Full Length Research Paper

Maritime continent winter circulation as a predictor of El Niño-Southern Oscillation (ENSO) influence on Ethiopia summer rainfall

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Received 26 May, 2015; Accepted 2 September, 2015

Summer rainfall over the cropping region of Ethiopia is related to the precursor winter circulation around the Maritime Continent and El Niño–Southern Oscillation (ENSO) development and influence. Investigation of this link reveals that sea surface temperature (SST) in the north Indian Ocean and China Sea are anomalously cold and there are low level north-westerly wind anomalies around the Maritime Continent prior to dry summers in Ethiopia. The analysis shows that wind anomalies spread into the Pacific - increasing convection, and across the Indian Ocean and Africa - suppressing convection. Two indices that represent Asian winter monsoon penetration near the Maritime Continent are used to predict Ethiopian summer rainfall at long-lead time. The hindcast fit of the statistical algorithm exceeds 50% during the satellite era (1981-2014).

Key words: Climate prediction, Ethiopia.

INTRODUCTION

Climate variability in Ethiopia is influenced by the Pacific El Niño Southern Oscillation (ENSO) (Semazzi et al., 1988; Rowell et al., 1992; Janicot et al., 1996, 2001; Rowell, 2001) and associated tropical ocean thermocline (White and Tourre, 2003; Jury and Huang, 2004). During warm phase, atmospheric convection spreads across the equatorial Pacific causing upper westerly winds over the Atlantic and subsidence over much of Africa (Hoskins and Ambrizzi, 1993; Jury et al., 1994; Branstator, 2002; Yeshanew and Jury, 2007; Joly and Voldoire, 2009; Segele et al., 2009; Shaman et al., 2009).

Wang and Fan (2009) demonstrate that knowledge on the evolution of climate patterns in analogue years can improve the prediction of Asian summer monsoon rainfall. During the preceding dry winter season (Dec-Mar) the circulation is governed by the Tibetan high pressure, jet stream waves that conduct cold fronts across Indo-China and circulation patterns over the west Pacific. In the

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reviews of Chang et al. (2006) and Lau and Wang (2006), Asian monsoon winter outflow to the Maritime Continent is connected with ENSO phase and equatorially propagating Madden Julian Oscillation (MJO). Cold air outbreaks over the China Sea are more frequent and join with westerly MJO surges at the onset of Pacific El Niño and its convection. How this affects the Indian Ocean circulation and African convection is the focus of this study.

The main goals here are to understand the ocean-atmosphere coupling and climatic controls on summer rainfall in Ethiopia's crop growing region. The primary scientific question is: How does Asian Monsoon winter outflow near the Maritime Continent link with ENSO and reach across the Indian Ocean to affect African rainfall? A spin-off scientific question is: how can this knowledge be exploited to offer operational seasonal forecasts at a lead time suitable for intervention?

DATA AND METHODS

The data and methods employed to develop prediction algorithms are described. The primary index is the observed June to September rainfall averaged over the crop growing region of Ethiopia 36.5°-40.5°E and 7°-14°N. The ocean and atmospheric predictors are drawn from satellite-era reanalysis products in the preceding December to March season. This work expands on earlier studies of Korecha and Barnston (2007) and Jury (2013).

Target and predictor data

The CHIRPS 5 km resolution global land-only rainfall dataset forms the basis of this study. Monthly data from over 150 Ethiopian National Meteorological Agency gauges are blended with satellite observations, as described in Funk et al. (2014) over the period 1981 to 2014. The interpolation procedure gives primary influence to in-situ observations and gauge climatology, and secondary influence to satellite and model data (Janowiak et al., 2001; Huffman et al., 2007, 2011; Saha et al., 2010; Knapp et al., 2011).

The target area is defined by crop reports from the Ethiopian Central Statistical Agency (www.csa.gov.et) and the US Dept of Agriculture Famine Early Warning System (FEWS) that show production in an eastern highlands zone: 7°-14°N and 36.5°-40.5°E (Figure 1a and b) including the states of Amhara and Oromia. This zone overlaps with the leading cluster of satellite vegetation fraction (Tucker et al 2005) which has a uni-modal peak from July to October that lags 1-month behind rainfall. The mean annual cycle of rainfall (Figure 1c) rises above 100 mm/month from June to September, peaking above 200 mm/month in July and August. Hence the season of interest extends across these four months.

Summer rainfall forecasts in April would be most useful for planning purposes, so predictors are drawn from the preceding December to March (winter) season. The CHIRPS monthly rainfall is area-averaged to create a time series and then applied to search for key predictors in fields of sea surface temperature from the Hadley Centre (Kennedy et al., 2011) and 850 mb winds from the European Centre for Medium-range Weather Forecasts (ECMWF) reanalysis (Dee et al., 2011). Exploratory analysis determined that the eastern hemisphere held most of the climate signal: 20°S-35°N and 0°-180°E. All time series were converted to standardized departures and linearly detrended.

Methods of analysis

Predictors were assembled from correlation maps analyzed for December-March in respect of detrended June-September rainfall, with values < 80% significance masked. For extraction of predictor time series, the area for averaging should exceed 15° latitude × 20° longitude in size. The candidate predictor pool was four over a training period of 33 years: 1981 to 2014. A statistical algorithm was formulated via backward stepwise linear regression onto the target time series. Initially all predictors were included and their partial correlation was evaluated. Those with lower significance (or colinearity) were screened out and the algorithm was re-calculated from the remaining variables. An optimal fit was reached with three predictors, however when repeated for the second half of the time (1998-2014), one predictor dropped out (Indian SST 45°-145°E, 5°S-25°N), leaving only the low level winds near the Maritime Continent as contributors: Indian meridional wind 45°-135°E, 7°S-12°N and Pacific zonal wind 120°-170°E, 15°S-15°N.

The performance of the multivariate linear algorithm was evaluated by $r^2$ fit, adjusted for the number of predictors. Conservatively assuming 16 degrees of freedom, the Pearson product-moment $r^2$ fit should exceed 35% for statistical significance at 99% confidence. Predicted vs observed scatterplots were analyzed for slope, tercile hits and outliers. The algorithm stability was validated by removing the first and last 7 years and comparing differences in $r^2$ fit and predictor coefficients. The algorithm is developed from detrended time series to minimize the effect of climate change across the 33 year record. In an operational situation, detrending is believed to have little influence.

To study the interaction of the Asian winter monsoon and Pacific ENSO over the Maritime Continent, precursor and simultaneous composites were analyzed for Ethiopian dry and wet seasons corresponding with the 850 hPa wind predictors. Dry seasons include 1982, 1987, 1997, 2002, 2014, and wet seasons include: 1988, 1996, 1998, 1999, 2000. Composites of dry minus wet were analyzed for NCEP2 winds, vertical motion and specific humidity (Kanamitsu et al., 2002), and satellite GPCP wind (Adler et al., 2003) and SST. These datasets are used because NCEP winds are available in vertical section and the GPCP rainfall covers both land and ocean. Similarly composites for the upper ocean were analyzed longitudinally in the 5°-15°N band using NOAA ocean reanalysis (Behringer, 2007). To quantify the local response of Ethiopian rainfall to ENSO, correlation maps (5°-15°N, 35°-42°E) were analyzed with respect to June-September Nino3.4 Pacific SST index (170°-120°W, 5°S-5°N) and with Jul-Oct satellite vegetation fraction (Tucker et al., 2005). Lag-correlations were calculated based on the time series of the Ethiopian summer rainfall and Pacific Nino3.4 SST index from -6 (December-March) to +4 months.

RESULTS AND DISCUSSION

Targets and correlation maps

The correlation of June-September rain onto regional SST fields in the preceding December-March (Figure 2a) reflects anomalous warm conditions in the north Indian Ocean and northwest Pacific (China Sea), encompassing the zone east of the target area. The corresponding 850 hPa V wind correlation field (Figure 2b) shows significant values over the equatorial Indian Ocean and Maritime
Figure 1. (a) Loading pattern of first mode of vegetation fraction 1981-2013 shaded light to dark green from zero to one standard deviation with state boundaries and target area. (b) Grain crop growing areas from FEWS shaded yellow to hatch orange with increasing yield, with key cities and rivers. (c) Mean annual cycle of CHIRPS rainfall over the target area (bold) and quintiles.

Continent. The wind correlations, following the edge of the SST correlations, point to diminished tropical penetration of the Asian winter monsoon prior to above-normal Ethiopian summer rainfall. An integral feature is zonal winds over the west Pacific, whereby decreased westerlies correspond with an early onset of ENSO in
respect of wet conditions in Ethiopia six months later.

The time series of observed and statistically predicted rainfall is given in Figure 3a, scatterplots are provided in Figure 3b and c. The corresponding multi-variate algorithm is Ethiopia June-September rain = +0.53*(Indian V wind) -0.33*(Pacific U wind) in the preceding December-March season. These indicate an $r^2$ fit > 50% for both two and three predictor algorithms, values above those of Wang and Fan (2009) for Asian summer rainfall. Tercile hit rates in the dry category are 64%, with misses in 1984, 1995, 2009 and 2013. Tercile hits in the wet category are 67%, and outliers are noted in the recent
Figure 3. (a) Time series of observed Jun-Sep target rainfall and 2-predictor model rainfall; scatterplot of linear multi-variate regression of predicted and observed rainfall using (b) 3 predictor model, and (c) two predictor model, with trend fit.

To check for stability of the forecast algorithm, the same 2-predictor model is fitted to the observed rainfall time series after removing the first and last 7 years. The $R^2$ fit remains constant: 56%, but the coefficients change. The Ind V coefficient is +.37 recent +.57 past, while the Pac U is –.41 recent –.27 past. Hence the Pacific (Indian) influence grows (shrinks) with time, but predictability is steady. In the section below, we switch our analysis from patterns favouring above normal rainfall to those bringing drought conditions to Ethiopia.

**Composites of maritime continent ENSO circulation**

Time series of Ethiopian summer rainfall and preceding
Figure 4. Composite maps of dry minus wet: (a) preceding Dec-Mar 850 hPa winds and (b) satellite GPCP rainfall, and (c, d) same for Jun-Sep rainy season. Vectors in (a) highlight Asian winter monsoon outflow that anticipates drought. Shading in (a, c) and (b, d) is consistent, and areas with minor differences are unshaded.

winter winds (as indicated by the predictive algorithm) around the Maritime Continent are ranked to provide a selection of years in lower and upper quintiles. Composite maps of dry (1982, 1987, 1997, 2002, 2014) minus wet (1988, 1996, 1998, 1999, 2000) December-March and June-September 850 hPa winds, satellite rainfall and sea temperature and vertical motion are analyzed. The atmospheric fields (Figure 4a to d) in antecedent and simultaneous times show that zonal winds east of the Maritime Continent constitute a significant and stable signal dividing a convective Pacific (El Niño) zone from a dry Indian Ocean. The dry minus wet composite in December-March (year -1) exhibits cooler SST over the northwest Pacific (Figure 5a and c), extending to the NW Indian Ocean and SE Atlantic. The cooler SST correspond with atmospheric subsidence over the China Sea that shifts to the Maritime Continent by summer (Figure 5b and d) and spreads westward across the Indian Ocean to Africa.

The analysis is extended by composite height sections averaged 5°-15°N that show upper westerlies over Africa subside toward a region of low humidity over the Maritime Continent in the preceding winter (Figure 6a to b). Meridional winds are from north (< -1 m/s) from 120°E to 140°E in the 850 to 600 hPa layer, and constitute an enhanced Asian winter monsoon outflow. The dry minus wet scenario evolves to summer with a low level westerly anomaly over the west Pacific, consistent with a developing El Niño. A corresponding dipole develops in the humidity field (Figure 6c and d): moist-Pacific, dry-Indian. Easterly winds on the east African escarpment derive from the divergent ENSO circulation over the Indian Ocean, and correspond with expansion of the dry zone from the Maritime Continent to North Africa, that inhibits moisture transport from the Congo Basin to Ethiopia (Viste and Sorteberg, 2013).

A complementary depth section of ocean temperatures and zonal circulation is given in Figure 7a and b, similarly averaged over the 5° to 15°N band. Composite differences for dry minus wet conditions reflect cooling in the upper ocean to the east and west of the Maritime Continent in the preceding December-March season. The sub-surface ocean circulation differences exhibit zonal divergence and corresponding upwelling in the northwest Pacific. The upwelling strengthens in the Pacific as westerly currents intensify in the June-September season. Ocean temperature differences are < -3°C in depths from 60 to 200 m from 130 to 170°E signifying
Figure 5. Composite maps of dry minus wet: (a) preceding Dec-Mar satellite SST and (b) 500 hPa omega, and (c, d) same for Jun-Sep rainy season. Shading in (a, c) and (b, d) is consistent, and areas with minor differences are unshaded.

uplift of the west Pacific thermocline, corresponding with onset of El Niño in the east Pacific and deficient rains over Ethiopia.

The impact of Pacific ENSO on Ethiopian summer rainfall and subsequent response of vegetation is analyzed in Figure 8a and b. The map indicates a significant simultaneous correlation of Nino3.4 index and rainfall over the southeastern highlands and Rift Valley. The subsequent response of vegetation to rainfall variability tends to concentrate in the Rift Valley and eastern escarpment. The northwestern highlands (Gonder area) vegetation show little response to rainfall, suggesting lower vulnerability to climatic anomalies there. Lag correlation between rainfall and Nino3.4 indices (Figure 8b) reveals that significant values are reached by two month lead time, too short for intervention and mitigating actions. Hence our analysis of Maritime Continent circulation links to ENSO is essential for predictability at the longer lead times required.

Conclusion

Rainfall over the grain-crop growing areas of Ethiopia has been investigated. A new dataset that blends > 150 rain gauges with satellite estimates provides an accurate reflection of local climate. Previous studies have revealed that winter outflow toward the Maritime Continent is connected with ENSO phase, and could be exploited to uncover predictability. Correlation maps at six month lead time with respect to Ethiopia rainfall found that the SST and wind circulation around the Maritime Continent were most influential. A forecast algorithm based on two wind predictors achieved an overall fit of 50% and tercile hit rate of two-thirds. Atmospheric memory is imparted by large-scale coupling with the tropical ocean. Composite differences between five dry and five wet seasons with corresponding winds gave evidence that the signal shifts from the Asian winter monsoon to the Maritime Continent. By summer a divergent circulation over the East Indian Ocean (cf Figure 6c) drives tropical convection into the central Pacific, and inhibits convection over tropical North Africa. The ocean thermocline lifts in the west Pacific (Figure 7b) signalling the onset of El Niño and corresponding dry weather over Ethiopia. The statistical links depend on historical replication, and predictive outliers since 2006 are of concern. How are these results applied? Ethiopia currently experiences food deficits
Figure 6. Composite longitudinal sections (averaged 5-15° N) of dry minus wet: (a) preceding Dec-Mar zonal wind and (b) specific humidity, and (c, d) same for Jun-Sep season. Zonal circulation vectors (max = 3 m/s) shown in a, c. Meridional wind differences < - .5 m/s grey shaded in b,d, represent Asian monsoon outflow before and during drought in Ethiopia. Topography illustrated, vertical motion exaggerated. Shading in (a, c) and (b, d) is consistent, and areas with minor differences are unshaded.

because of low resource inputs, high population density and variable climate. Shortfalls can be overcome with scientific information and practical engineering solutions (Goddard et al., 2010). Rainfall predictions are formulated by the Ethiopian Institute for Agriculture Research and shaped into coherent advice to collective decision-makers/resource managers and community based farming groups. Mitigating actions are suggested by agricultural extension services, with feedback from a network of cultivators dealing with impacts. We have sought to enhance our predictive capacity by statistically analyzing how near-surface winds around the Maritime Continent anticipate shifts in the zonal circulation and tropical convection associated with ENSO (Chang et al., 2006; Lau and Wang, 2006). Seasonal forecasts of summer rainfall over the grain-crop growing areas of the Ethiopia highlands based on December-March predictors near the Maritime Continent will provide the necessary lead time for strategic decisions to mitigate adverse impacts or take advantage of favourable weather. Processes underlying the apparent skill of the tropical wind predictors need to be tested via coupled ensemble model simulations. The search for predictability could be extended to targets such as vegetation fraction and
Figure 7. Composite longitudinal sections (averaged 5-15 N) of dry minus wet: (a) preceding Dec-Mar subsurface ocean temperature and zonal circulation (vectors), and (b) same for Jun-Sep season. Vertical motions are exaggerated.

Conflict of Interest

The authors have not declared any conflict of interest.

ACKNOWLEDGEMENTS

This study is part of a Rockefeller Foundation project with the Ethiopian Institute for Agriculture Research, Melkasa, conceived with help from J. Seid and G. Mamo.
Figure 8. (a) Correlation of Jun-Sep rainfall with Jul-Oct satellite vegetation fraction (shaded) and Jun-Sep Nino3.4 index (contours < -0.4), (b) lag correlation between summer rainfall and Nino3.4 index, negative (months) refer to Pacific SST leading rainfall. The 98% confidence is achieved at -0.4 (dashed). Red line is mean and green lines are upper and lower quintiles.

REFERENCES


