ASSESSMENT OF SELECTED GLOBAL MODELS IN SHORT RANGE FORECASTING OVER WEST AFRICA: CASE STUDY OF SENEGAL

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Abstract

Severe weather events in West Africa are associated mainly with meso-scale thunderstorms and squall lines. Forecasting such severe weather to reduce the risk of hazards is one of the challenges faced by many met services. However, the recent progress in the area of numerical weather prediction has enabled some countries to forecast these events in a better way.

Due to lack of capacity, many of the West African countries were not able to use numerical weather prediction systems effectively in their day to day forecasting activities. The CPC/African Desk has been playing big role in building the capacities of the African Meteorological Services. Apart from the regular training activities organized by the Desk, it also hosts useful weather and climate information and products on a dedicated website.

Numerical weather prediction products require verifications in time and space before they are factored into decision making activities. In this work, attempt was made to perform a diagnostic and prognostic analysis with respect to three heavy rainfall events that occurred across Senegal and the neighboring areas during August 2011. We report the results of various verification statistics. The report also contains inter-comparison studies using selected Global models (ECWMF, GFS, UKMET) and attempts to evaluate the strengths and weaknesses of each model with respect to the three rainfall events.

In general, the results of this study show that the deterministic models were able to capture the patterns of the West African Monsoon with respect to the GDAS analysis. In addition, the skill scores for probabilistic rainfall forecasts (10mm and 20mm threshold values) indicated significantly high values (RPSS as high as 0.5 and BSS as high as 0.7) of rainfall mainly for the 10mm and 20mm probability forecasts. Thus, the results of this preliminary work indicate the importance of the use of ensemble forecast system in West Africa.
I. Introduction

The Sahel region is dominated by dry conditions for most of the year, with a single peak in rainfall during the summer June-October. The severe weather events in this region are mainly associated with thunderstorms and squall lines. Forecasting this severe weather to reduce the risk of hazards is one of the challenges faced by many met services. On the other hand, the recent progress of the numerical weather prediction worldwide has improved the ability of some countries to forecast these events. However, in West Africa, the lack of the observations data and lack of interest in the numerical prediction activities have contributed to weather prediction related problems.

Verification activities are useful only if they lead to some decisions regarding the product being verified (Stanski et al. 1987). Accordingly, the NOAA/CPC African Desk in general, and the National Meteorological Services of Africa attempt to provide quality information and products to their users for the benefit of the society. Feedback from users will make the Met Services to improve their products accordingly. Forecast verification studies play the greater role in improving the products of Met Services.

Scientific forecast verification involves answering questions about spatial or temporal variations of the model to provide information that can be fed back to model developers to improve the model or to forecasters on how to modify the guidance. Case studies are an extreme example of verification of this type: a single case or event is chosen for detailed analysis in an attempt to reveal the strengths and limitations of the model’s simulation of the structure and evolution of the storm. In this study, we have selected three cases of extremes rainfall events: August 8, 2011, August 18, 2011 and August 21, 2011.

The purpose of this work is to make diagnostic and statistical studies of the three global model systems (ECWMF, UKMET and GFS), evaluate their performance with respect to using them in the operational weather forecasts over Senegal and West Africa. Identifying strengths and weaknesses of the models so as to make appropriate adjustments to the products is another goal of
this work. The study also enables us to identify research problems that require further investigation with more data and resources.

II. Data and Methods

1. Data
A brief description of the configuration of all three models and the GDAS Analysis is presented in this chapter.

1.1. GDAS
The National Weather Service's National Centers for Environmental Prediction (NCEP) runs a series of computer analyses and forecasts operationally. One of the operational systems is the Global Data Assimilation System, which uses the spectral Medium Range Forecast model (MRF) for the forecast.

The 6-hourly archive data come from NCEP's GDAS. The GDAS is the final run in the series of NCEP operational model runs; it therefore is known as the Final Run at NCEP and includes late arriving conventional and satellite data. It is run 4 times a day, i.e., at 00, 06, 12, and 18 UTC. Model output is for the analysis time and a 6-hour forecast. Some fields such as precipitation and surface fluxes are only available at the forecast time.

The GDAS has 0.5x0.5 data resolution. The GDAS data were obtained through the NCEP portal.

1.2. GFS Model
The GFS model is run by the US National Weather Service. Its data resolution was selected at 0.5 x 0.5 and 1.0 x 1.0 for verification and comparison analysis over the specified domain. Model data are obtained from the NCEP-CPC data facility. Ensemble probabilistic verification of the model was conducted based on the available ensemble members. In this study, GEFS had 20 members involved in the inter-comparison of the forecasting systems. The Data resolution for the ensemble model is 1.0 x 1.0. Probabilities were obtained based on the ensemble outputs by setting threshold values. The ensemble verification was done using
gridded observations methodology (model oriented approach) on a 1.0 x 1.0 grid resolution. The GEFS data were obtained from TIGGE portal.

1.3. ECWMF Model

The ECWMF model is run by the European Center. Its data resolution was selected at 0.25 x 0.25 and 1.0 x 1.0 for verification and comparison analysis over the specified domain. Ensemble probabilistic verification of the model was conducted based on the available ensemble members. In this study, ECWMF had 50 members involved in the inter-comparison of the forecasting systems. The Data resolution for the ensemble model is 0.25 x 0.25. Probabilities were obtained based on the ensemble outputs by setting threshold values. The ensemble verification was done using gridded observations methodology (model oriented approach) on a 10 x10 grid resolution. The ECWMF model data were obtained from TIGGE portal.

1.4. UKMET Model

The UKMET Model is run operationally, in a number of configurations, for weather forecasting at the Met Office. Table1 shows he Model characteristics. Ensemble probabilistic verification of the model was conducted based on the available ensemble members. In this study, UKMET model had 23 members involved in the inter-comparison of the forecasting systems. The Data resolution for the ensemble model is 0.50 x 0.50. Probabilities were obtained based on the ensemble outputs by setting threshold values. The ensemble verification was done using gridded observations methodology (model oriented approach) on a 10 x10 grid resolution. Both deterministic and ensemble forecasts were obtained from TIGGE portal.
Table 1: Characteristics of the UKMET global model

<table>
<thead>
<tr>
<th>Model</th>
<th>Grid length in mid-latitudes</th>
<th>Grid points</th>
<th>Vertical levels</th>
<th>Forecast length</th>
<th>Run times (UTC)</th>
<th>Initial conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global</td>
<td>25 km</td>
<td>1024 x 769</td>
<td>70 (lid ~80 km)</td>
<td>144 hrs. (for 00z and 12z)</td>
<td>00, 06, 12, 18 hrs.</td>
<td>Hybrid Incremental 4D-Var with MOGREPS Ensemble</td>
</tr>
</tbody>
</table>

1.5. **RFE**

RFE version 2.0 has been implemented by NOAA's Climate Prediction Center. Created by Ping-Ping Xie, this replaces RFE 1.0, the previous rainfall estimation algorithm that was operational from 1995 through 2000. RFE 2.0 uses additional techniques to better estimate precipitation while continuing the use of cloud top temperature and station rainfall data that formed the basis of RFE 1.0. Meteosat 7 geostationary satellite infrared data is acquired in 30-minute intervals, and areas depicting cloud top temperatures of less than 235K are used to estimate convective rainfall. WMO Global Telecommunication System (GTS) data taken from ~1000 stations provide accurate rainfall totals, and are assumed to be the true rainfall near each station. RFE 1.0 used an interpolation method to combine Meteosat and GTS data for daily precipitation estimates, and warm cloud information was included to obtain dekadal estimates. The RFE has 0.1x0.1 data resolution. The RFE data were obtained from the NCEP-CPC facility.

1.6. **Gauge Observation**

The Senegal Meteorological Service (ANAMS) administers a number of synoptic and climatological stations nationwide. Rainfall from about 48 stations was obtained from the ANAMS in this study.
1.7. African Rainfall Climatology (ARC)

Forecast skill refers to the relative accuracy of a set of forecasts, with to some set of standard control, or reference, forecasts. Common choices for the reference forecasts are climatological average values of the predictand, persistence forecasts (values of the predictand in the previous time period), or random forecasts (with respect to the climatological relative of the forecast events) (Wilks, 1995).

The CPC/FEWS African Climatology (ARC) is used as reference data for computing probabilistic skill scores.

2. Method

2.1 Diagnostics

Before using the pertinent parameters (figure 2) and the time which will be analyze, an exhaustive diagnostic is done for all the patterns at every 6 hour the day of the event (00h, 06h 12h 18h 24h 30h). This diagnostic suggest taking the MSLP, The streamlines 925hpa and the dew point, the divergence at 925 and 200hpa, the moisture flux, the vorticity at 700hpa and the wind at 500hpa. The time where we notice some significant changes is the 18h. According to the literature and what we know about the tropical meteorology, it is reasonable.

Figure 2: GDAS Analysys for 00, 06, 12, 18, 00, 06Z; left to right MSLP (barb indicates wind 10m and shading indicates pressure), divergence (shading indicates divergence at 925hpa and contour indicates divergence at 200hpa), moisture flux (barb indicates wind direction and shading indicates magnitude), and Wind500hpa (barb indicates wind direction and shading indicates magnitude).
2.2 Skills and scores

The scores available through the WMO website is listed below including their characteristics.

2.2.1 Mean Error

\[
\text{Mean Error} = \frac{1}{N} \sum_{i=1}^{N} (F_i - O_i)
\]

**Answers the question:** What is the average forecast error?

The mean range to infinite and score of 0 implies a perfect forecast.

**Characteristics:** Simple, familiar. It does not measure the magnitude of the errors. Does not measure the correspondence between forecasts and observations, i.e., it is possible to get a perfect score for a bad forecast if there are compensating errors.

2.2.2 Root mean square error

\[
\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (F_i - O_i)^2}
\]

**Answers the question:** What is the average magnitude of the forecast errors?

The RMSE range from 0 to infinite to infinite and a score of 0 indicates perfect forecast.

**Characteristics:** Simple, familiar. Measures "average" error, weighted according to the square of the error. It does not indicate the direction of the deviations. The RMSE puts greater influence on large errors than smaller errors, which may be a
good thing if large errors are especially undesirable, but may also encourage conservative forecasting.

### 2.2.3 Correlation coefficient

\[
    r = \frac{\sum (F - \bar{F})(O - \bar{O})}{\sqrt{\sum (F - \bar{F})^2} \sqrt{\sum (O - \bar{O})^2}}
\]

**Addresses the question:** How well did the forecast values correspond to the observed values?

This score ranges from -1 to 1 and a score of 1 means perfect forecast.

**Characteristics:** Good measure of linear association or phase error. Visually, the correlation measures how close the points of a scatter plot are to a straight line. Does not take forecast bias into account -- it is possible for a forecast with large errors to still have a good correlation coefficient with the observations.

### 2.2.4 Taylor diagrams

To quantify how well models simulate an observed climate field, it is useful to rely on three non-dimensional statistics: the ratio of the variances of the two fields:

\[
    \gamma_2 = \frac{s_2\text{mod}}{s_2\text{obs}}
\]

Is the correlation between the two fields (R, which is computed after removing the overall means), and the r.m.s, difference between the two fields (E, which is normalised by the standard deviation of the observed field). The ratio of variance indicates the relative amplitude of the simulated and observed variations, whereas the correlation indicates whether the fields have similar patterns of variation, regardless of amplitude. The normalized r.m.s error can be resolved
into a part due to differences in the overall means (E0), and a part due to errors in the pattern of variations (E').

These statistics provide complementary, but not completely independent, information. Often the overall differences in means (E0) is reported separately from the three pattern statistics (E', γ, and R), but they are in fact related by the following equation:

\[ E'^2 = E^2 - E0^2 = 1 + \gamma^2 - 2\gamma R \]

This relationship makes it possible to display the three pattern statistics on a two-dimensional plot. The plot is constructed based on the Law of Cosines. The observed field is represented by a point at unit distance from the origin along the abscissa. All other points, which represent simulated fields, are positioned such that \( \gamma \) is the radial distance from the origin, R is the cosine of the azimuthal angle, and E' is the distance to the observed point. When the distance to the point representing the observed field is relatively short, good agreement is found between the simulated and observed fields. In the limit of perfect agreement (which is, however, generally not achievable because there are fundamental limits to the predictability of climate), E' would approach zero, and \( \gamma \) and R would approach unity.

### 2.2.5 Skill score

\[
\text{Skill score} = \frac{\text{score}_{\text{forecast}} - \text{score}_{\text{reference}}}{\text{score}_{\text{perfect forecast}} - \text{score}_{\text{reference}}}
\]

**Answers the question:** What is the relative improvement of the forecast over some reference forecast?

Lower bound depends on what score is being used to compute skill and what reference forecast is used, but upper bound is always 1; 0 indicates no improvement over the reference forecast. Perfect score: 1.
Characteristics: Implies information about the value or worth of a forecast relative to an alternative (reference) forecast. In meteorology the reference forecast is usually persistence (no change from most recent observation) or climatology. The skill score can be unstable for small sample sizes. When MSE is the score used in the above expression then the resulting statistic is called the reduction of variance.

### 2.2.6 Brier score

\[
BS = \frac{1}{N} \sum_{i=1}^{N} (p_i - o_i)^2 - \frac{1}{N} \sum_{k=1}^{K} n_k (p_k - \bar{o}_k)^2 - \frac{1}{N} \sum_{k=1}^{K} n_k (\bar{o}_k - \bar{o})^2 + \bar{o}(1 - \bar{o})
\]

Answers the question: What is the magnitude of the probability forecast errors?

It measures the mean squared probability error. Murphy (1973) showed that it could be partitioned into three terms: (1) reliability, (2) resolution, and (3) uncertainty.

The Brier Score ranges from 0 to 1 and 0 means perfect score.

Characteristics: Sensitive to climatological frequency of the event: the more rare an event, the easier it is to get a good BS without having any real skill. Negative orientation (smaller score better) - can "fix" by subtracting BS from 1.

### 2.2.7 Brier skill score

\[
BSS = \frac{BS - BS_{\text{reference}}}{0 - BS_{\text{reference}}} = 1 - \frac{BS}{BS_{\text{reference}}}
\]

Answers the question: What is the relative skill of the probabilistic forecast over that of climatology, in terms of predicting whether or not an event occurred?
The BSS ranges from infinite to 1, and 0 indicates no skill when compared to the reference forecast, and 1 indicates perfect score.

**Characteristics:** Measures the improvement of the probabilistic forecast relative to a reference forecast (usually the long-term or sample climatology), thus taking climatological frequency into account. Not strictly proper. Unstable when applied to small data sets; the rarer the event, the larger the number of samples needed.

### 2.2.8 Ranked probability score

\[
RPS = \frac{1}{M-1} \sum_{m=1}^{M} \left[ \left( \sum_{k=1}^{M} p_{k}^{m} \right) - \left( \sum_{k=1}^{M} o_{k}^{m} \right) \right]^{2}
\]

where \( M \) is the number of forecast categories, \( p_{k}^{m} \) is the predicted probability in forecast category \( k \), and \( o_{k}^{m} \) is an indicator (0=no, 1=yes) for the observation in category \( k \).

**Answers the question:** How well did the probability forecast predict the category that the observation fell into?

The RPS ranges from 0 to 1, and 0 implies a perfect score.

**Characteristics:** Measures the sum of squared differences in cumulative probability space for a multi-category probabilistic forecast. It penalizes forecasts more severely when their probabilities are further from the actual outcome. Negative orientation - can "fix" by subtracting RPS from 1. For two forecast categories the RPS is the same as the Brier Score.

### 2.2.9 Ranked probability skill score

\[
RPSS = \frac{RPS - RPS_{\text{reference}}}{0 - RPS_{\text{reference}}} = 1 - \frac{RPS}{RPS_{\text{reference}}}
\]
**Answers the question:** What is the relative improvement of the probability forecast over climatology in predicting the category that the observations fell into?

The RPSS ranges from infinite to 1, 0 indicates no skill when compared to the reference forecast and 1 means perfect score.

**Characteristics:** Measures the improvement of the multi-category probabilistic forecast relative to a reference forecast (usually the long-term or sample climatology). Strictly proper, it takes climatological frequency into account. Unstable when applied to small data sets.

2.2.10 Multi-category Contingency Table

Quantitative statistical analysis of the model in predicting occurrence of the event was done using a non-parametric skill score following (Wilks, 1995, Hanssen Kuiper, 1965) methodology. The analysis was decomposed categorically for a number of precipitation thresholds forecasts and observations. This methodology was chosen because of its suitability for this kind of verification and often Forecasters conceptually interpret model output in a similar way. Moreover the methodology avoids penalization of the model for the forecasts that are not exact but can be considered approximately correct and useful.

The skill scores are summarized using a Spatial Mult-Category Contingency Table for a range of thresholds on the forecasts resulting into multiple categories to each forecast. For a range of K thresholds on the forecasts then the frequency of forecasts and observations in the various windows can be summarized in a contingency table (See table 1). Where n(Fi,Oj) denotes the number of forecasts in category i that had observation in category j, and the total number of the forecasts in category i is given by N(Fi). N(Oj) denotes the total number of observations in category j and N is the total number of forecasts.
Using this methodology a perfect forecast system (model) would have non-zero elements along the diagonal and zero values entries elsewhere. The off-diagonal entries provide some information on the specific nature of the model forecast errors (Murphy et al. 1987) and (Brooks and Doswel, 1996).

To determine the fraction of the forecast that was in the correct category the formula for accuracy was applied.

\[
\text{Accuracy} = \frac{1}{N} \sum_{i=1}^{K} n(F_i, O_i)
\]

**Answers the question:** Overall, what fraction of the forecasts was in the correct category?

The accuracy ranges from 0 to 1 and 1 indicates perfect score.
**Characteristics**: Simple, intuitive. It can be misleading since it is heavily influenced by the most common category.

### 2.2.11 Heidke skill score

\[
HSS = \frac{1}{N} \sum_{i=1}^{k} n(F_i, O_i) - \frac{1}{N^2} \sum_{i=1}^{k} N(F_i)N(O_i) \\
1 - \frac{1}{N^2} \sum_{i=1}^{k} N(F_i)N(O_i)
\]

**Answers the question**: What was the accuracy of the forecast in predicting the correct category, relative to that of random chance?

The HSS ranges from infinite to 1, 1 indicates perfect score.

**Characteristics**: Measures the fraction of correct forecasts after eliminating those forecasts which would be correct due purely to random chance. This is one form of a generalized skill score, where the score in the numerator is the number of correct forecasts, and the reference forecast in this case is random chance. It requires a large sample size to make sure that the elements of the contingency table are all adequately sampled. In meteorology, at least, random chance is usually not the best forecast to compare to - it may be better to use climatology (long-term average value) or persistence (forecast is most recent observation, i.e., no change) or some other standard.
III. Analysis and Discussions

1. Rainfall Validation

As mentioned, 48 stations gauge rainfall were used to be compared with the RFE. Figure 1 shows the temporal distribution of those data. It indicates that the RFE and the gauge data rainfall are well correlated. However, the RFE underestimates the rainfall in some areas. Thus, the RFE are used to compute the skills and scores of the rainfall.

![Figure 1: Comparison between Gauge rainfall data and RFE](image)

2. Eyeball Verification for Rainfall

One of the oldest and best verification methods is the good old fashioned visual, or "eyeball", method: look at the forecast and observations side by side and use human judgment to discern the forecast errors. Common ways to present data are as time series and maps. Here we show the maps of the RFE rainfall (observed) and the forecasts (ECWMF, GFS and UKMET). Both deterministic and probabilistic forecasts are shown for 24H, 48H and 72H. Figure 2 & 3 indicate that deterministic models have a bad correlation with the observed. Unlike deterministic, the ensemble forecasts have the same pattern than the observations, mainly for the 10mm and 20mm probability forecasts (figure 4).
Figure 2: Rainfall observed against deterministic forecasts for GFS, ECWMF and UKMET case A, August 08, (Top left, 24H; top right, 48H and bottom left 72H).
Figure 3: Rainfall observed against deterministic forecasts for GFS, ECWMF and UKMET case C, August 21, (Top left, 24H; top right, 48H and bottom left 72H).
Figure 4: Rainfall observed against probabilistic forecasts for GEFS, ECWMF and UKMET case C, August 21, (Top left, 24H; top right, 48H and bottom left 72H).
3. Dynamics

Generally, all the three deterministic (figure 5, 6 & 7) models have the same path for almost of the variables. Hence, the difference among the GDAS and the dew point is between negative two and positive two for the three events. The systematic error in figure 6 indicates that clearly UKMET and GFS models feature positive bias which means they underestimate the low over the Sahel. The three models seem to overestimate the moisture flux, but the behavior of the models is acceptable for all of them. The convergence line at surface between southerly and northerly winds, the strong gradient of the dew point and the Heat Low allow us to delimited the ITZ for all the three models. In addition, the vorticity shows an axis of the trough oriented north-south and corresponds to the maximum curvature of the winds at 700 hPa. The three models are in general able to forecast theses vorticities.

On the other hand, the convergence of the three models for the event of August 3, 2011 has a strong difference from the GDAS. This case shows again the difficulty for the models to predict such event. For remind, the Ziguinchor station has reported 200mm for the 24hour.

The three deterministic models and the GDAS show very big resemblances for all of the parameters, except for event of local event. The ECWMF is the one which have the most resemblance.

![Figure 5: Case A 08/08/11: GDAS Analysis, ECWMF, GFS, and UKMET forecast at 18Z, top: left to right MSLP (barb shows wind 10m and shading indicates difference between model to GDAS pressure), wind 925hpa, vorticity, bottom: left to right moisture flux, divergence (shading indicates divergence at 925hpa and contour shows divergence at 200hpa), and wind 500hpa.](image-url)
Figure 6: Case B 08/18/11: GDAS Analysis, ECWMF, GFS, and UKMET forecast at 18Z, top: left to right MSLP (barb shows wind 10m and shading indicates difference between model to GDAS pressure), wind 925hpa, vorticity, bottom: left to right moisture flux, divergence (shading indicates divergence at 925hpa and contour shows divergence at 200hpa), and wind 500hpa.

Figure 7: Case C 08/21/11: GDAS Analysis, ECWMF, GFS, and UKMET forecast at 18Z, top: left to right MSLP (barb shows wind 10m and shading indicates difference between model to GDAS pressure), wind 925hpa, vorticity, bottom: left to right moisture flux, divergence (shading indicates divergence at 925hpa and contour shows divergence at 200hpa), and wind 500hpa.
4. Skill and scores for precipitation

As we can see in the figure 8, the taylor diagrams show a slight correlation between the forecasts and observations and big jumpiness of models among 24h, 48h and 72h. The contingence table (table3) establishes that the accuracy is 0.36 but the skill relative to Heidke score is around 0.

Concerning the probabilistic forecasts, the Rank probability skill score computed clearly indicates a good score (0.5), even for the 72hour forecast. Although, the predictability for the case A (August, 8, 2011, small scale) (figure 7) is very hard. The Brier Skill score establishes that all the three models show a very good score (0.70) for the probability of 10mm and 20mm rainfall. However, the skill is low for the big values (extreme events). The multi-ensemble forecast features a good skill score but not pretty much than the ensemble model.

![Taylor diagrams for 24h, 48h and 72h for Case A, B and C.](image)

Figure 8: Taylor diagrams for 24h, 48h and 72h for Case A, B and C.

![Rank Probability skill score for 24h, 48h and 72h for Case A, B and C.](image)

Figure 9: Rank Probability skill score for 24h, 48h and 72h for Case A, B and C.
IV. Conclusion

This study uses the objective and subjective tools to evaluate the models (GFS, UKMET, ECWMF) forecasts over west Africa. It allows us to make some remarks. Indeed, the behavior of the GDAS and models shows the flow crossing the southern part and the convergence activities which are a typical characteristic of the African Monsoon. The deterministic models indicate well captured monsoon with very similar patterns to the GDAS. The systematic error for the rainfall shows a dry bias for all the models. Score probabilistic rainfall forecasts clearly indicates
near perfect forecast (RPSS~0.5, BSS~0.7) of rainfall mainly for the 10mm and 20mm probability forecasts. However, the predictability of the small scale and extreme events remain still hard for the models. The jumpiness of the models for day1, day2 and day3 is not stable for the deterministic forecasts but the scores slightly increase through the day forecast.

This work suggests the use of the probabilistic forecasts to make more reliable forecasts over West Africa. The NHMS can build a numerical weather prediction reduce the risk of hazards. However, the three cases events are not enough to make rigorous conclusions and bring consistency.

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