A Characterization of the Variation in Relative Humidity across West Africa during the Dry Season

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ABSTRACT

The variation of relative humidity across West Africa during the dry season is evaluated using the Modern Era Retrospective Analysis for Research and Applications (MERRA) dataset and the method of self-organizing maps. Interest in the dry season of West Africa is related to the connection between near-surface atmospheric moisture and the occurrence of meningitis across West Africa, most notably in the region known as the meningitis belt. The patterns in relative humidity are analyzed in terms of frequency of each pattern as well as the sequencing from one pattern to the next. The variations in relative humidity are characterized subannually for individual years from 1979 to 2009 as well as decadally over the entire 30-yr duration of dry seasons in West Africa. The progression from relatively moist patterns to relatively dry patterns and back to the moist patterns over the course of the dry season corresponds to the northward and then southward migration of the intertropical convergence zone. The results indicate distinctly different frequency and sequencing of relative humidity patterns from year to year. The year-to-year changes in relative humidity patterns are gradual. There is some indication of a larger, possibly decadal, pattern to the year-to-year changes in the variation of relative humidity over the course of the dry season. The results are reflective of the reanalysis data including potentially unusual and erroneously dry conditions in central Africa after the mid-1990s.

1. Introduction

The purpose of this study is to evaluate and characterize the near-surface humidity across West Africa during the dry season. There are few climatological studies that have closely examined the dry season of West Africa where most of the focus is on the monsoon season. One reason for studying the dry season is the relationship of low atmospheric moisture conditions and the occurrence of meningococcal meningitis in the region. An evaluation of the dry seasons of West Africa is completed through the use of the National Aeronautics and Space Administration (NASA) Modern Era Retrospective Analysis for Research and Applications (MERRA). The MERRA dataset is used with the method of self-organizing maps (SOMs) to identify common patterns in near-surface relative humidity over the course of 30 dry seasons ranging from October 1979 to June 2009. The method of SOMs is particularly useful in this synoptic-climatology study, with its ability to highlight common moisture patterns as well as the frequency and sequencing of different moisture patterns.

The climate of West Africa can be generalized as having two seasons. The rainy, also referred to as the monsoon, season and the dry season. The clearly defined summer rainy season runs from approximately May to October, depending on the region of interest in West Africa. The dry season is characterized by prevailing northeasterly harmattan winds bringing dry and dusty conditions across the region. Nicholson and Grist (2003) provide a good overview of the rainfall in the region, the dominant atmospheric circulation features, and the
The best predictors in the model for identifying the humidity and land-cover type were determined to be susceptible to meningitis epidemics in Africa. Absolute mental conditions as a predictor of the regions that are African meningitis belt countries (Fig. 1). Molesworth epidemics. Included in the results is a description of the and environmental conditions related to the meningitis (1963) provides an early description of the geographic pending on the intensity of the epidemic. Lapeyssonnie are responsible for 3000–10 000 deaths annually de- meningococcal meningitis epidemics in Africa, which more recently shown the threshold-like behavior of men- and regionwide unpublished results by one coauthor have explored the relationship to the importance of socioeconomic and other factors in affecting disease severity. Dukic et al. (2012) for Ghana showing that 25% of the meningitis yearly disease variance for Niger could be explained by climate variables (including relative humidity), although results also pointed to the importance of socioeconomic and other factors in affecting disease severity. Dukic et al. (2012) for Ghana and regionwide unpublished results by one coauthor have more recently shown the threshold-like behavior of men- ingitis cases occurring with a relative humidity level around 40%. It is likely that other climate variables (rainfall, temperature, wind, etc.) or a combination thereof may also be linked as causative factors in meningitis. For this study, however, relative humidity will be the focus because of its known correlation (Dukic et al. 2012).

Section 2 provides a description of the data sources, SOM method, and application of SOM using 2-m relative humidity. Section 3 provides an evaluation of the dry season from the SOM analysis. A discussion summarizing the major conclusions and a discussion for additional work are covered in section 4. There are different patterns in the variation and progression of relative humidity patterns over the course of each dry season. The year-to-year changes in relative humidity are gradual, indicating a potentially longer, possibly decadal, pattern. The distribution of near-surface relative humidity early in the season can provide an indicator for the conditions over the duration of the dry season.

2. Method

a. Data source: MERRA

MERRA is a reanalysis project from NASA’s Global Modeling and Assimilation Office. Rienecker et al. (2011) provides a complete description of MERRA including an evaluation of the dataset in comparison with other reanalysis products. The two primary reasons
for the development of MERRA were to place the observations from NASA’s Earth Observing Systems satellites in a climate context and to improve on the representation of the hydrological cycle from previous reanalyses. The improvement of the hydrological cycle is of particular importance in this study, which examines the variation of relative humidity across West Africa. The MERRA dataset also provides higher spatial resolution across West Africa than did previous-generation reanalyses. The MERRA dataset focuses on the satellite era, from 1979 to present. The focus on the satellite era is beneficial for regions with sparse observations, such as West Africa, where satellites can provide additional coverage. The continual creation of climate analysis products in near–real time is another advantage of using MERRA for this study. The availability of more recent MERRA products will allow for potential further analysis and possible forecasting of the connections between relative humidity and meningitis outbreaks.

MERRA is created with the Goddard Earth Observing System (GEOS) atmospheric model and data assimilation system, version 5.2.0. A wide array of assimilated data from conventional surface and upper-air in situ observations to more modern remote sensing sources are included in the processing. More details on the GEOS5 data assimilation system and the incorporated observations can be found in Rienecker et al. (2011). Bosilovich et al. (2011) evaluates the earth’s global water and energy budgets in MERRA through a comparison with other reanalyses and merged satellite precipitation observation datasets. The results indicate that MERRA performs better than the previous generation of reanalyses. An improvement in the precipitation field is particularly noteworthy, especially in the tropics. Weaknesses that are present in previous reanalyses are similarly present in MERRA. One example involves changes in the assimilated observations that have led to discrepancies in the reanalysis results, which we discuss later in this work.

The MERRA dataset was retrieved from the Goddard Earth Sciences Data and Information Services Center (GES DISC; http://disc.gsfc.nasa.gov/mdisc/). The native three-dimensional grid is ½° latitude by ½° longitude with 72 vertical model layers. The near-surface files ("tavg1_2d_slv_Nx") were retrieved for this analysis of near-surface atmospheric moisture. The MERRA near-surface files are time-averaged hourly values. Files were retrieved for 1 October–30 June during 1979–2009. These files represent the dry season and the transition months into and out of the dry season. Additional processing was done to add relative humidity to the near-surface fields as well as in creating daily means of all fields. The end result is a collection of daily mean near-surface fields, including moisture data, representing 30 dry seasons (October–June 1979–80 to 2008–09) for West Africa.
b. Self-organizing maps

The SOM method was chosen as the analysis tool for this study. SOMs are one of several techniques in synoptic climatology that can be used to stratify large volumes of data into a small number of recurring patterns on a physically meaningful basis. Sheridan and Lee (2011) provide a robust review of the application of SOMs in synoptic climatology. The SOM method uses an unsupervised and objective classification procedure to group events into common patterns or clusters known as nodes. The patterns are then visually displayed as a two-dimensional array of nodes known as a map (Fig. 2). Used in this manner, the SOM technique is similar to other cluster analysis methods in that it seeks to define common patterns in the input data. Kohonen (2001) provides a theoretical discussion on the SOM technique. The resulting map from the SOM training is organized such that similar patterns are located near each other and contrasting patterns are placed on opposing sides. The four corners generally capture the extreme patterns with a smooth continuum in between. This distribution allows for a more simplified analysis allowing for both node-by-node analysis as well as area-by-area analysis. The SOM method was chosen for this study because of its ability to identify a set number of commonly recurring patterns representing the entire spectrum of the conditions of relative humidity present in the MERRA dataset. This provides confidence that the entire range of occurrences of the variation of relative humidity during the dry season is included. Hewitson and Crane (2002) and Cassano et al. (2006) include a thorough description of similar synoptic-climatology methods as well as an in-depth discussion on the application of the SOM technique to atmospheric data. Reusch et al. (2005) performed a comparison of the SOM technique with the well-established method of principal component analysis (PCA) using synthetic datasets. The results showed that the SOM method provides a complementary analysis to PCA and includes some advantages over PCA. One advantage of SOMs is a better visualization of the resulting patterns across the resultant SOM.

c. Application of the SOM method to the variation of relative humidity

A critical step in using the SOM analysis is selecting the variable of interest. Relative humidity at a height of 2 m, derived from the MERRA dataset, is the variable of interest for this study. There is ongoing debate as to which measure of atmospheric moisture best correlates the atmospheric conditions to occurrences of the meningitis epidemics (absolute humidity, relative humidity, etc.). Here, we use relative humidity as the measure of atmospheric moisture and identify a relative humidity of 40% as the threshold for when a region becomes susceptible to meningitis epidemics. One of the weaknesses of using relative humidity is the diurnal cycle of relative humidity related to the temperature. This variability was removed by creating daily means from the MERRA data. SOMs for relative humidity and specific humidity were created for a final comparison in selecting the preferred variable of interest. There was little difference in the resulting specific humidity and relative humidity SOM patterns over the land. There were some differences over the ocean. The relative humidity SOM shows little to no variation over the ocean, and the specific humidity SOM shows decreasing values extending away from the equator. Overall, no additional benefits were found in using specific humidity.

A second key component of a SOM analysis is the selection of the SOM domain. The selected geographic region needs to be large enough to capture the entire region of interest and not too large that unwanted features have an impact on the SOM training. For example, in this study if the selected region extends outward over the ocean, the SOM training will be influenced by the variation in relative humidity over the ocean, which is not of interest in this study. The selected geographic region extends from 20°W to 20°E and 0° to 20°N (see Fig. 1). This region extends south to north from the relatively constant values of high atmospheric moisture of the Atlantic Ocean, south of West Africa, to the relatively dry Sahara Desert. The region extends from west to east from the western edge of West Africa to the eastern extent of central Africa. This region covers approximately the western two-thirds of the meningitis belt. The resulting domain from the MERRA dataset is 61 points × 41 points (2501 points). The SOM training covers the entire duration of the dry season as well as the transitions into and out of the dry season. This period will hereinafter be referred to collectively as the dry season, and it extends from 1 October to 30 June of the following year. Thirty dry seasons were extracted from the MERRA dataset running from October 1979 to June 2009 (8198 days).

The software package used for the SOM analysis is freely available online (http://www.cis.hut.fi/research/som-research). Kohonen et al. (1996) provide an in-depth description of the software. The SOM training software was applied to a total of 8198 daily mean values (30 yr of dry seasons) of 2-m relative humidity covering the 2501 points of the SOM domain. A range of SOM sizes including 4 × 3, 5 × 4, 6 × 4, 6 × 5, 7 × 5, 8 × 6, and 9 × 7 were created during the study. The range of sizes, from 12 to 63 nodes, was created to determine the best-size map to represent the range and variety of relative
FIG. 2. SOM for 2-m relative humidity for West Africa. The SOM is trained from the MERRA dataset using 30 yr of dry seasons (1 Oct–30 Jun) covering 1979–2009. The node reference is indicated in brackets, and the frequency of occurrence (%) of each node is indicated in parentheses above each node. Isohume (line of constant relative humidity) contours are in intervals of 10%. The 40% isohume is highlighted by the solid red line. The 30% and 70% isohumes are highlighted by dashed red lines.
humidity patterns. The $5 \times 4$ SOM was selected because it was determined to provide a representative range of relative humidity conditions across West Africa. The $5 \times 4$ SOM is also compact enough to provide straightforward additional analysis. Figure 2 is the resultant master SOM for this study.

After the creation of the master SOM, individual daily means can be mapped to the SOM by identifying the node that has the smallest cumulative squared difference in 2-m relative humidity, over all grid points in the analysis domain, to the day of interest. This is repeated for all 8198 daily mean values, resulting in the conditions for each day being associated with a single node on the SOM. The frequency of occurrence of each node in the dataset can be calculated from this mapping of individual days to specific nodes. The sequencing of days over the course of a dry season and over multiple dry seasons can also be studied.

3. Evaluation of the dry season

An examination of the SOM for 2-m relative humidity (Fig. 2) shows the range of patterns typically found across West Africa during the dry season. Individual SOM nodes are labeled in brackets above the top-left corner. The 40% isohume (line of constant relative humidity) has been highlighted with a solid red line to better distinguish the different patterns in relative humidity. This 40% isohume corresponds to Dukic et al. (2012) and a recent unpublished study that have shown that regions with a relative humidity of less than 40% result in an environment susceptible to meningitis epidemics. At a minimum, the 40% isohume will be used to quantitatively indicate the variation of the relative humidity in the SOM analysis. The 30% and 70% isohumes are highlighted with dashed red lines. These isohumes are highlighted to more clearly show the differences in the gradient of relative humidity across the different SOM patterns. The 30% and 70% isohumes represent an approximation to the southern and northern extents of the intertropical discontinuity (ITD). The ITD marks the convergence zone at the ground between the dry and warm northeastern harmattan flow from the Sahara and the moist southwesterly monsoon flow (Pospichal et al. 2010; Hastenrath 1985).

One of the features of the SOM analysis is that similar patterns are placed near each other and dissimilar patterns are placed on opposing sides. The node with the most-moist conditions is node [1,1]. This node has the 40% isohume passing along the northern border of Burkina Faso and crossing through central Niger. The 70% isohume is as far north as central Burkina Faso and northern Nigeria. Both of these isohumes are extended to the farthest north in this most-moist node. The driest node is [5,4] on the opposite corner of the SOM. The 40% isohume cuts across approximately the northern one-third of Ghana and Nigeria. The 70% isohume is in the southern half of Ghana and Nigeria. The patterns in 2-m relative humidity progress from relatively moist conditions to dry conditions going from top to bottom as well as from left to right across the SOM. The changes are more pronounced going from left to right. For example, going across the top row from nodes [1,1] to [5,1] the 40% isohume goes from the northern border to the southern border of Burkina Faso. Another key difference in the SOM patterns is that the nodes on the right side have more pronounced dry conditions over the eastern region of the SOM domain in central Africa. For example the 30% and 40% isohumes extend as far south as central Cameroon and the southern part of the Central Africa Republic.

An analysis of the position of the 40% isohume and the distance between the 30% and 70% isohumes provides a quantitative description of the variations in the nodes across the SOM. Table 1 shows the mean latitude of the 40% isohume and the mean south-to-north distance in kilometers between the 30% and 70% isohumes from 15°W to 15°E. The region of 15°W–15°E was chosen so as not to include the influence of the Atlantic Ocean along the west coast of Africa, near Senegal, and to remove the patterns on the eastern edge of the SOM domain in central Africa. Table 1 shows node [1,1] being the relatively most moist pattern with the farthest-north position of the 40% isohume at 15°N and nearly the largest mean south-to-north distance between the 30% and 70% isohumes (the neighboring node [1,2] has a slightly larger mean distance). Similar south-to-north positions of the 40% isohume can be seen across diagonals of the SOM. For example the diagonal made up

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of nodes [3,4], [4,4], and [5,3] all have a mean position of approximately 10.5°N for the 40% isohume.

The frequency of occurrence of each node is calculated by determining the number of days, from the input MERRA dataset, that are mapped to a given node. A given day is mapped to a given node by matching the day to the node with the smallest cumulative squared difference across all grid points. The number in the top-right corner, in parentheses, for each node in Fig. 2 indicates the overall node frequency for the 30 dry seasons. Figure 3 shows the overall node frequency for each node, as well as the frequency of each node for a given month of the dry season (October–June), for the 30 dry seasons. The shading in Fig. 3 corresponds to the frequency of occurrence (darker indicates more frequent). The asterisk indicates the centroid position for the node distribution (see text for a description) for a given year.

![Fig. 3. Node frequencies for the SOM of relative humidity at 2 m for West Africa (Fig. 2). The values indicate the percentage of days for a particular node to occur during the entire SOM and during specific months. The top line indicates the node reference in brackets and the frequency for all months in parentheses. The monthly frequencies for October, November, December, January, February, March, April, May, and June are indicated beneath the top line for each node. The shading corresponds to the frequency of occurrence (darker indicates more frequent). The asterisk indicates the centroid position for the node distribution (see text for a description) for a given year.](image)

...over the course of the dry season, we can look at a progression through the relative humidity patterns during the dry season. This sequencing of the node patterns over a given year will be covered later in this discussion.

The distribution of node frequencies by month is not as straightforward when specific years are examined. Figure 4 is a plot of the node frequency by month for six select years from the 30-yr study. The selected years were chosen as a sampling for the different patterns exhibited over the 30 yr. The year 1979/80 (Fig. 4a) can be described as being a relatively moist year during the dry season. The most-moist pattern, node [1,1], has a total frequency of occurrence of 29.9% (indicated next to the node label in parentheses), which is more than 3 times the 30-yr average (Fig. 3). The node [1,1] pattern persisted for all of October, most of November, some of May, and nearly all of June. Meanwhile none of the relatively dry nodes ([5,1], [5,4], etc.) occurred at any time during that year. Eight nodes, including all nodes from the far-right column, were not present for 1979/80. These patterns represent the relatively dry conditions and specifically extreme dry air extending far south in central Africa. The southern extension of the dry air is indicated by the 40% isohume extending to near or beyond approximately 5°N (Fig. 2). The year 1985/86 (Fig. 4b) shows a pattern similar to that for 1979/80 in being a relatively moist year, especially with the absence of the patterns on the far-right and top-right nodes of the SOM. There are slight differences between 1985/86 and 1979/80, including a higher frequency of nodes in the bottom-left corner of the SOM indicating less-moist...
conditions than are seen in 1979/80, but both still lack the patterns of the dry air extending southward over the eastern portion of the SOM domain. The years 1979/80 and 1985/86 will be used to represent relatively moist years across the region.

The opposite of these relatively moist years is seen in 2001/02 (Fig. 4e), where the dry patterns dominate. During this year all of the nodes on the left side of the SOM do not occur. Ten of the 20 nodes occur less than 1% of the time in 2001/02. The nodes that are present and that are not present are nearly the exact opposite of what is seen in 1979/80 (Fig. 4a). Nodes [3,1], [4,1], and [5,1] dominate during the transition months (October, November, May, and June). The nodes of the far-right column of the SOM ([5,1]–[5,4]) make up most all of the patterns during the bulk of the dry season. These nodes correspond to the extension of the very dry air to near or beyond approximately 5°N, as indicated by the 40% isohume.

Other variations in the monthly node frequencies are seen in the remaining selected years (Figs. 4c,d,f). The year 1989/90 (Fig. 4c) shows the patterns being distributed somewhat equally over most all of the SOM except for the top-right corner (nodes [4,1], [5,1], and [5,2]). Over the course of the year, the patterns flow from approximately the more relatively moist patterns to the drier patterns and then back to the relatively moist nodes. The year 1994/95 (Fig. 4d) shows distributions of node frequencies that are not too far off from what is seen in 1989/90. There are some differences in the frequency of occurrence of selected nodes for selected months, but the overall pattern is similar between the two years. The year 2008/09 (Fig. 4f) shows an overall pattern that looks somewhat like 1979/80 with the no matches for the extreme dry patterns in the bottom-right corner of the SOM. There are some differences between 2008/09 and 1979/80. The node patterns in the top-right occur with moderate frequency in 2008/09, whereas they did not occur at all in 1979/80. Analysis of the monthly frequency for individual years shows that there is great variability in the patterns of relative humidity across different years for West Africa.
For each year, a weighted centroid for the node frequency has been calculated. The centroid position for a given year is calculated by multiplying the node position from the center by the frequency of occurrence for that node. The centroid positions for the six selected years are indicated in Figs. 4a–f with the asterisk at the position of the centroid. For example, the centroid position for 1979/80 is located near the center between nodes [2,2] and [2,3]. It can be seen that the years with more relatively moist patterns (e.g., 1979/80) have a centroid position that is located farther to the left of the SOM; years with more dry patterns (e.g., 2001/02) have a centroid position that is located toward the right side of the SOM. Figure 5 shows the centroid positions of all 30 years from the MERRA dataset that were used in training the SOM. It can be seen that the year-to-year shifts are gradual across the SOM. The early-1980s show the more relatively moist patterns, with centroids near nodes [2,2] and [2,3]. The late-1980s and most of the 1990s have centroid positions that are more toward the center of the SOM, indicating years with patterns that are somewhat equally distributed across the SOM. The 2000s have centroid positions that are more toward the right of the SOM at approximately node [4,2]. The centroid positions from the 2000s are indicating a prevalence of the more-dry patterns in the SOM. The last two years, 2007/08 and 2008/09, show a gradual shift back toward the relatively moist dominated pattern seen in the early 1980s. The change in centroid position is reasonably gradual from one year to the next. A longer time scale, possibly decadal, appears to be present and is playing a role in the variation of the centroid position of node frequencies for the different years. It can be seen that there would be great benefit in applying this SOM study to a reanalysis dataset with a longer time frame to better identify the longer, possibly decadal, time-scale patterns.

The progression through the different nodes over the course of a dry season shows a distinctive pattern each year with widely varying results among the different years. This is not a surprise given the year-to-year differences in the node frequencies of occurrence. Figure 6 is a plot showing the sequencing of nodes over the course of six selected dry seasons. The selected dry seasons correspond to those that are evaluated in Fig. 4. Each point represents a 5-day-average node position. For example, a 5-day period with 3 days mapped to node [1,1] and 2 days mapped to node [1,2] would show an average node placement 3/5ths of the way between nodes [1,1] and [1,2]. The dot representing the average node placement position is increased in size if a position stayed constant over successive 5-day averages. The shading of the lines and node positions in the figure corresponds to the time of year of occurrence. The lighter shades are for earlier in the season, and the darker shades are for later in the season. The relatively moist year of 1979/80 (Fig. 6a) shows a node-sequencing pattern with a frequency of occurrence in the top left early in the dry season, which moves to the center node positions around December and then toward the bottom-left nodes into the early spring months, returning to the top-left corner at the end of the dry season. The most common pattern over the 30 years follows that of 1979/80 (Fig. 6a) to some degree. The dry season starts with the top-left nodes and then progresses diagonally toward the bottom-right nodes. The sequencing moves along the bottom to the left edge and then moves up the left edge to back to the top-left corner by the end of the dry season. Figures 6b–d show three other occurrences of this general pattern. This general pattern is not exclusive, as can be seen in Figs. 6e and 6f. The 1998/99 dry season (not shown) has a pattern almost diagonally opposite to the general pattern. After proceeding to the bottom-right corner, the pattern moves up the right side and back across to the left along the top row. The 2005/06 dry season (not shown) has a pattern that is almost entirely located in the nodes along the top row ([1,1]–[5,1]) and the far-right column ([5,1]–[5,5]).

![Figure 5. Plot of centroid positions for all 30 dry seasons from 1979 to 2009. The centroid positions are the same statistic as those indicated for select years in Fig. 4.](image-url)
The moisture patterns across West Africa at the start of the dry season provide an early indicator as to the conditions that will be experienced throughout the dry season. When the relative humidity patterns start out in the relatively less moist nodes, such as node [3,1], it is likely that the entire dry season will experience more relatively dry patterns. There is also a high probability of the more-extreme dry patterns, such as node [5,4], occurring for extended periods of time. An example of this seasonal pattern is seen in 2001/02 (Figs. 4e and 6e). Such a correlation is not as clear when the pattern starts out as a relatively moist node, such as node [1,1]. There are many patterns during the dry season that have been seen when starting from this pattern. The longer that the early season stays in the relatively moist nodes, however, the more likely it is that the dry season will persist in the

FIG. 6. Plot of sequencing of nodes over the course of a selected dry season. Each point represents the average node placement of a 5-day average. Progressively larger points indicate successive 5-day averages at the same location. The sequencing shows the progression of the relative humidity conditions over the course of the dry season. The shading corresponds to the time of year, with lighter shading early in the dry season and darker shades late in the dry season. The years correspond to those in selected in Fig. 4.
The observations assimilated into the reanalysis. The most-identifying feature of the top-right corner of the SOM is the southern extent of the low relative humidity isohumes in central Africa, as seen in the master SOM (Fig. 2). For example, a comparison of node [3,4] with node [5,2] shows that the only significant difference is in the isohume pattern east of 20°E. The presence of these extreme dry conditions in central Africa is not apparent in every year and has a concentration in 1998/99–2008/09. In looking at the nodes making up the top-right corner ([4,1], [5,1], [4,2], and [5,2]), it is seen that there are minimal occurrences of these nodes during the years 1979/80–1994/95. During all of these years the total occurrence of these four nodes was never more than 5% in a given dry season. Meanwhile, these four nodes occurred over 29% of the time for all but one of the years from 1998/99 to 2008/09. Five of these 11 years had these four nodes composing over 50% of the dry season. The explanation for these conditions likely lies in the results of Bosilovich et al. (2011). The study compared the MERRA precipitation data at the point 4.5°N, 18.67°E with observations [Fig. 15a in Bosilovich et al. (2011)]. The MERRA precipitation is comparable to observations through late 1995, and then there is a sharp drop in the MERRA precipitation. The reason for this drop is attributed to a change in the ground-station equipment for the radiosonde station at Bangui, Central African Republic. It is the sole radiosonde station in the interior of the continent, and therefore any changes at this site have a dramatic effect on the reanalysis for that location and the surrounding region. These results reaffirm that the quality of a study is limited to the quality of the reanalysis used to conduct the study, which is limited by the observations assimilated into the reanalysis.

4. Summary and conclusions

The method of self-organizing maps has been used to characterize the changes in relative humidity across West Africa during the dry season. The variation of moisture across West Africa is significant from a health standpoint. A large section of West Africa composes the region known as the meningitis belt because of the frequent occurrences of meningitis epidemics. Studies have indicated that there is a correlation between the dry conditions and meningitis epidemics. The MERRA reanalysis dataset from NASA was used as the source of moisture data for this SOM study. The SOM method is an analysis tool that is useful in synoptic-climatology studies that stratify large quantities of data into physically recurring patterns. The resultant SOM is a collection of common patterns, referred to as nodes, that are placed in a two-dimensional array. The daily-mean 2-m relative humidity was chosen as the moisture variable of interest. Individual daily means can be matched with individual nodes to develop an understanding of the frequency of occurrence as well as the sequencing of patterns over time. The months of October–June were selected to represent the dry season and the transition months into and out of the dry season. Thirty years of dry seasons were selected, covering October 1979–June 2009.

A summary of the key points from the results is given here:

- Differences in the patterns of relative humidity are quantified in reference to the position of the 40% isohume and the south-to-north gradient from the 30% to the 70% isohumes. The more-moist nodes are characterized by the 40% isohume extending to around 14°N. The more-dry nodes have the 40% isohume at around 10°N. The more-dry nodes are also characterized by a larger moisture gradient between the 30% and 70% isohumes. The larger gradient is expected given that the relative humidity over the ocean, south of West Africa, is relatively constant over the course of the year.

- The occurrences of the different patterns of relative humidity have a strong correlation with the time of year. The more-moist nodes (e.g., [1,1] and [1,2]) occur only during the transition months into and out of the dry season. The more-dry nodes (e.g., [4,4], [5,3], and [5,4]) occur only during the middle of the dry season. The changes in dominant patterns over the course of the dry season are as expected, with the patterns following the southward and then northward progression of the intertropical convergence zone, also referred to as the rainbelt, over the duration of the dry season.

- There is significant year-to-year variation in the occurrence of relatively moist and dry patterns. The degree to which a year is considered to be relatively moist or dry is indicated by the centroid position for the frequency of occurrence (Fig. 5). During relatively moist years (e.g., 1979/80), the more-moist patterns occur with great frequency while the more-dry patterns do not occur at all. The opposite occurs during the relatively dry years (e.g., 2001/02).

- The general year-to-year variation in relative humidity patterns does not change dramatically from one year to the next. The change in patterns is instead progressive over a span of years. The more relatively moist years were found primarily in the early-1980s. The late-1980s and most of the 1990s indicate frequencies that are more equally distributed across the
patterns. Most of the early-2000s represent the more-dry years. There appears to be a larger time scale, possibly decadal, that plays a role in the variation of the moisture patterns.

- The yearly progression through the different relative humidity patterns during a dry season has a unique pattern; there can be wide variability in the year-to-year sequencing of the relative humidity patterns, however. Using the master SOM (Fig. 2) as a reference, the general succession starts in the top left, the relatively moist patterns, during the months leading up to the dry season. The pattern then progresses diagonally across the SOM to the bottom right and the more-dry patterns. The extent and timing of the diagonal movement across the SOM changes from year to year. The pattern then progresses along the bottom row toward the left and then up the left column, toward the more-moist patterns, by the end of the dry season.

- The pattern of relative humidity across West Africa at the beginning of the dry season provides an indication of the conditions experienced throughout the season. Years that start in less-moist nodes will experience more relatively dry patterns throughout the dry season. The longer that the early season stays in the more-moist nodes, the less likely it is that the dry season will contain occurrences of the more-dry patterns.

- Some of the more-extreme and defined patterns of the relatively dry conditions are related to occurrences of very dry conditions over central Africa (between 10° and 20°E) extending to the south. The driest years (e.g., 2001/02, 2002/03, and 2005/06) are characterized by high frequency of occurrence of nodes along the right side of the SOM. The increased frequency of these nodes is likely related to a change in instrumentation at a single radiosonde station in central Africa. This analysis, similar to all others that are based on reanalyses, is limited by weaknesses in the reanalysis that are often related to the assimilated observations.

An extension for this study would be to compare the corresponding meteorological fields that map to the different SOM node patterns. For example, all of the upper-level wind fields, for the days that have been matched to a given node, can be averaged to provide the mean conditions of upper-level winds associated for a given node. Such an analysis can focus on studying the general circulation features and forcing mechanisms associated with the different patterns of relative humidity. Such an analysis of the corresponding meteorological fields was beyond the scope of this project. Another possible future study would be to perform a similar analysis using a longer reanalysis dataset. The use of a longer dataset might provide a more in-depth understanding of the near-decadal changes from relatively moist patterns to dry patterns in relative humidity. Correlations might also be found between the different patterns and larger global multiyear signals.

This study may also be helpful in investigating the links between the patterns in humidity and the occurrences of meningitis across the meningitis-belt region. In addition to humidity variations, there are multiple other factors that have been shown to play a role in the occurrences of meningitis in the region. To the significant extent that climate and humidity variations link to meningitis susceptibility, however, we hope that studies such as this one on the spatial and temporal transitional patterns of humidity across the belt region can provide an additional source of information for epidemiologists in their fight against meningitis outbreaks and the resulting loss of life.

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REFERENCES


