2005; Jury and Funk 2013; Viste et al. 2012; Williams et al. 2012). The eastern Ethiopian highlands have exhibited recurrent soil moisture and runoff deficits since the 1990s (Funk et al. 2015c). NE rains in 2015 were the driest on record, but station data density prior to 1950 is very sparse for Ethiopia (Funk et al. 2015b). SA rainfall does not exhibit a decline, but the 2015–16 drought was severe. The impact of ENSO on Ethiopian rainfall is well documented (Fig. S15.1; Camberlin 1997; Degefu 1987; Diro et al. 2011; Gissila et al. 2004; Korecha and Barnston 2007; Korecha and Sorteberg 2013; Segele and Lamb 2005): the warm phase of ENSO is associated with suppressed rains during the main wet season (JJAS) over north and central Ethiopia. There have also been numerous papers documenting a negative teleconnection between El Niño and SA rainfall (Supplemental Fig. S15.1; Hoell et al. 2015; Jury et al. 1994; Lindesay 1988; Misra 2003; Nicholson and Entekhabi 1986; Nicholson and Kim 1997; Reason et al. 2000; Rocha and Simmonds 1997).

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*Is Anthropogenic Climate Change Causing More Extreme El Niños?* Our attribution approach is similar to our 2014 study (Funk et al. 2015a) examining boreal spring rainfall deficits in Kenya and southeastern Ethiopia. We first assess changes in Niño-3.4 SST extremes based on climate change simulations and then interpret these results using empirical relationships between Niño-3.4 SSTs and regional rainfall and air temperatures. Figures 15.1a,b examine JJAS and DJF Niño-3.4 SSTs (Huang et al. 2015) from observations (blue/red bars) and a multimodel climate change ensemble (red lines and blue shading; SST simulations from 19 model combinations and 34 simulations; 2006–15 simulation values were based on the RCP8.5 experiment; for details see https://climexp.knmi.nl) based on simulations from 1861 through 2100. For each of the 34 simulations, for each year, the top six Niño-3.4 SST events from the surrounding 30 years typified El Niño. The heavy red lines depict the ensemble average of these values for each year. The thin red lines identify the 80% confidence interval associated with the ensemble spread. The climate change distribution agrees reasonably well with the observed increasing strength of moderate-strong Niño-3.4 events. The simulations predict increasingly extreme Niño-3.4 events, and

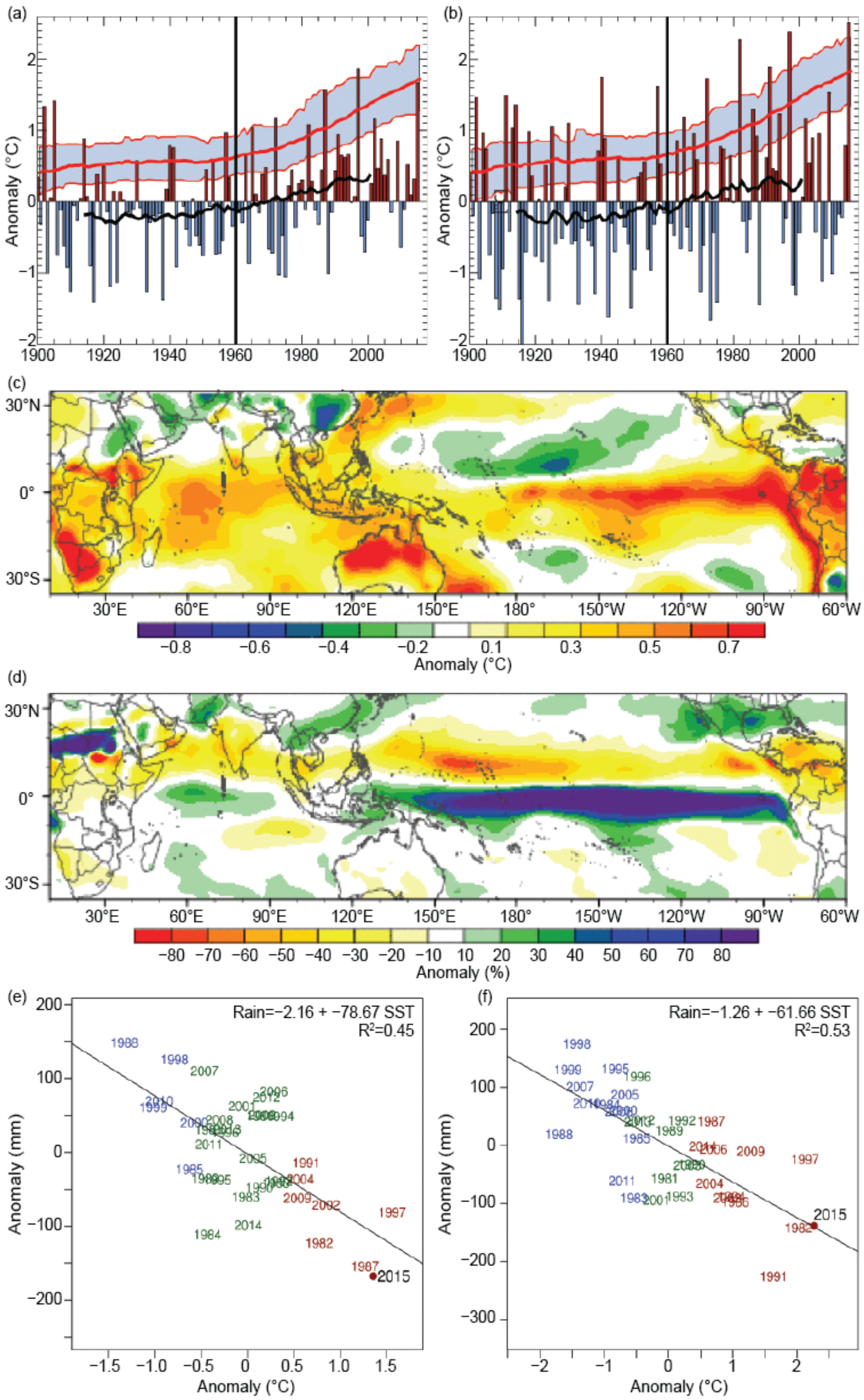


**Fig. 15.1. (a),(b) Observed Niño-3.4 SST anomalies (bars) along with associated 30-yr means (thick black line). SST simulations are from 19 model combinations and 34 simulations; 2006–15 simulation values were based on the RCP8.5 experiment (for details see https://climexp.knmi.nl). Thick and thin red lines show running 30-yr climate change ensemble El Niño SSTs (see www.esrl.noaa.gov/psd/repository/alias/facts). (c),(d) Changes in the DJF Geophysical Fluid Dynamics Laboratory Atmospheric Model version 3 near-surface air temperatures and precipitation during 1980–2015 El Niño events versus 1920–79 El Niño events. Results based on the 17-member ensemble mean. (e),(f) Scatterplots between Niño-3.4 SST and observed NE and SA rainfall anomalies.**

this is what we see in the SST observations (Supplemental Figs. S15.1a,b): increasingly intense El Niño events.

To estimate radiatively forced changes in ENSO maxima, we subtracted the average 1946–75 ensemble sea surface temperatures over the Niño-3.4 region (temporal center point marked with the black vertical lines in Figs. 15.1a,b) from the 2000–29 Niño-3.4 values (the last point on the thick red line). For DJF and JJAS, this gives us an estimated change of +1.2°C. Using the 80% confidence intervals for 2015–16 and repeating this calculation lets us establish a range of values $\Delta T_{DJF} = +1.2° \pm 0.5°C$ and $\Delta T_{JJAS} = +1.1° \pm 0.5°C$.

We next examine three atmospheric GCM simulation ensembles, drawn from the Earth Systems Research Laboratory Facility for Climate Assessments (FACTS; see www.esrl.noaa.gov/psd/repository/alias/facts). Using FACTS, we examined differences between 1980–2015 and 1920–79 moderate-to-strong El Niños, using atmospheric General Circulation Model (AGCM) simulations. Figures 15.1c,d show results for a single model for DJF. Supplemental Fig. S15.2 shows similar results for all three models for both seasons. Over the tropical Pacific and Indian Oceans (Fig. 15.1c), recent El Niños have been associated with much warmer conditions (> +0.8°C), consistent with Figs. 15.1a,b, but have also been potentially influenced by natural decadal variability (Wittenberg 2009).

Accompanying the warming is a very large (70%+)

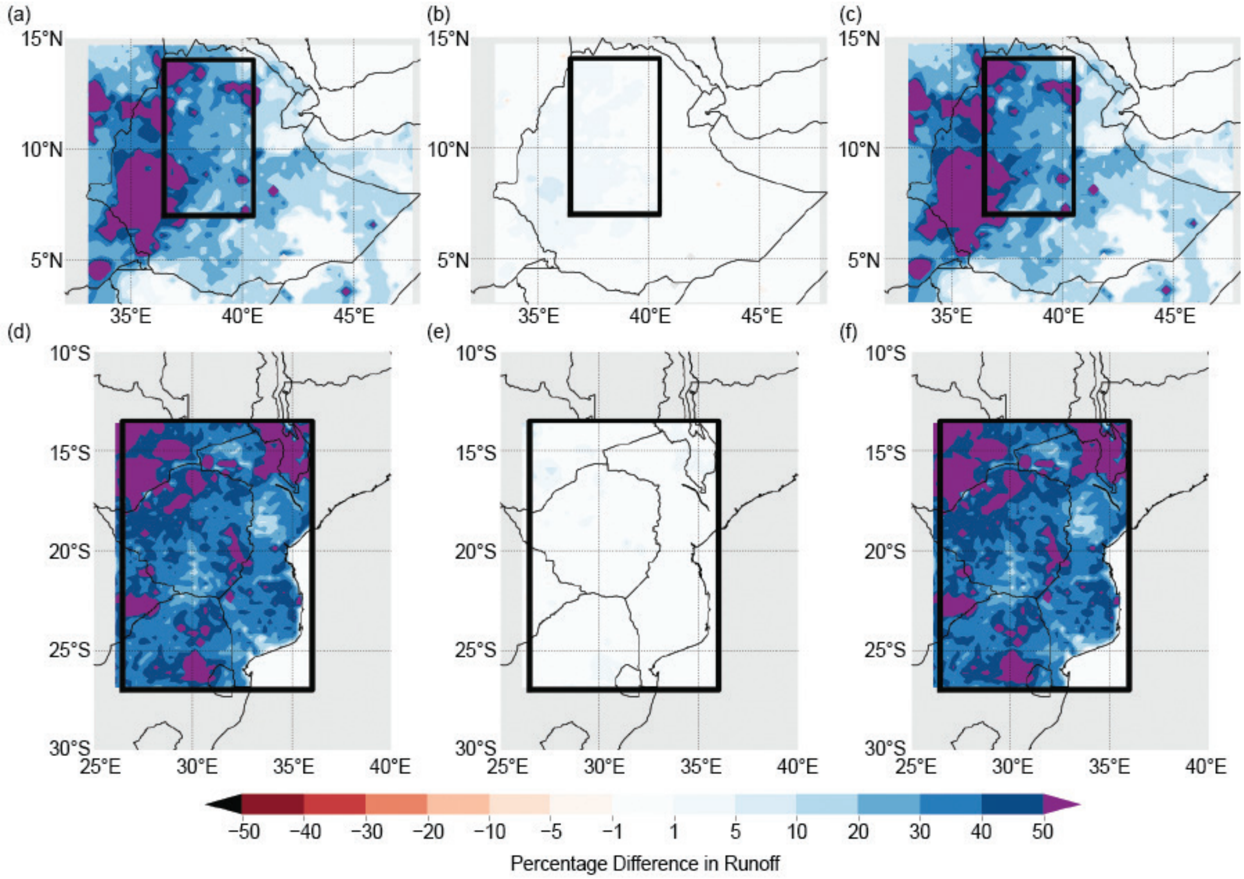


**FIG. 15.2. Hydrologic sensitivity experiment results for runoff. (a),(d) The influence of anthropogenic rainfall reductions. (b),(e) The influence of local air temperature increases. (c),(f) Combines the effects of low rainfall and warm air temperatures. (a)–(c) NE experiments. (d)–(f) SA experiments. Each panel shows the change in runoff, in comparison with observed conditions, when rainfall and air temperatures are increased and/or cooled.**

increase in eastern Pacific rainfall (Fig. 15.1d), one measure of the strength of ENSO (Chiodi and Harrison 2010; Chiodi and Harrison 2015; Curtis and Adler 2000). The magnitude of El Niño precipitation increases over the eastern Pacific would strongly influence El Niño's atmospheric forcing strength, and we find a precipitation decline (Fig. 15.1d) over southern Africa that is broadly consistent with our empirical analysis. Results from two other models and JJAS are similar (Supplemental Fig. S15.2).

*Estimating Rainfall and Air Temperature Changes due to El Niño.* Figures 15.1e,f show regressions between NE/SA rainfall and Niño-3.4 SSTs. Our study regions were chosen based on historical teleconnections (Supplemental Figs. S15.1e,f) and the pattern of the 2015–16 deficits. In Ethiopia and southern Africa, Niño-3.4 SSTs explained 45% and 53% of the 1981–82 to 2015–16 rainfall variance, respectively. While rainfall performance varied substantially during strong El Niños (the 1997–98 response was relatively modest in both regions), the observations suggest that a 1°C increase in El Niño-3.4 SSTs produces a 79 mm and 62 mm decrease in NE and SA rainfall, respectively. These regressions slopes suggest that without anthropogenic Niño-3.4 warming, NE and SA rainfall would have been approximately 16% and 24% greater, respectively.

ENSO teleconnections and warming trends were used to estimate anthropogenic air temperature changes of +0.9°C (Supplemental Material). Using the lower bounds of Niño-3.4 SST change ($T_{JJAS}$=0.6°C, $T_{DJF}$=0.7°C) gives estimates of a 9% and 14% rainfall change and a 0.8°C and 0.7°C JJAS/DJF air temperature change in NE and SA, respectively.

*Contrapositive Hydrologic Experiment.* We performed four hydrologic experiments using the variable infiltration capacity (VIC) model. In these experiments, we drove the VIC model with (i) observed weather forcings, (ii) weather forcing in which we increased NE/SA precipitation by 16% and 24%, (iii) weather forcings with air temperatures cooled by +0.9°C/+0.9°C NE/SA, and (iv) weather forcings with both (i) and (ii) changes. Figure 15.2 shows results for experiments (ii)–(iv), expressed as anomalies from (i). Our contrapositive NE runoff changes, in our region of interest, for (ii)–(iv) were: +35%, +1%, +37%; for SA (ii)–(iv) changes were: +48%, +1%, +49%. Clearly, anthropogenic disruptions in precipitation, associated with the large increases in ENSO SST (Figs. 15.1a,b), provided the dominant contribution. As was the case for 2014 (Funk et al. 2015a), we find that a ~1°C warming over the tropical Pacific can have a much greater impact than a ~1°C warming in local air temperatures.

*Conclusions.* Anthropogenic warming contributed substantially to the very warm 2015/16 El Niño SSTs, and this anthropogenic contribution likely reduced NE and SA rainfall by approximately 16% and 24%. The associated simulated runoff reductions were much larger, 35% and 48%, respectively. A ~1°C warming over the tropical Pacific appears associated with a large (>70%) increase in El Niño diabatic forcing (Fig. 15.1f), and modest (~20%) precipitation reductions over NE/SA. These "modest" rainfall reductions, acting to accentuate natural El Niño impacts, have contributed to substantial food crises.

Recent El Niños appear to be more intense (Supplemental Fig. S15.2). During El Niños, warmer Indo-Pacific SSTs, and associated rainfall changes, may be more influential than the direct impacts of local increases in air temperatures. The contrast between Figs. 15.2a,b and 15.2d,e tell us that, based on these hydrologic simulations, nonlocal warming in the tropical Pacific had a much stronger drought impact than did relatively small local air temperature impacts. We feel this result is quite important, possibly indicating that a major mode of "climate change" may be associated with more extreme tropical SST and SST gradients. "Global warming" expressed as local increases in air temperatures may have less dramatic impacts. Assessments (Brown et al. 2015) of local temperature impacts on crop yields suggest relatively small yield reductions per degree of warming (~2% per °C). A degree of warming in Niño-3.4 SSTs, concomitant with a warm ENSO event, can have larger impacts due to teleconnected precipitation declines.

Because runoff forms a relatively small fraction of the hydrologic balance, the influence of rainfall deficits can be amplified, potentially leading to severe hydropower shortages (Davison 2015; Onishi 2016) and even severe drinking water deficits (Gauette 2016). These crises are just one aspect of the widespread food insecurity related to the extreme 2015/16 El Niño (Fig. 15.1), which is thought to have contributed to the severe food insecurity of 60 million people "primarily in the most vulnerable regions of southern Africa, East Africa, Central America, and the Pacific Islands" (OCHA 2016). If La Niña conditions follow, extreme warming in the western Pacific may lead to dry conditions over equatorial East Africa (Funk et al. 2015a; Funk et al. 2014; Shukla et al. 2014), exacerbating food insecurity conditions.

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