ECMWF System 4 forecasts for Malaria in Senegal

This analysis employs the European Centre for Medium Range Weather Forecasting (ECMWF) System 4 hindcast ensemble of 15 members starting on the 1st of every month for the years 1981-2010, and run for 7 months. The system consists of an initial ocean analysis to estimate the initial state of the ocean and a global coupled ocean-atmosphere general circulation model to calculate the evolution of the ocean and atmosphere. Daily temperature and precipitation from the System 4 ensemble are then used to drive the Liverpool Malaria Model (LMM), with a one-year spin up period driven by ERA-Interim climatological values for Africa. The output is compared to various sets of gridded climatological products:

- Temperature observations from the Climate Research Unit (CRUT3.1, Mitchell and Jones, 2005) covering the period 1950-2009.
- Mixed satellite and rain gauges observations from the Global Precipitation Climatology Project (GPCP) dataset (Huffman et al, 2001). Monthly values are available for rainfall between 1979 and 2010, however daily values required to drive LMM were only available between 1997 and 2008.
- Mixed satellite and rain gauges observations from the NASA Goddard Space Flight Center Tropical Rainfall Measuring Mission (TRMM) dataset (Huffman et al, 2001) for 1998-2010.
- Temperature and rainfall products based on NCEP-NCAR (1948-2010, Kalnay et al, 1996) and ERA Interim for (ERAI, 1979-2011, Uppala et al, 2008) reanalyses (blend of climate model outputs and various sources of observations using complex assimilation methods).

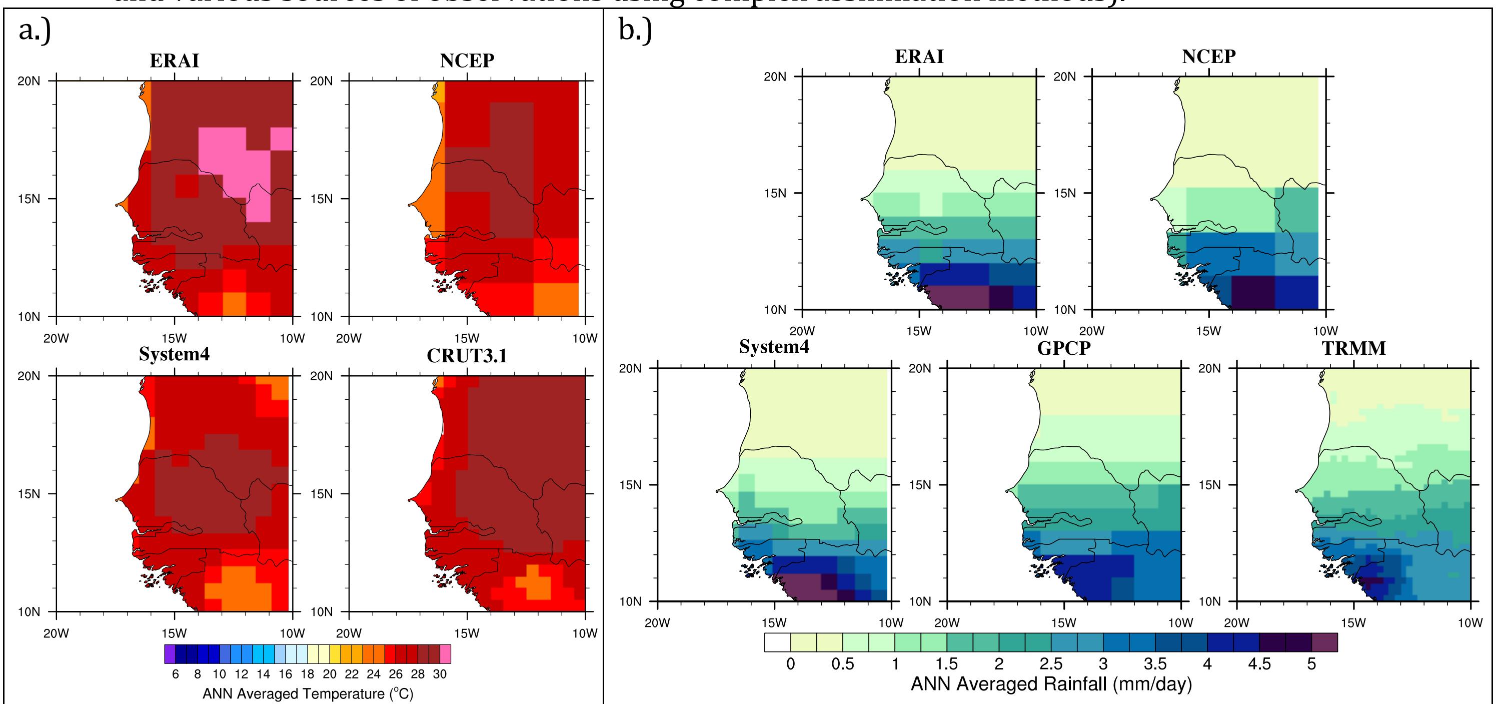


Figure 1: Annual average a.) temperature and b.) precipitation for Senegal. System 4 forecasts take the fourth month forecasted from each start date (see table 1 for explanation).

The annual averages for System 4 (forecast month 4, see table 1 for explanation) compare reasonably well with the climatological values, with cooler coastal temperatures than inland (compare NCEP and System 4 in Fig.1a) there is particularly good agreement compared to the observations (CRUTS) within Senegal, however temperatures in Mauritania are somewhat lower in the forecast particularly compared to ERAI. Annual averaged rainfall is elevated in the south and decreases towards the north of Senegal (Fig.1b). The location of the transitional rain band in the System 4 forecast compares particularly well with ERAI and NCEP but is located approximately 2-3° too far south compared to the hybrid satellite/model climatologies of GPCP and TRMM, where the band is located around 15°N.

The seasonal cycles of temperature and precipitation (Fig.2, averaged exclusively over Senegal) show a distinct pattern of warm temperatures and low rainfall in the first six months of the year, with peak temperatures occurring in AMJ and peak rainfall occurring in JAS, with a reduction in temperature during this season. Rainfall is negligible between November and May, with GPCP and TRMM consistently wetter during the rainy season compared to ERAI and NCEP, particularly during the peak in JAS.

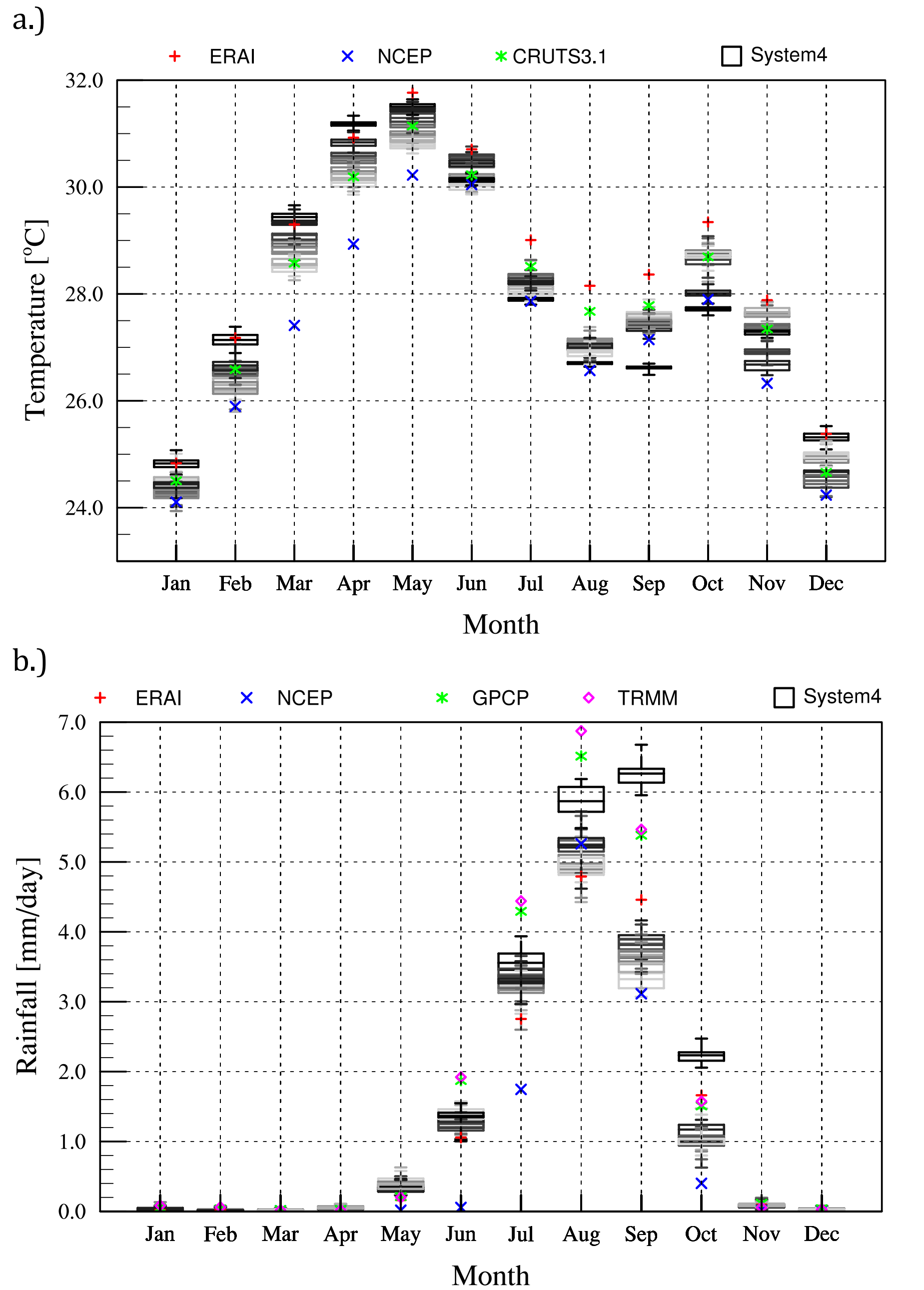


Figure 2: Seasonal cycle of (a.) temperature and (b.) precipitation in Senegal, masked using the Database of Global Administrative Areas (GADMv2.1). System 4 forecasts are shown as box and whisker plots for forecast months 1 to 7 (black – light grey) for the lower tercile, mean and upper tercile values.

There is relatively small spread in System 4 forecast distances of 1 to 7 months from the start date (see Table 1). Notably, System 4 August and September precipitation decreases with forecast month (black to grey boxes), diverging from the average TRMM and GPCP values towards the dry ERAI and NCEP values. This is probably the result of the tropical rain band encroaching further north into Senegal in GPCP and

TRMM compared to the more southern location of the rain belt in ERAI and NCEP, just outside the Senegalese borders.

Table 1: Illustration of the System 4 seasonal forecast scheme. Each System 4 forecast is seven months long, with a start date in each month of the year. The "Forecast month" is the distance in time from the in initial conditions with 1 being the first month of the forecast (same month as the start date) and 7 being the final month of the forecast. To build a timeseries, we chose the value for "Forecast month" and extract that month's data from each start date. For example, for Forecast month = 1, we take Jan from the first start date in 1981, Feb from the second start date in 1981, etc. For Forecast month = 7, we take Jul from the first start date in 1981, Aug from the second start date in 1981, etc. When Forecast month > 1, the timeseries extends into 2011 since the last start date (12) in 2010 gives Dec when Forecast month=1, Jan when Forecast month=2 to Jun when Forecast month=7.

Forecast month	1981												…	2010			2011					
1	J	F	M	A	M	J	J	A	S	O	N	D	…	J	…	D						
2		F	M	A	M	J	J	A	S	O	N	D	…	J	…	D	J					
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
6						J	J	A	S	O	N	D	…	J	…	D	J	F	M	A	M	
7							J	A	S	O	N	D	…	J	…	D	D	F	M	A	M	J

Average JAS distributions of temperature and rainfall (Fig.3) again compare well with the other datasets. ERAI, NCEP and System 4 precipitation transition to drier conditions in the north is again too far south compared to GPCP and TRMM confirming that this is the cause for the discrepancy between the datasets in the annual average and seasonal cycle (Figs.1 and 2).

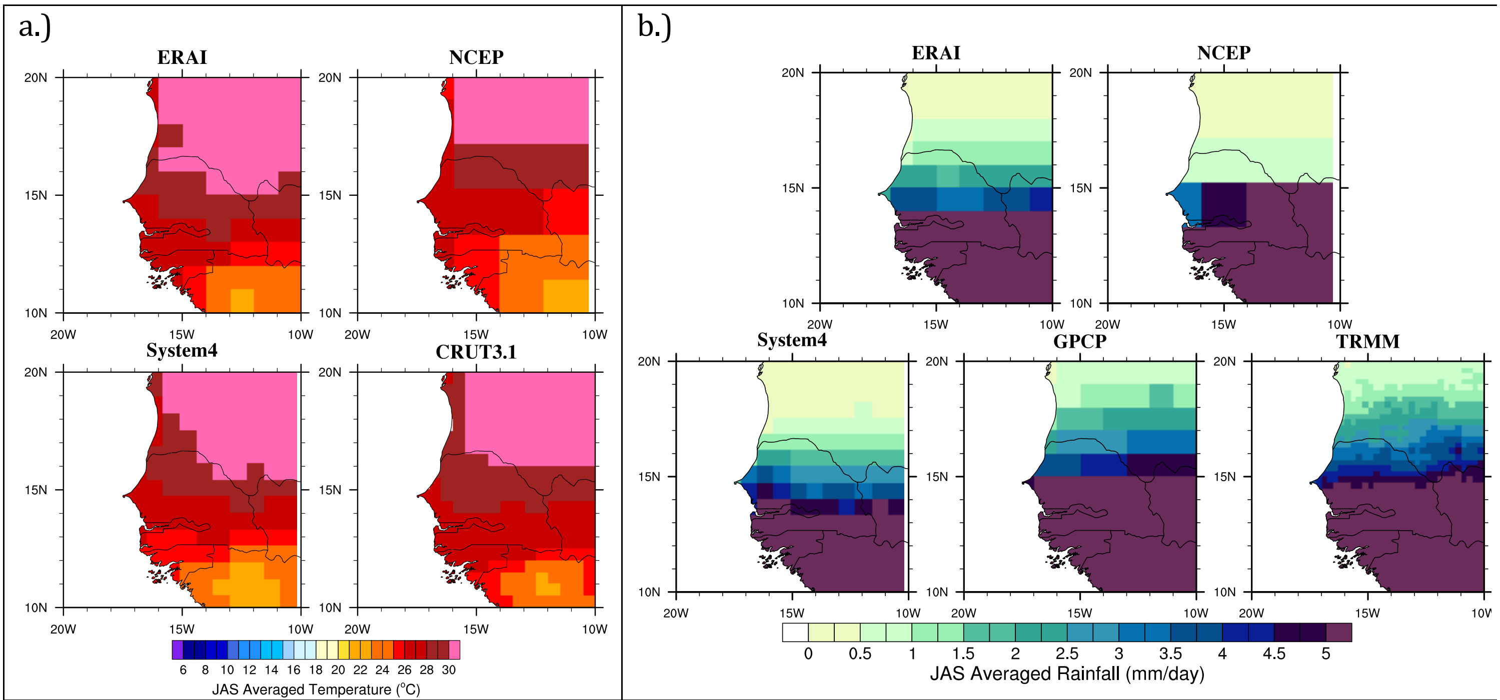


Figure 3: JAS average a.) temperature and b.) precipitation for Senegal. System 4 forecasts use a four-month lead time using March start dates for an JAS target.

The seasonal cycle of malaria in Senegal, simulated by the Liverpool Malaria Model (LMM, Fig.4), is consistently low in the forecast and climatologically-driven malaria incidence between January and August as a result of the arid conditions, particularly before July. Following the JAS precipitation season, there is a rapid rise in malaria incidence in September and October captured by the forecast and climatologies. Associated with the wetter conditions in GPCP and TRMM compared to ERAI, NCEP and System 4 causes the hybrid satellite/rain gauge datasets to produce consistently higher malaria incidence than the climatological reanalyses, although ERAI appears to perform better than NCEP, which never simulates malaria incidences of greater than 25% compared to the ~60% of GPCP and TRMM in October.

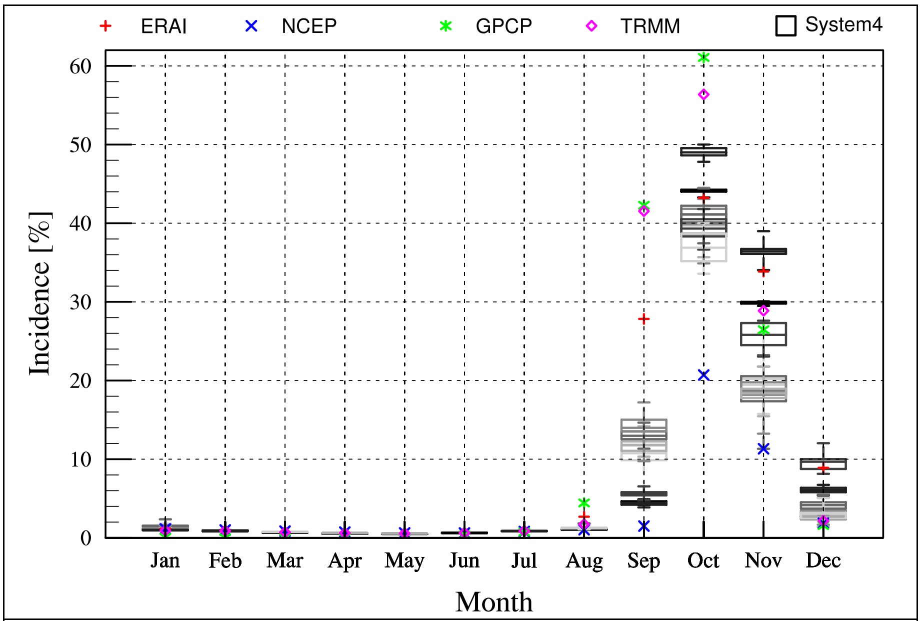


Figure 4: Seasonal cycle of malaria incidence in Senegal, masked using the Database of Global Administrative Areas (GADMv2.0). System 4 forecasts are shown as box and whisker plots for forecast months 1 to 7 (black – light grey) for the lower tercile, mean and upper tercile values.

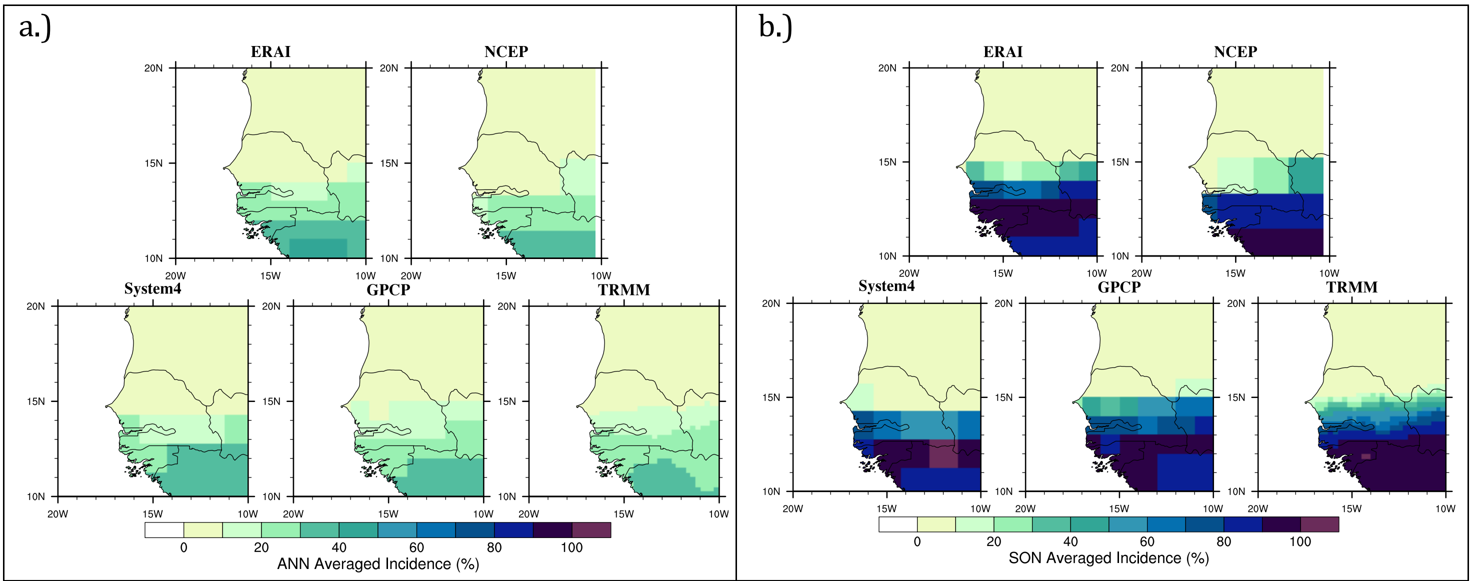


Figure 5: Malaria Incidence a.) annually averaged and b.) averaged over the peak malaria season SON. System 4 forecasts use a four-month lead time using June start dates for an SON target.

The distribution of malaria incidence is comparable across the range of temperature and rainfall products used to drive the model in the annual average (Fig.5a), with elevated average incidence in southern Senegal and Guinea and decreasing towards the north of Senegal. For the SON peak incidence season (Fig.5b), malaria occurrence shows a similar pattern, with peak incidence in the south and low incidence in the north. However, as with JAS peak precipitation (Fig.3b) the transitional band stretching across Senegal is located at roughly 13°N in ERAI, NCEP and System 4 forecasts compared to further north at ~14-15°N in GPCP and TRMM.

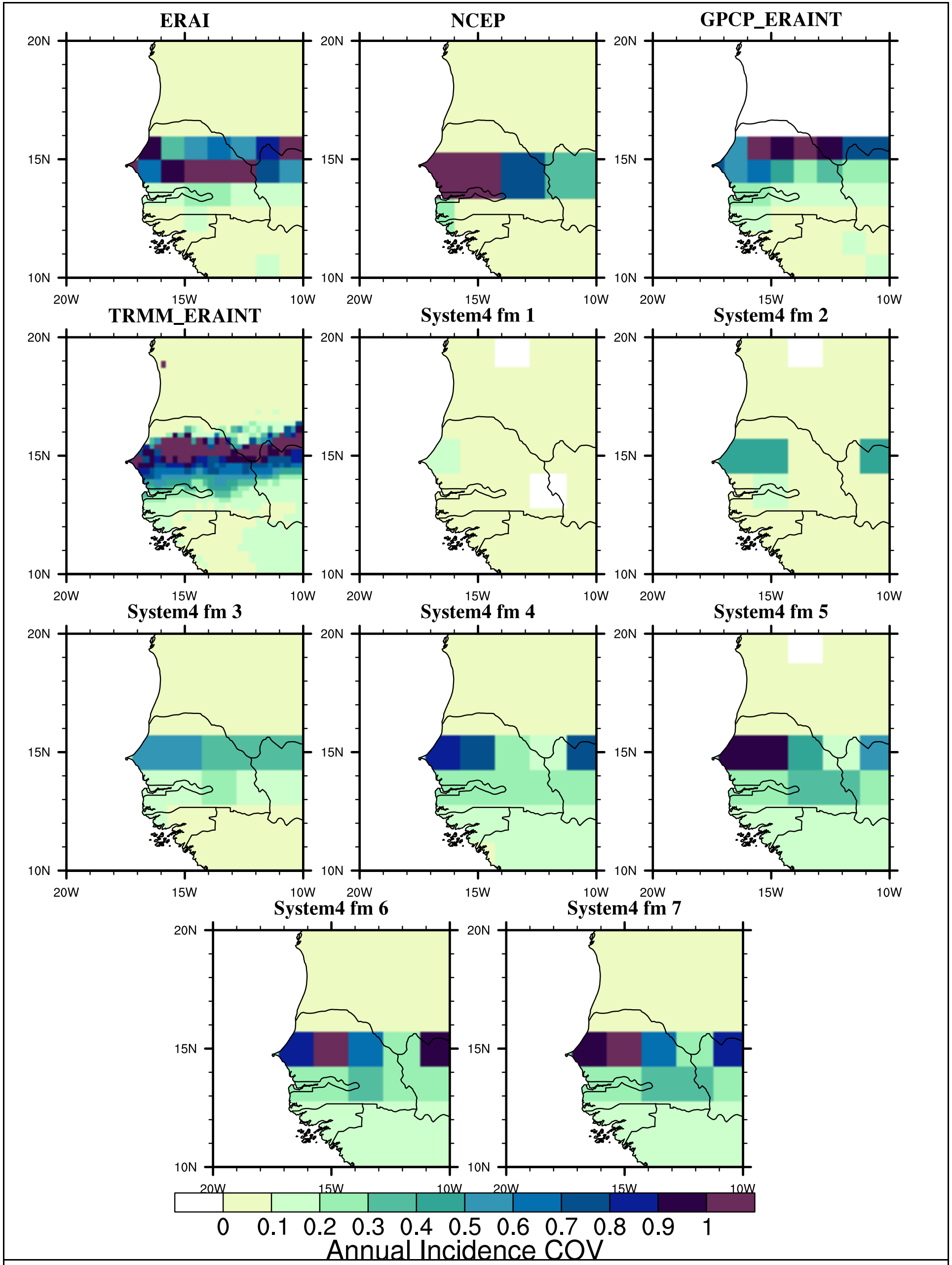


Figure 6: Malaria incidence coefficient of variation (COV) which is the standard deviation divided by the annual mean for the datasets driving LMM. System 4 values are shown for each month of the forecast.

The epidemic fringe in the north of Senegal (Fig.6) is present in all climatological datasets, while System 4 values suggest that long lead times of 4-6 months (forecast months 5-7) capture the high interannual variability of malaria incidence in this region.

The same diagnostic, repeated for only the peak malaria season (SON) with a four month System 4 forecast lead time (in this case, fm 6 represents a June start date) produces a similar result with the epidemic fringe in the north of Senegal highlighted at 15°N in ERAI, NCEP, TRMM, GPCP and System 4 (Fig.7).

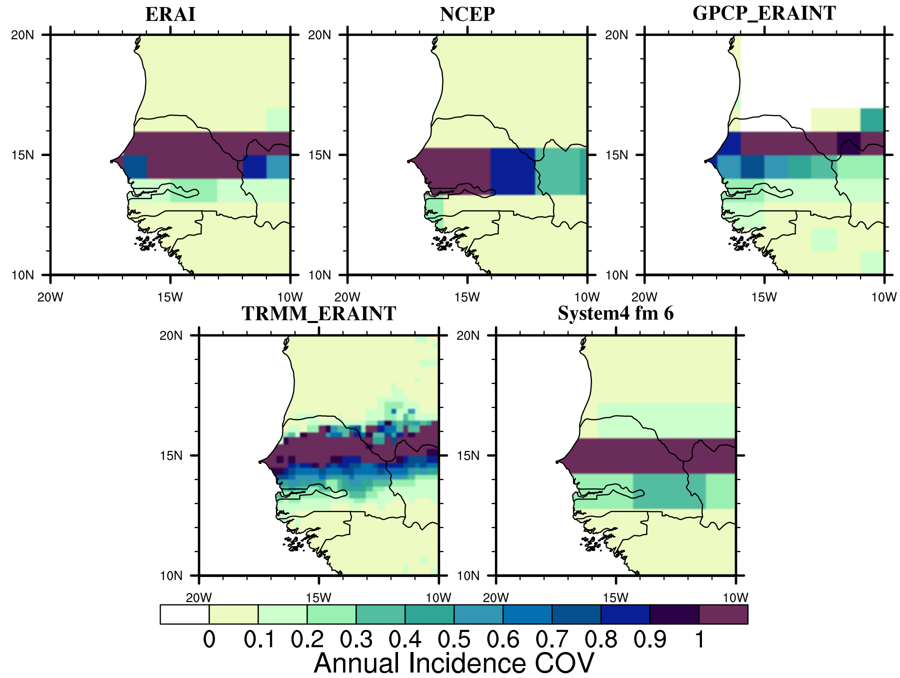


Figure 7: Malaria incidence coefficient of variation (COV) which is the standard deviation divided by the SON mean for the datasets driving LMM. System 4 values use a four-month lead-time using May start dates for an SON target.

Interannual variability of temperature, precipitation and malaria incidence averaged over Senegal for the peak malaria season (SON) are shown in Fig.8, with the System 4 forecasts taken with increasing lead times from the target season, allowing five realisations (see table 2 for explanation).

Table 2: Illustration of the different System 4 forecast start dates used for the two target seasons to calculate interannual variability and Relative Operating Characteristics (ROC) curve areas at several forecast lead times. Three month seasonal averages could not be computed for lead times of 6 and 7 months.

Forecast Month (fm)	1	2	3	4	5	6	7
JAS Target Start Date	7 (Jul)	6 (Jun)	5 (May)	4 (Apr)	3 (Mar)	2 (Feb)	1 (Jan)
SON Target Start Date	9 (Sep)	8 (Aug)	7 (Jul)	6 (Jun)	5 (May)	4 (Apr)	3 (Mar)
Target Months	1-3	2-4	3-5	4-6	5-7	N/A	N/A

Interannual variability for temperature is reasonably well captured by System 4 forecasts, even at short forecast lead times, with particularly good correspondence with the CRUTS observational data and ERAI climatology. The variability within the NCEP dataset is sometimes missed by the System 4 forecasts, often outside the forecast ensemble tercile.

The System 4 forecasts for precipitation compared to the climatological data are somewhat more scattered, but tend to compare better to the hybrid observation datasets GPCP and TRMM than the reanalyses ERAI and NCEP. Similarly, the Interannual variability in malaria incidence between the forecasts and climatologies is quite scattered, but correspondence somewhat greater with larger forecast lead times. For the peak malaria season SON, the NCEP climatology appears consistently lower that the other sources, which is consistent with the anomalously low malaria incidences seen in the average seasonal cycle (Fig.4).

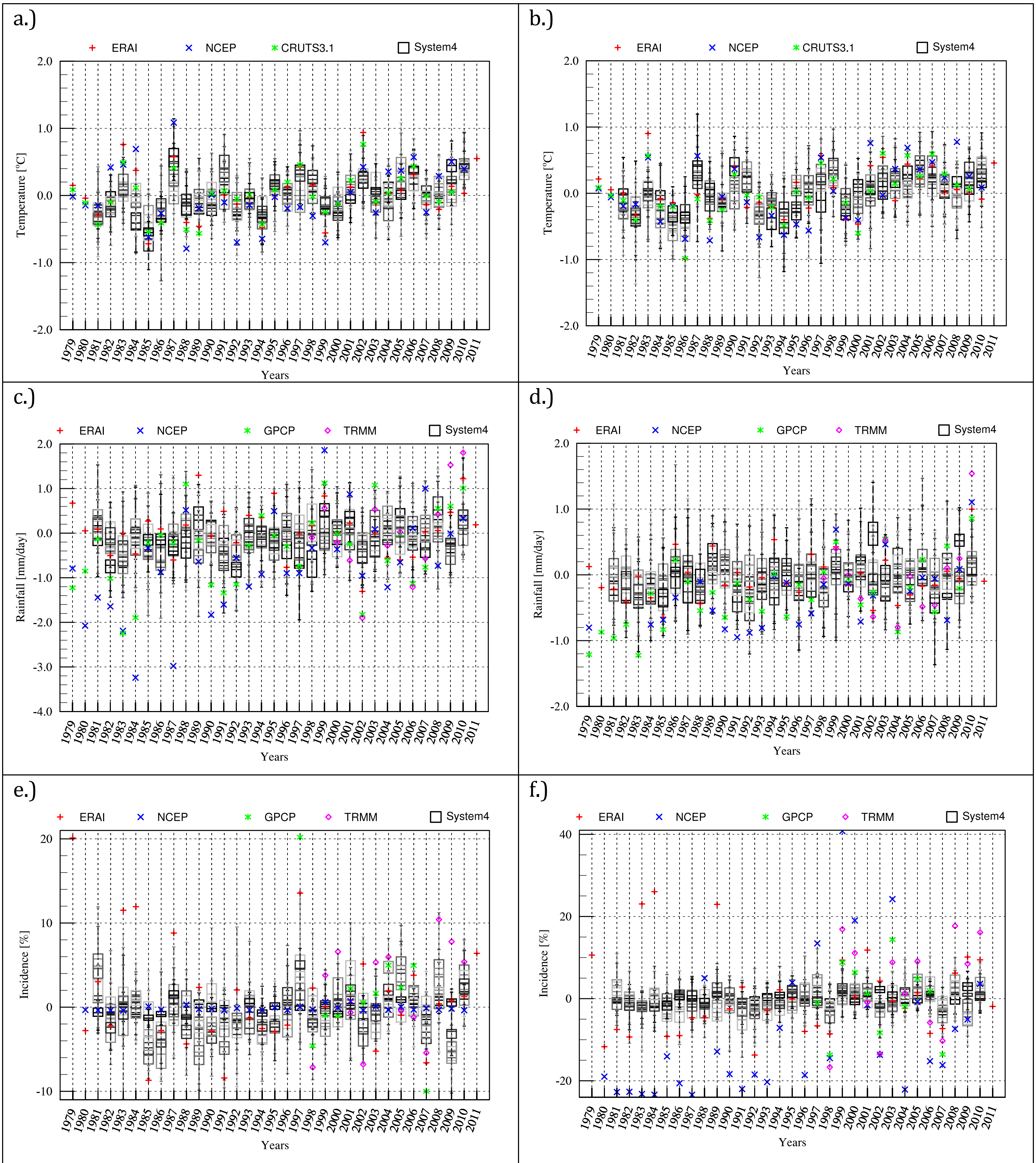


Figure 8: Interannual variability of (a,b) temperature, (c,d) precipitation and (e,f) malaria incidence for the peak rainfall season (JAS, left column) and the peak malaria season (SON, right column). The values are anomalies with a mean value subtracted that is calculated as the multi-year mean of each data product over their common, overlapping window of data availability. System 4 forecasts are plotted with increasing forecast start date lead times from 1 (black) to 5 (light grey) – see table 2 for details.

Skill in the System4 forecasts is determined by computing the geometrical area under the Relative Operating Characteristics (ROC) curve at each grid point for below lower tercile events, above median events and above upper tercile (extreme) events compared to the other climatologies. For perfect forecasts, all ensemble members will correctly predict an event (or non-event) in all years with a ROC area under the curve of 1.0, the maximum possible value. Forecasts with little or no skill that perform no better than climatology return ROC areas of less than 0.5. ROC areas were calculated for targets of the three-month peak rainfall season (JAS) and the peak malaria season (SON), with 5 increasing forecast lead times (see table 2).

The significance of these values can be determined by performing a two-tailed Mann-Whitney U-statistic test, using a look-up table referencing the number of events and non-events, and calculating a critical ROC area value that must be exceeded. For example, upper tercile events, with a probability of 33%, in a 30-year timeseries, should produce 10 events (N_e) and 20 non-events (N_n). At the 95% confidence level, the critical U value from a reference table is 55, giving a ROC area of $0.5+U/(N_eN_n) = 0.775$. Calculated ROC scores comparing upper tercile events in 30 years of data that exceed 0.775 are therefore significant where $p<0.05$.

There is a moderate but largely significant skill in forecasting SON temperatures in Senegal compared to the three climatological datasets (Fig.9), which is relatively consistent across all three event categories as forecast lead-time increases. The System 4 forecasts are noticeably less skillful in the central region of Senegal, with increasing skill in north Senegal and Mauritania as well as to the south of The Gambia and in Guinea.

There appears to be marginal skill in the System 4 forecasts of JAS rainfall (Fig.10) in north Senegal compared to climatology with low-lead time forecasts compared to ERAI, GPCP and TRMM are significantly skillful. The situation is similar for forecasts of SON rainfall (Fig.11), where the forecasts compared to ERAI are skillful across the north of the country, as are forecasts compared to GPCP.

ROC skill for malaria incidence in SON (Fig.12) should be interpreted in conjunction with geographical incidence variability (Fig.6 and 7) since the useful skill occurs in regions of high interannual variability between roughly 13-16°N, where epidemics are possible. With this in mind, the System 4 forecasts do show some significant skill on the southern edge of the fringe in ERAI and GPCP. Compared to TRMM the ROC area is particularly patchy and there is not much skill compared to the NCEP climatology.

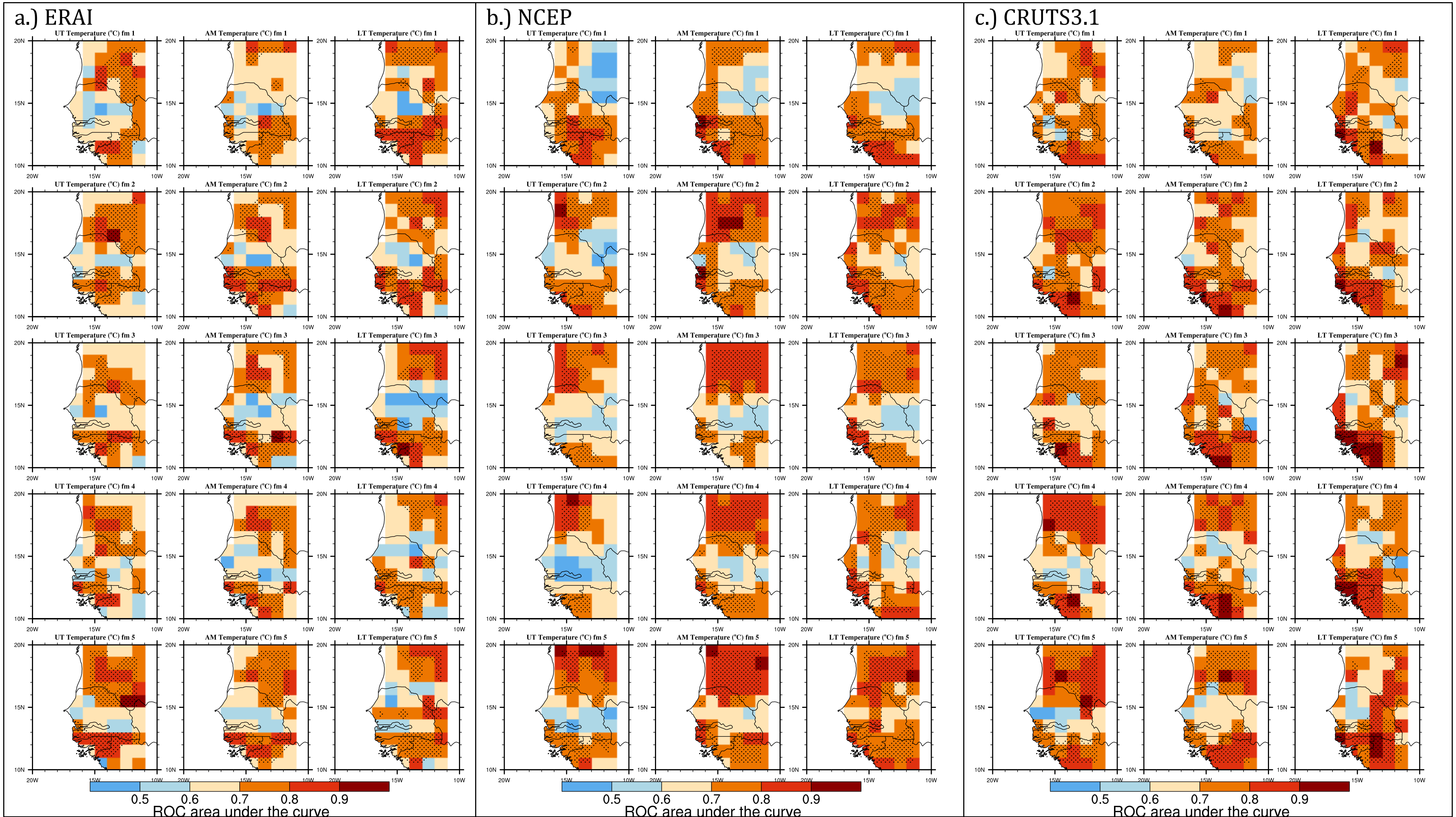


Figure 9: Relative Operating Characteristics (ROC) areas under the curve for SON season temperature forecast skill for above upper tercile (extreme) events (UT, left column), above median events (AM, central column) and below lower tercile events (LT, right column) compared to a.) ERAI, b.) NCEP and c.) CRUTS3.1 climatological data. The five different rows represent increasing forecast lead times from 1 month (top row) to 5 months (bottom row) of the target season (see table 2). Stippling indicates significance at the 95% confidence interval, calculated by performing a two-tailed Mann-Whitney U-statistic test.

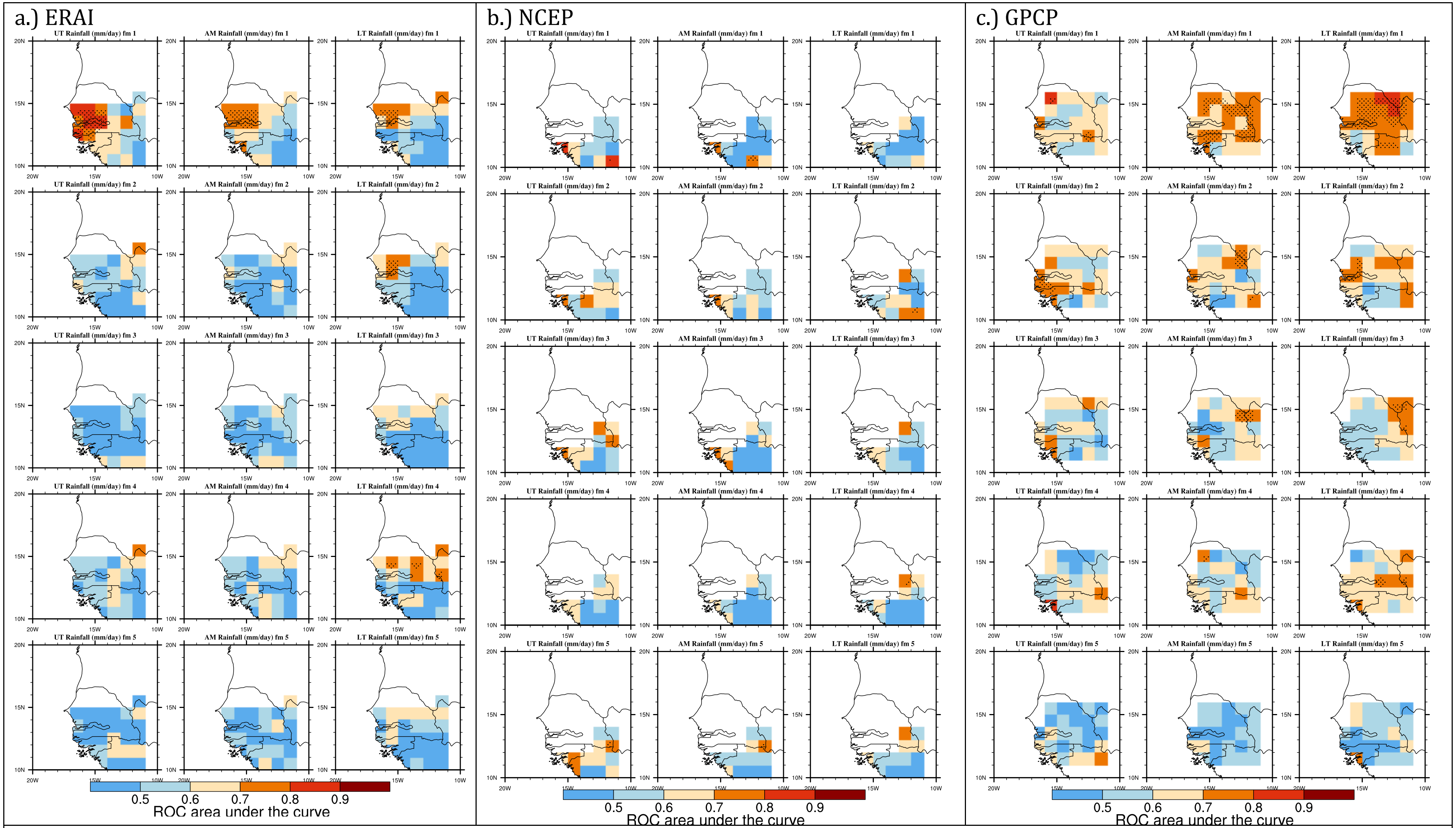
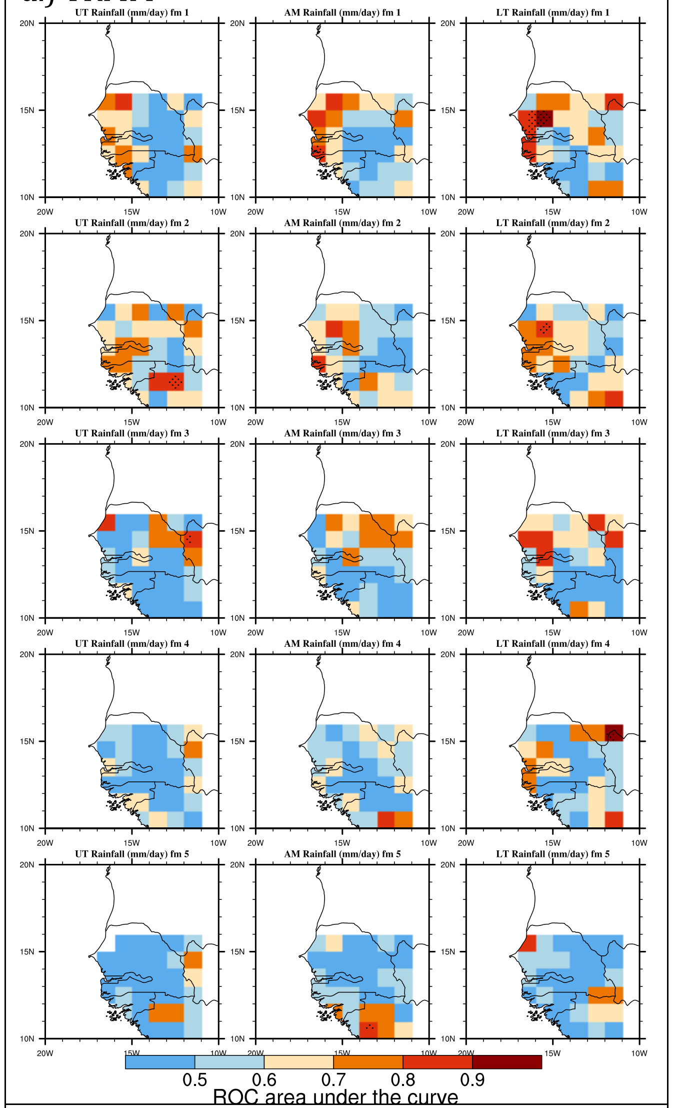


Figure 10: Relative Operating Characteristics (ROC) areas under the curve for JAS season rainfall forecast skill for above upper tercile (extreme) events (UT, left column), above median events (AM, central column) and below lower tercile events (LT, right column) compared to a.) ERAI, b.) NCEP, c.) GPCP and d.) TRMM climatological data. Data were masked by very low perecipitation (<1mm/day). The five different rows represent increasing forecast lead times from 1 month (top row) to 5 months (bottom row) of the target season (see table 2). Stippling indicates significance at the 95% confidence interval, calculated by performing a two-tailed Mann-Whitney U-statistic test.

d.) TRMM



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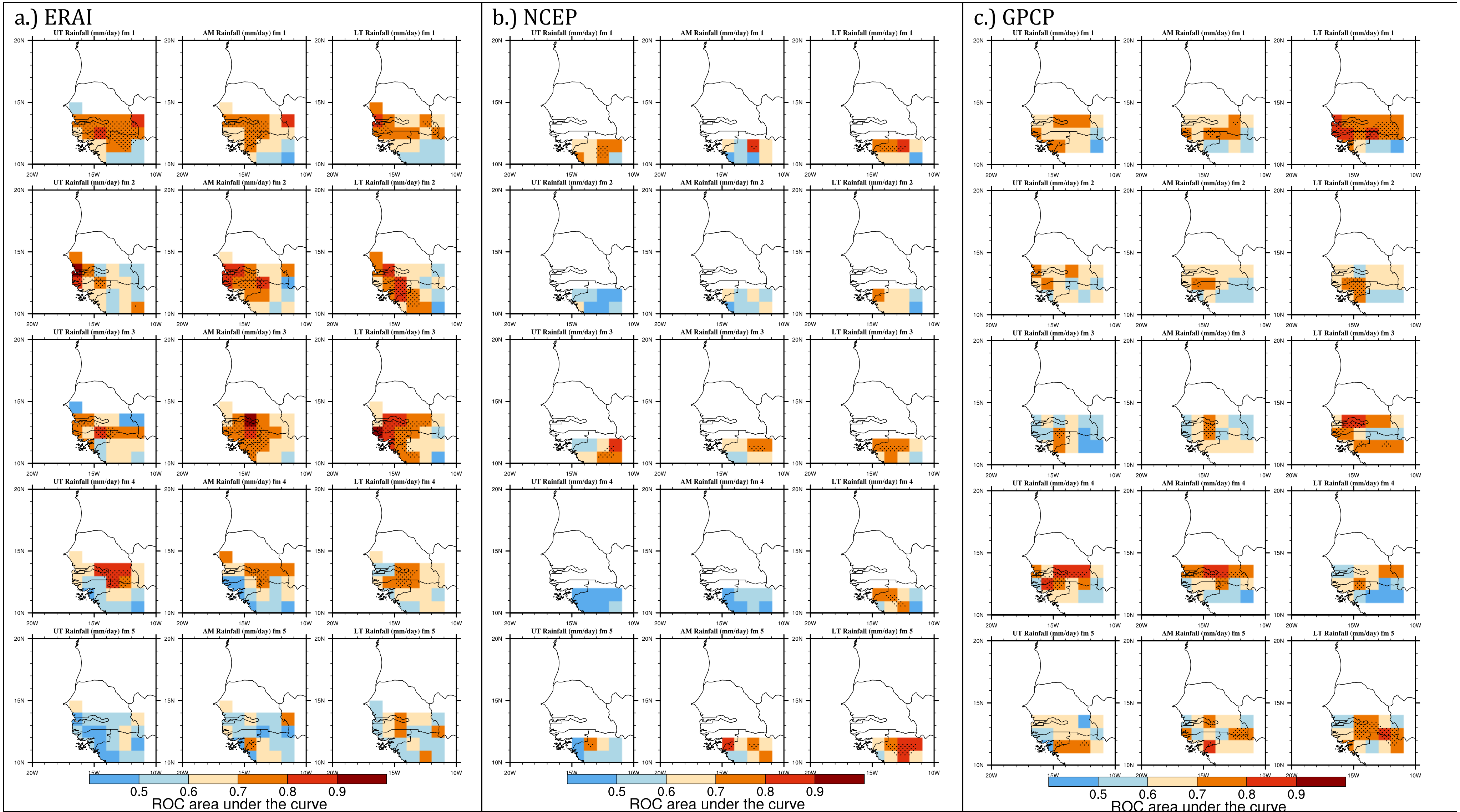
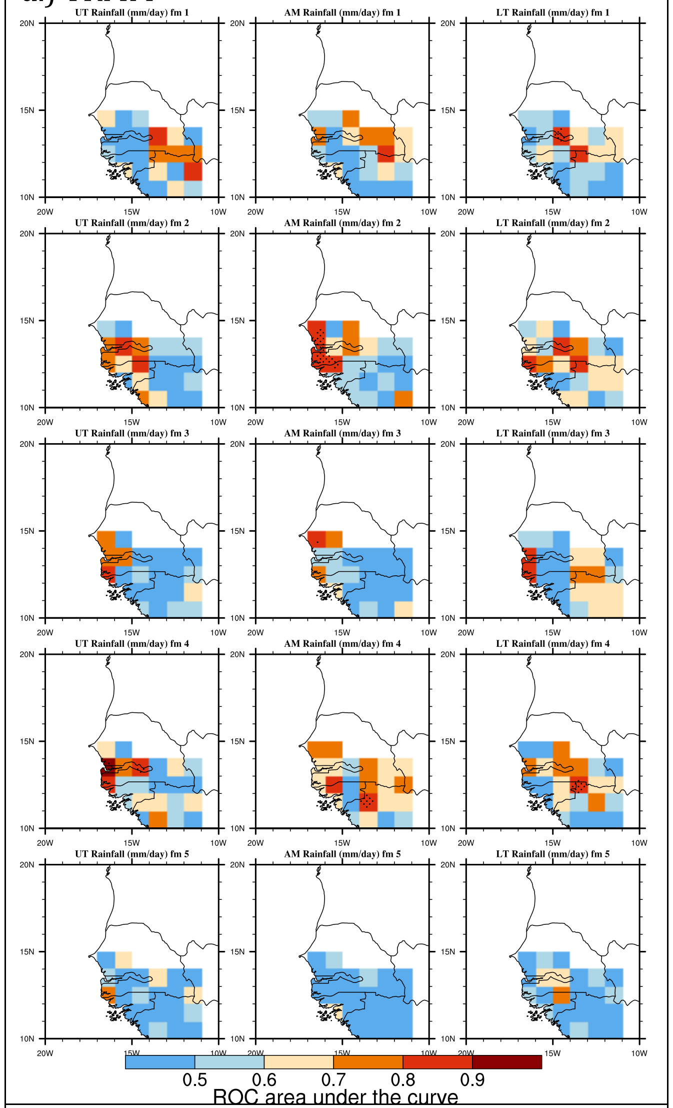


Figure 11: Relative Operating Characteristics (ROC) areas under the curve for SON season rainfall forecast skill for above upper tercile (extreme) events (UT, left column), above median events (AM, central column) and below lower tercile events (LT, right column) compared to a.) ERAI, b.) NCEP, c.) GPCP and d.) TRMM climatological data. Data were masked by very low perecipitation (<1mm/day). The five different rows represent increasing forecast lead times from 1 month (top row) to 5 months (bottom row) of the target season (see table 2). Stippling indicates significance at the 95% confidence interval, calculated by performing a two-tailed Mann-Whitney U-statistic test.

d.) TRMM



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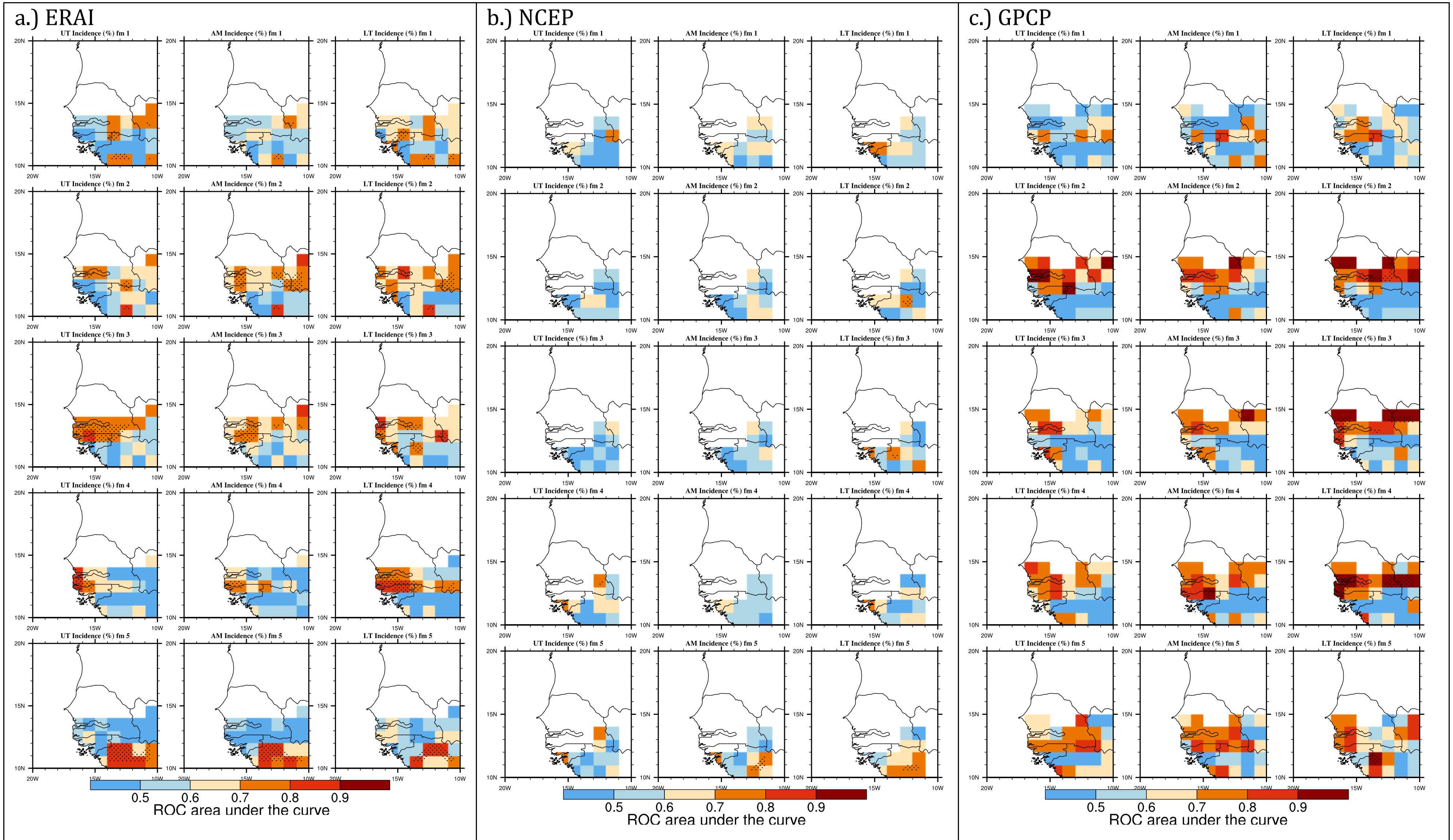
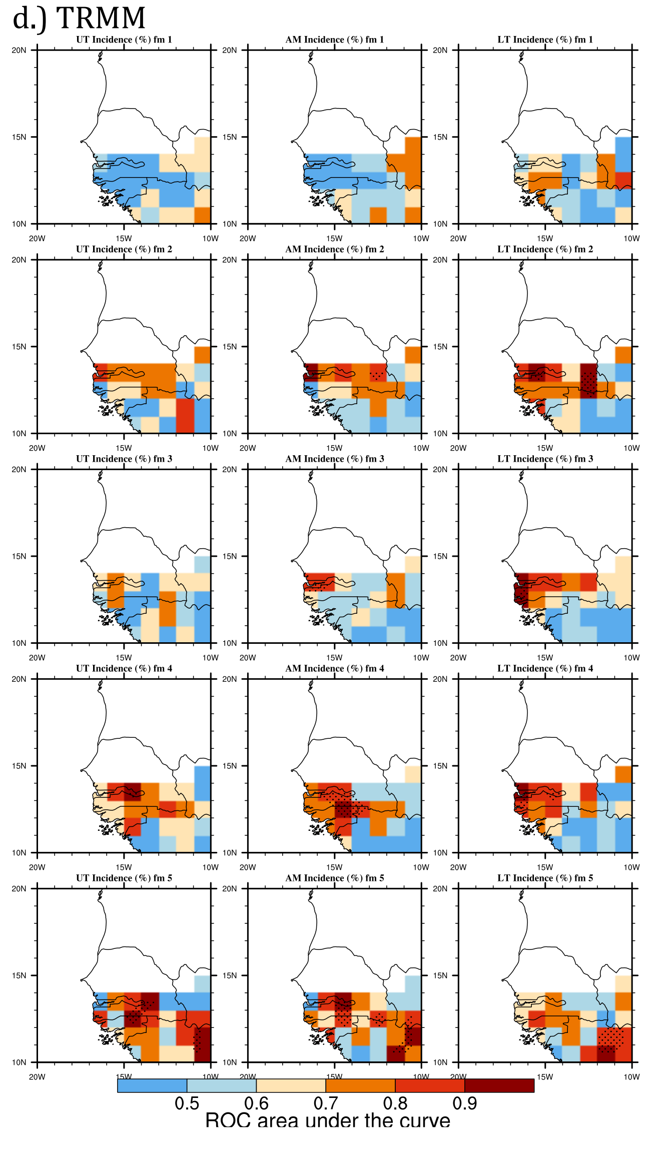


Figure 12: Relative Operating Characteristics (ROC) areas under the curve for SON season malaria incidence forecast skill for above upper tercile (extreme) events (UT, left column), above median events (AM, central column) and below lower tercile events (LT, right column) compared to a.) ERAI, b.) NCEP, c.) GPCP and d.) TRMM climatological data. Data were masked by very low perecipitation (<1%). The five different rows represent increasing forecast lead times from 1 month (top row) to 5 months (bottom row) of the target season (see table 2). Stippling indicates significance at the 95% confidence interval, calculated by performing a two-tailed Mann-Whitney U-statistic test.



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