Ensemble-Based Empirical Prediction of Ethiopian Monthly-to-Seasonal Monsoon Rainfall

Rainfall is the most important climate element affecting the livelihood and wellbeing of the majority of Ethiopians. The main Kiremt rainy season is from June-September (JJAS) and supports 85-95% of the country's food crop. Because all agricultural activities and resulting national crop production hinge on the amount and distribution of JJAS rainfall, accurate monthly and seasonal predictions of this rainfall are crucial for agricultural planning and disaster mitigation.

A time-frequency based analysis was performed for concurrent teleconnections between monthly-to-seasonal Ethiopian rainfall and large-scale atmospheric circulation and global sea surface temperature (SST) patterns. This analysis linked Kiremt rainfall variation principally (66% explained variance) with annual time-scale atmospheric circulation patterns involving fluctuations in the major components of the monsoon system (e.g., monsoon trough, Somali low-level jet, tropical easterly jet). It also is shown that although variability on quasi-biennial (5%) and El Niño-Southern Oscillation (2%) time-scales account for much less rainfall variance than the above annual mode, they significantly affect Ethiopian rainfall by preferentially modulating the major regional monsoon components through their season-long persistence. Because the effects of slowly evolving SST variations on Ethiopian rainfall must be realized through changes in local and regional circulations and oceanic patterns, a viable and successful monthly-to-seasonal Ethiopian rainfall prediction is best achieved by additionally identifying potential local and regional predictors and incorporating their aggregate effects by ensemble prediction methods.

In this study, an ensemble-based multiple linear regression technique is developed to assess the predictability of regional and national JJAS anomalies and local monthly rainfall totals for Ethiopia (Fig. 1). The ensemble prediction approach captures potential predictive signals in regional circulations and global SSTs two to three months in advance of the monsoon season. Sets of 20 potential predictors are selected from assessments of correlation maps that relate rainfall with regional and global predictors. Individual predictors in each set are utilized to initialize individual forward stepwise regression models to develop ensembles of equal number of statistical model estimates, which allow quantifying prediction uncertainties related to individual predictors and models. Prediction skill improvement is achieved through error minimization afforded by the ensemble.

For retroactive validation (RV), the ensemble predictions reproduced well the observed all-Ethiopian JJAS rainfall variability two months in advance (Figs. 2, 3). The ensemble mean prediction outperforms climatology, with mean square error reduction, SSClim, of 62%. The skill of the prediction remained high for leave one out cross validation (LOOCV), with the observed-predicted correlation, r, (SSClim) being +0.81 (65%) for 1970-2002 (Fig. 4). For tercile predictions (below, near, above normal), the ranked probability skill score is 0.45, indicating improvement compared to climatological forecasts. Similarly high prediction skill is found for local prediction of monthly rainfall total at Addis Ababa (r = +0.72) and Combolcha (r = +0.68), and for regional prediction of JJAS standardized rainfall anomalies for northeastern Ethiopia (r = +0.80). Compared to the previous generation of rainfall forecasts, the ensemble predictions developed in this paper show substantial value to benefit society.

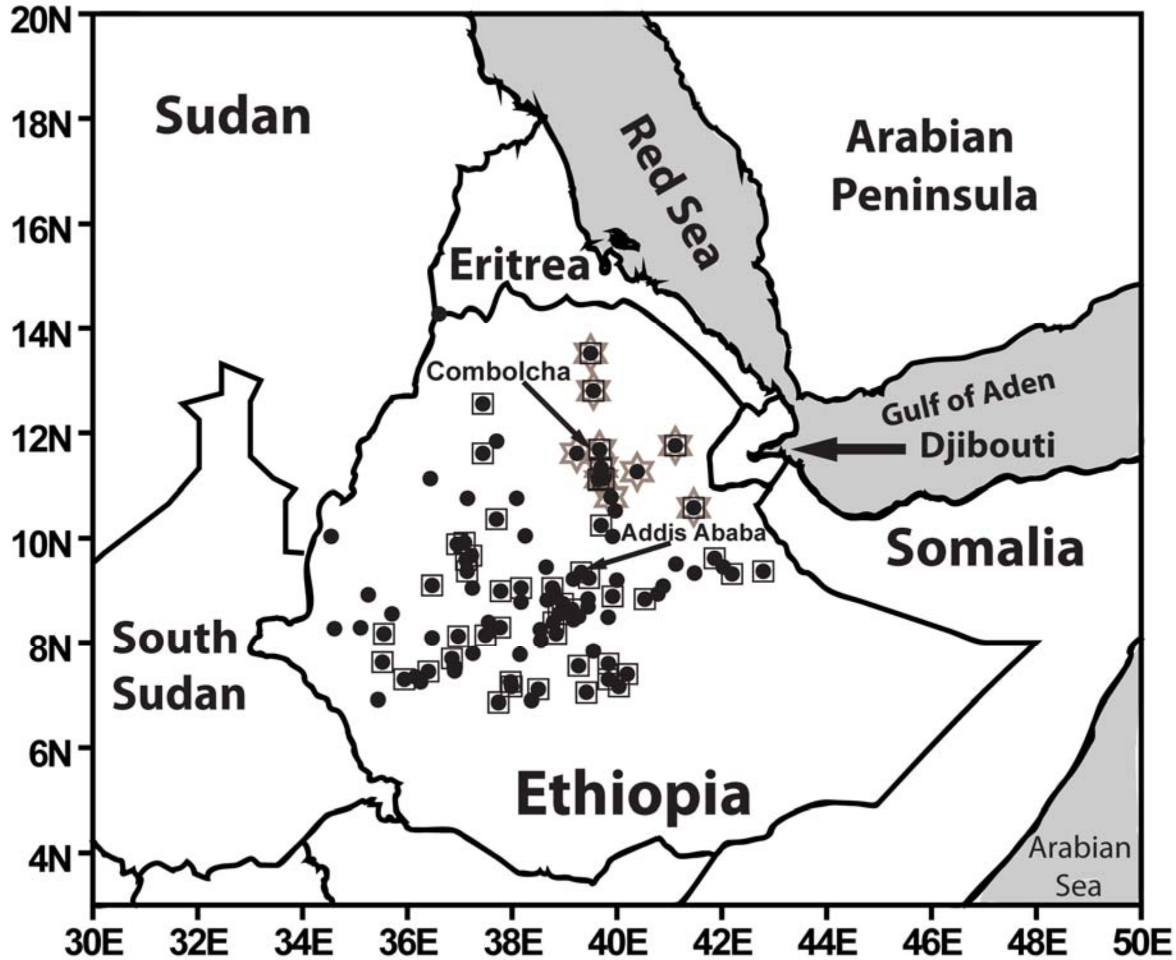

Fig. 1. Regional map showing locations of 100 Ethiopian raingauge stations (solid circles) with data for 1970-1999. Boxes enclose 52 stations for which 2000-2002 data were added to those for 1970-1999 to extend use of the retroactive verification (RV) and leave-one-out cross-validation (LOOCV) methods for all-Ethiopian June-September rainfall anomaly prediction through 2002. Stars locate 11 northeastern Ethiopia stations with 1970-1999 data, with collocated 7 boxes added to extend use of LOOCV for northeastern Ethiopia regional prediction of June-September rainfall anomaly through 2002. Thin arrows locate Addis Ababa and Combolcha, which were used for local August rainfall total prediction for 1970-1999 using the LOOCV approach.

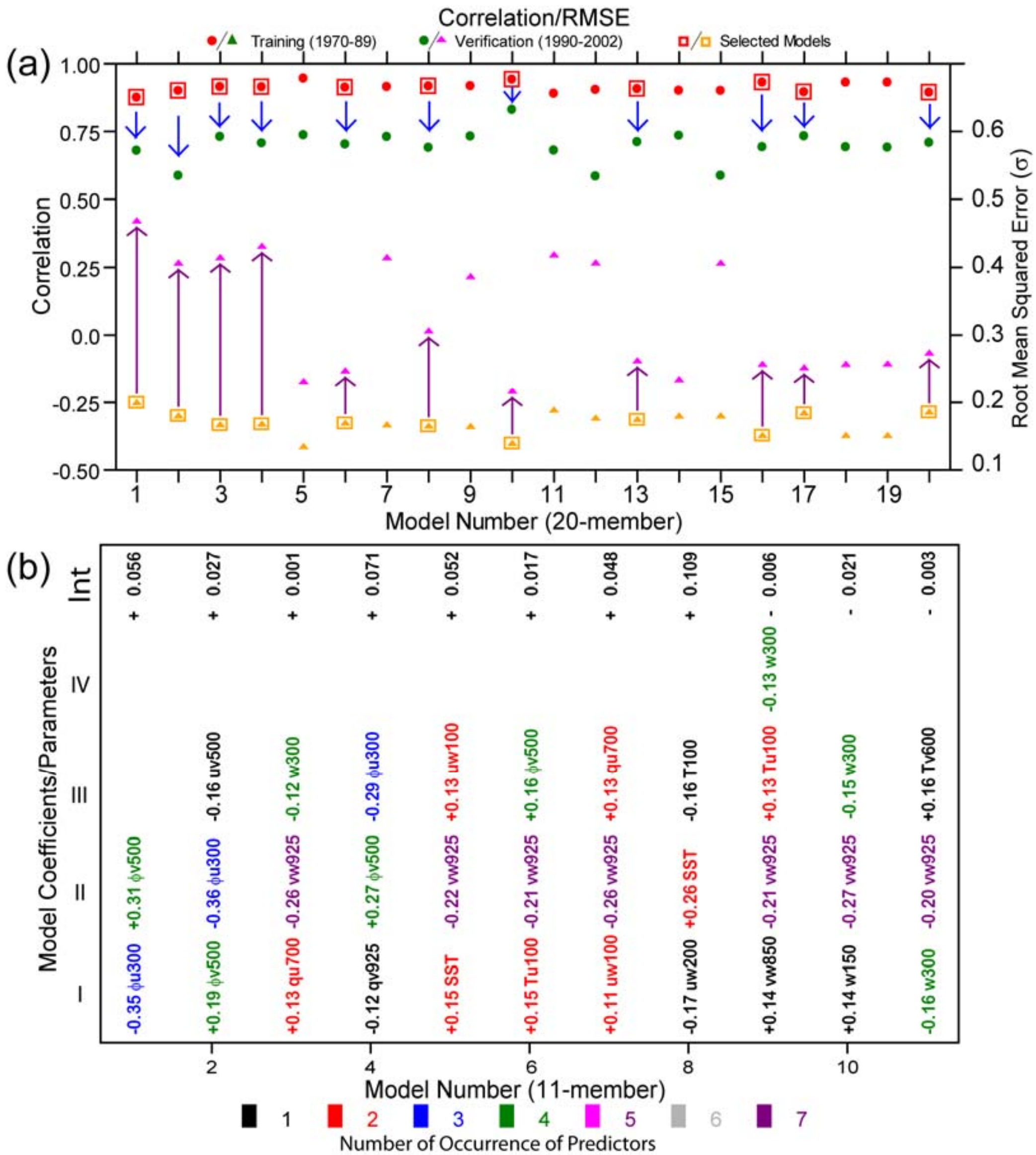

Fig. 2. Retroactive verification (RV) of model performance initiated from average March atmospheric and SST conditions. (**a**) Correlations/root mean squared errors (RMSEs) between predicted and observed Kiremt (JJAS) standardized all-Ethiopian (Fig. 1, 100 stations for 1970-1999, solid circles; 52 stations for 2000-2002, squares) rainfall anomalies are shown for the 1970-1989 training (red/orange) and 1990-2002 independent verification (green/magenta) periods for each of the initial 20 regression models (model sequence number along abscissa). Red/orange squares show 11 models that were selected as final ensemble members, with blue (purple) arrows indicating the decreased (increased) correlations (RMSE) between their predicted values and observations for 1990-2002 independent verification period. (**b**) Regression equations for the final 11-member multi-model ensemble (abscissa) and the frequency of occurrence of March predictors (color coded at bottom). The ordinate shows model coefficients/parameters, with numerals I-IV giving the order of predictor (ϕu, ϕv, uv, w, qu, qv, vw, uw, T, Tu) appearances in that model and the three digit numbers following predictor names giving the pressure levels (hPa) of the variables.

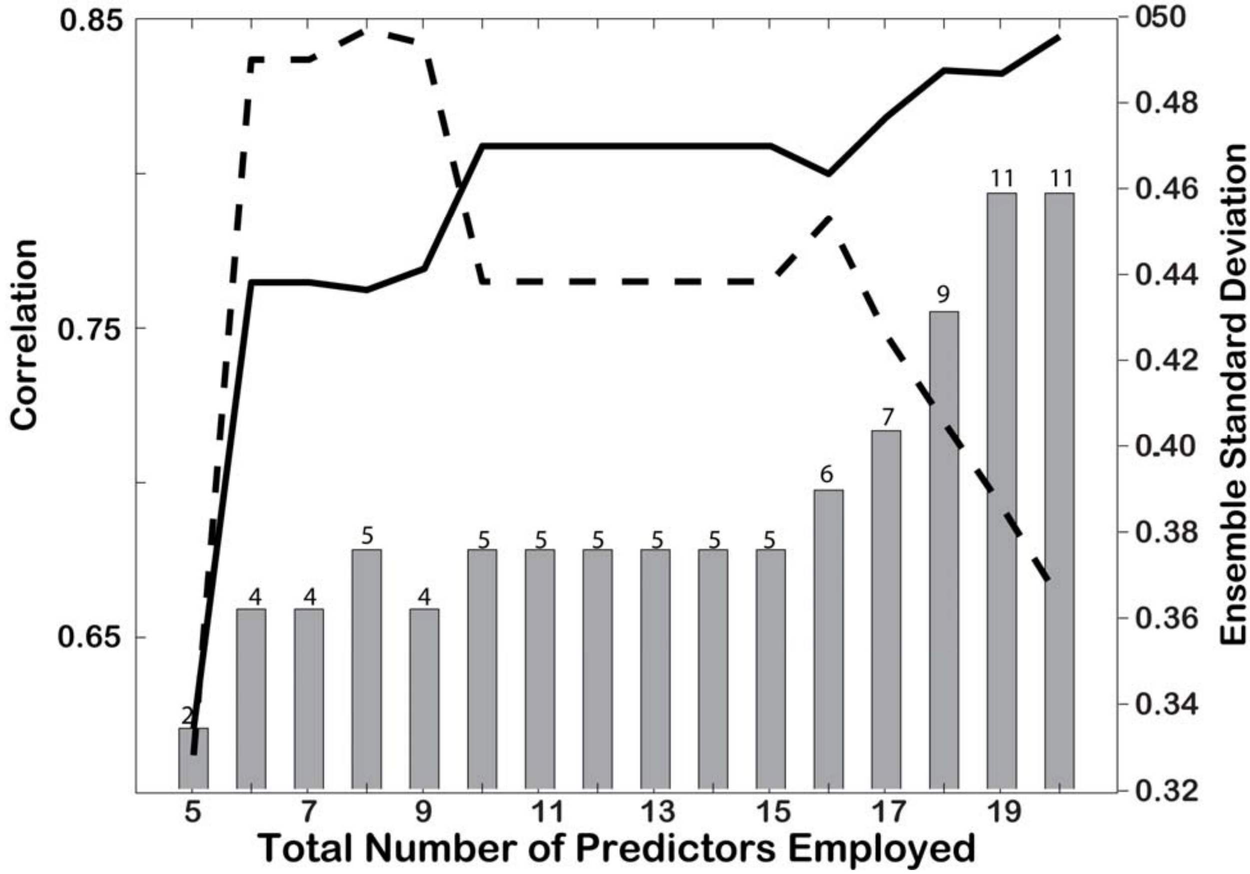

Fig. 3. Sensitivity of cross-validated model performance to ensemble size. Correlation between observed and ensemble predicted (solid black line, left axis) and ensemble mean standard deviation (dashed line, right axis) for two-month lead-time prediction of standardized all-Ethiopian (Fig. 1, 100 stations for 1970-1999, solid circles; 52 stations for 2000-2002, squares) rainfall anomalies for 1990-2002 using retroactive verification (RV) approach as a function of the total number of predictors (abscissa) used in developing models. Vertical bars (values given on top of each bar) show corresponding final ensemble size for each simulation. The first final model ensemble (2) was developed from 5-member predictor set, while the last final ensemble (11) was developed from 20 initial predictor set.

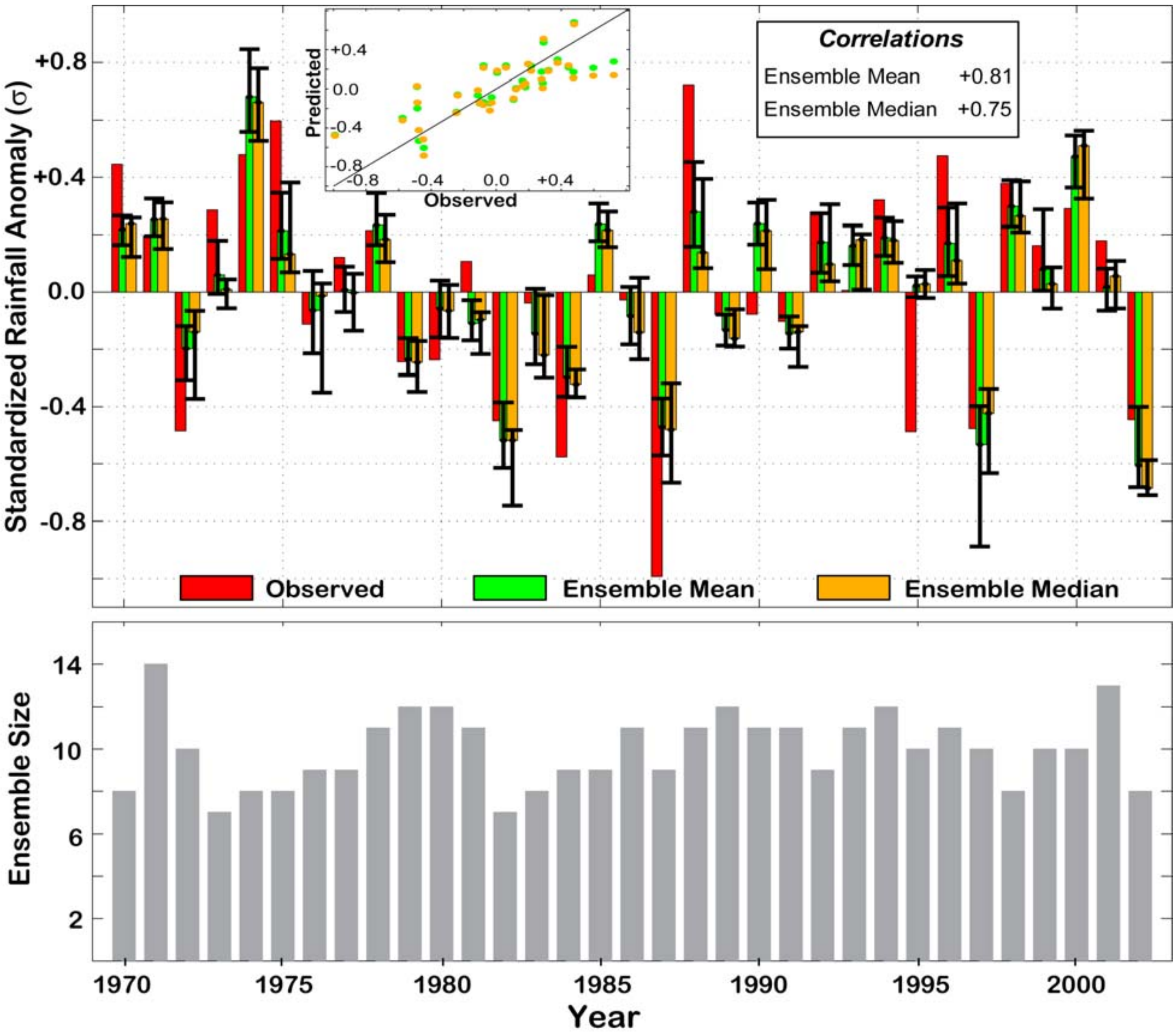

Fig. 4. Two-month lead time prediction of standardized all-Ethiopian (Fig. 1, 100 stations for 1970-1999, solid circles; 52 stations for 2000-2002, squares) Kiremt (JJAS) rainfall anomalies for 1970-2002 using a leave-one-out cross validation (LOOCV) approach that was initiated from average March atmospheric and SST conditions. ***Top***: Time series of observed (red) versus mean (green) and median (orange) of ensemble model-predicted Kiremt rainfall anomalies. Inset shows corresponding scatter diagram of observed versus ensemble-predicted mean (green) and median (orange). ***Bottom***: Number of final ensemble model members selected. Black vertical bars in top panel give 95% confidence intervals for the final multi-model predicted values, computed by applying the bootstrap bias-corrected and accelerated (BCa) method.