Nat Hazards (2007) 41:227–243
DOI 10.1007/s11069-006-9033-x

ORIGINAL PAPER

Application of weather prediction models for hazard mitigation planning: a case study of heavy off-season rains in Senegal

Souleymane Fall · Dev Niyogi · U. C. Mohanty · Anil Kumar

Received: 14 June 2006 / Accepted: 22 June 2006 / Published online: 3 August 2006

Abstract Heavy off-season rains in the tropics pose significant natural hazards largely because they are unexpected and the popular infrastructure is ill-prepared. One such event was observed from January 9 to 11, 2002 in Senegal (14.00° N, 14.00° W), West Africa. This tropical country is characterized by a long dry season from November to April or May. During this period, although the rain-bearing monsoonal flow does not reach Senegal, the region can occasionally experience off-season rains. We conducted a numerical simulation of the January 9–11, 2002 heavy off-season rain using the Fifth-Generation NCAR/Pennsylvania State University Mesoscale Model (MM5) and the Weather Research and Forecasting (WRF) model. The objective was to delineate the meteorological set-up that led to the heavy rains and flooding. A secondary objective was to test the model's performance in Senegal using relatively simpler (default) model configurations and local/regional observations. The model simulations for both MM5 and WRF agree satisfactorily

S. Fall
Department of Agronomy, Indiana State Climate Office, Purdue University,
West Lafayette, IN, USA

D. Niyogi (✉)
Department of Agronomy and Department of Earth and Atmospheric Sciences,
Indiana State Climate Office, Purdue University,
915 W. State Street, West Lafayette,
IN 47907-2054, USA
e-mail: climate@purdue.edu

U. C. Mohanty
Indian Institute of Technology, Center for Atmospheric Sciences,
Delhi, India

A. Kumar
Department of Earth and Atmospheric Sciences, Purdue University,
West Lafayette, IN, USA

A. Kumar
National Center for Atmospheric Research, Boulder, CO, USA

with the observations, particularly as regards the wind patterns, the intensification of the rainfall, and the associated drop in temperatures. This situation provided the environment for heavy rainfall accompanied by a cold wave. The results suggest that off-the-shelf weather forecast models can be applied with relatively simple physical options and modest computational resources to simulate local impacts of severe weather episodes. In addition, these models could become part of regional hazard mitigation planning and infrastructure.

Keywords Heavy rainfall · Tropics · Western Africa · Weather forecast model · Model evaluation

1 Introduction

Off-season heavy rains are generally unexpected in tropical regions, causing significant harm to human lives and socioeconomic well-being. Though a majority of countries prepare their national infrastructure and disaster mitigation plans for the seasonally expected natural hazards (e.g., rains and flooding in the monsoon period), there is a growing need for disaster response and mitigation efforts on a regional scale to account for off-season weather hazards.

One such regional heavy off-season rain accompanied with a cold wave prevailed in Senegal (14.00° N, 14.00° W), West Africa, from January 9 to 11, 2002. The northern part of the country experienced a rapid drop in temperature (from about 40°C to 14°C). This meteorological event, though off-season, is not unusual. Winter rain can represent about 1% of the annual total, and the regional climatology shows a signature for off-season heavy rainfall during this period (Fall et al. 2006a, b). However, the January 9–11, 2002 event reached an intensity that had never before been recorded.

The heavy rains (and cold temperatures) caused a major disruption in the socioeconomic well-being of the region. There were 28 reported deaths due to the collapse of homes and the sudden drop in temperature. About 180,000 people were affected and 40,000 homes were destroyed. An estimated 500,000 heads of livestock were lost. In the Senegal River valley, rains washed away more than 3,500 hectares of crops, including about 2,800 tons of rice (UN-OCHA 2002). This unprecedented catastrophe caused the government of Senegal to launch an emergency plan and an appeal for national and international support. In response, many countries and international organizations including France, the United States, Germany, Algeria, and the United Nations provided emergency humanitarian aid.

It has been suggested that the catastrophic impacts could be attenuated by adopting a warning system based on short-lead forecasts provided by mesoscale models (WMO 2004). So far, most of the models dealing with West African regions have been developed to investigate long-term rainfall variability or seasonal forecasts focusing on the wet season (June–October) on a regional scale (e.g., Druyan 1987; 1991; Rowell et al. 1992; 1995). Recent studies have addressed short-lead forecasts, but the focus is often to simulate the evolution of summer mesoscale convective systems which develop during summer within the monsoon flow (e.g., Chaboureau et al. 2005; Chapelet et al. 2005; Lafore et al. 2005; Fall et al. 2005).

This study aims (i) to delineate the characteristics of the meteorological conditions that led to the January 9–11, 2002 off-season heavy precipitation event using a numerical weather forecast model, MM5—the Fifth-Generation NCAR/ Pennsylvania State University Mesoscale Model (Grell et al. 1993)—and the Weather Research and Forecasting (WRF) model (Skamarock et al. 2005; Michalakes et al. 2005; WRF 2005), and (ii) to test the ability of the models to perform short-lead forecasts by comparing the results with observations and satellite data. It is anticipated that the availability of off-the-shelf technology will aid in local and regional scale environmental forecasting and hazard mitigation planning.

For many regions in Africa, including Senegal, local scale observations are generally not routinely available. For this study, through the Fulbright Fellowship Exchange Program, access to local observations was made possible, so these data have been used to test the models. The model variables we will focus on in this study are rainfall, air temperature, pressure, and winds at surface and at 500 mb. This choice has been dictated by the nature of the phenomena being investigated as well as on actual data availability. However, the model's output will also be compared with the mean values of Senegal's climate and the results from other studies dealing with these types of phenomena.

In the following section, the meteorological conditions for the January 9–11, 2002 case are presented. This is followed by a short description of the MM5 and WRF modeling systems, the physical options chosen, and the data availability for testing the model in Sect. 3. The results and comparison of the model fields with observations are shown in Sect. 4, and the conclusions are presented in Sect. 5.

2 Climatology and the meteorological conditions for the case study

Enclosed between the latitudes 12°30 N and 16°30 N, and the longitudes 11°30 W and 17°30 W, Senegal is the westernmost country in Africa and borders the north Atlantic Ocean. This location at the western edge of Africa exposes the country to a double influence from both oceanic and continental domains. This influence is particularly noticeable in the temperature and wind fields (Fall et al. 2006a, b). The geographical setting has three active processes that control the general atmospheric circulation: the Azores and North African anticyclones (the latter usually positioned over Libya in winter) from the northern hemisphere, and the St. Helens anticyclone from the southern hemisphere.

The wet season lasts from late May to October. It begins in the south and then spreads over the rest of the country as the ITCZ migrates northward and the monsoon covers the entire region (Dhonneur 1970; Leroux 1973). The rainfall almost exclusively occurs during this period. Precipitations vary from 1,500 mm per year in the southern regions to fewer than 300 mm in the north.

The dry season extends from October through early May in the south and from late September to June in the north. It occurs when the ITCZ migrates southward and the country is out of reach of the monsoon circulation (Fig. 1). A subtropical jet (winds varying between 50 and 70 m s^{-1}) is typically observed (Knippertz and Martin 2005). Both the mid level (500 mb) as well as upper level (100 mb) flow play an important role in the tropical moisture transport. As shown in the figure, the region is also prone to various convective cloud types ranging from cumulus, to altocumulus which eventually change into cumulonimbus, and cirrus floccus capping the whole system (De Felice and Viltard 1976). At the lower levels, a trade wind surge is often observed, and this northerly flow contributes to the development of an

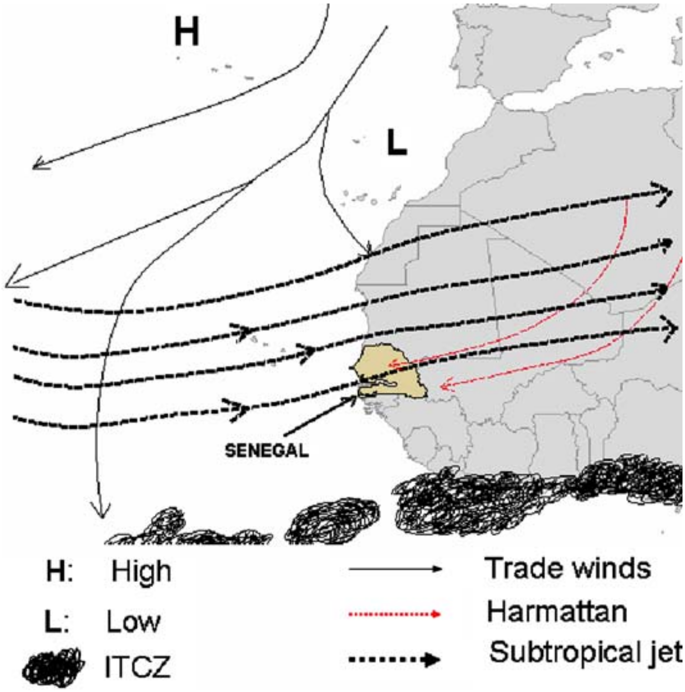

Fig. 1 Typical wind circulation over the eastern Atlantic Ocean and West Africa during the northern hemisphere winter (dry season)

intense convergence zone over the Atlantic Ocean and the subsequent moisture transport northeastward. During this period, the Harmattan, which is a dust-laden wind from the Sahara Desert, overlies the cool trade wind from the northwest (Dulac et al. 2001). Along the coast, the temperatures are cool because of the sea breeze, while further inland the weather is dry and warm, especially in the north.

In general, the meteorological situation that prevails over Senegal during off-season precipitation and cold temperatures can be summarized as follows: (i) at the upper level (from 700 up to 200 mb) a moisture transfer from the ITCZ to mid-latitudes along a SW–NE axis; and (ii) at the lower level, a cold spell coming from mid-latitudes, moving southward and causing a sudden drop in temperature. This situation is further investigated using numerical models and regional observations. The data and methods are described in the following section. Section 4 presents the results, which compare the model output with observed records and satellite images. In Section 5, a short summary is followed by a discussion about the need to use mesoscale models for short-lead forecasts in Senegal.

3 Data and methods

We use the MM5 and WRF modeling systems to simulate the meteorology. The model results are then discussed and the model fields are compared with observations and remote sensing data.

The numerical models were configured over Senegal with two nested domains (centered over 15° N, 16° W) encompassing the most western part of Africa and the adjacent ocean (eastern tropical Atlantic). The model domain is shown in Fig. 2.

The models were run for a 96-hour period (from 12 UTC on January 8, 2002 to 12 UTC on January 12, 2002) in an analysis mode by assimilating six hourly surface observations and upper air data twice a day (at 00 and 12 UTC) to develop the regional meteorological fields. The larger model boundary conditions were provided from the National Center for Environmental Prediction/National Center for Atmospheric Research Reanalysis Project (NNRP) data. The model physics options used in the study are summarized in Table 1.

The model validation data consist of rain gauge observations for 14 stations and temperature data for 12 stations (Fig. 3). The data were obtained from Météorologie

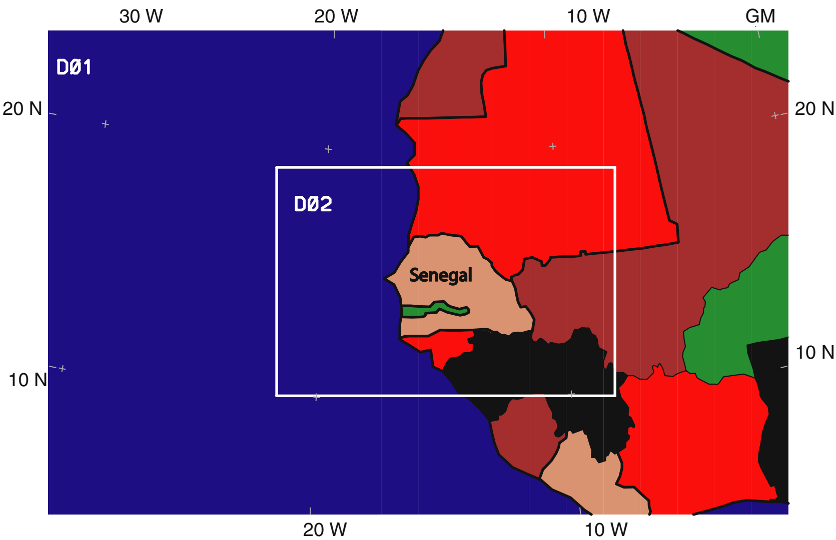

Fig. 2 MM5 and WRF single nested domain. Horizontal resolution: 45 km for the outer domain; 15 km for the inner domain

Table 1 MM5 and WRF options used in this study

	MM5	WRF
Domain: one-way nest interaction		
Outer	45 km grid spacing	45 km grid spacing
Inner	15 km grid spacing	15 km grid spacing
Explicit moisture scheme	Simple ice physics	Simple ice: WSM 3.0 (WRF single moment 3-class scheme, suitable for mesoscale grid size)
Cumulus parameterization	Kain–Fritsch scheme	Kain–Fritsch scheme
Planetary boundary layer physics	Medium range forecasting (MRF)	Yonsei University scheme (YSU)
Cloud radiation scheme	Default simple cloud radiation scheme	
Surface fluxes	Simple slab/bucket model	5-Layer thermal diffusion

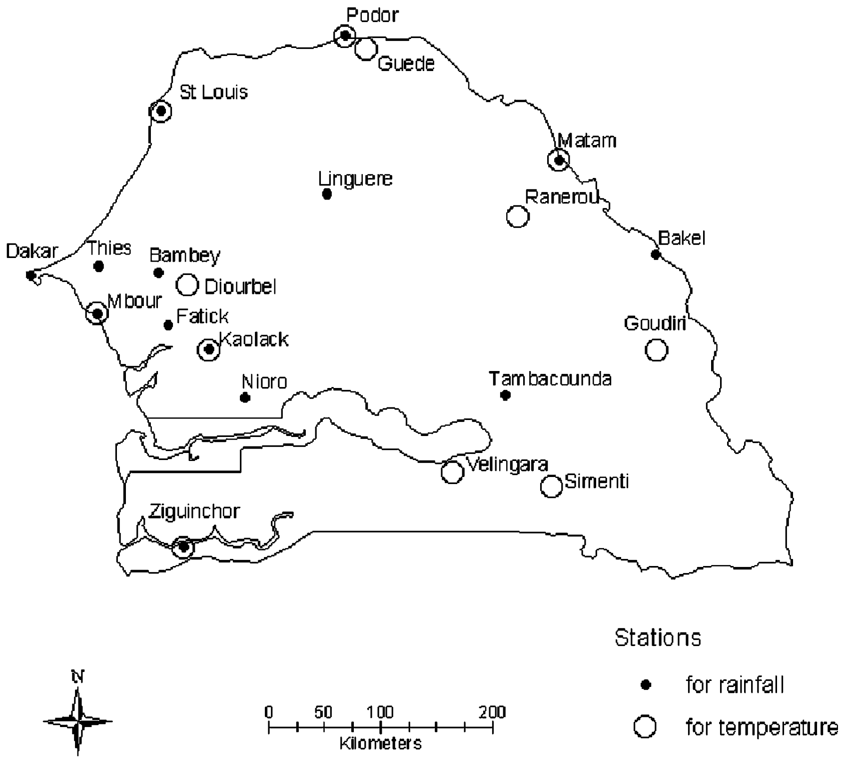

Fig. 3 Stations used in the study: (●) precipitation; (○) temperatures

Nationale, Dakar, Senegal. In addition, infrared satellite images from Meteosat 7 are used. The model and observed data are analyzed using ArcGIS Spatial Analyst.

4 Results and discussion

This section presents a summary of the meteorological features from an observational and 96-h simulation of the case study. Both the models had similar results and showed good results quantitatively and spatially in simulating the event using off-the-shelf configuration.

4.1 Rainfall

The models simulate a rapid evolution of climatic conditions over Senegal. As displayed in Fig. 4, the MM5 and WRF models show a rapid intensification of the rainfall from January 9 to 11, 2002. The rains developed offshore and moved inland with daily values exceeding 40 mm in the Senegal River valley area (Fig. 4b). The precipitation distribution followed a classical SW–NE axis, with the maximum values recorded in the north of Senegal (which is usually very dry) and the adjacent ocean. Podor, in the Senegal River valley is at the core of the rainy area and consequently experienced significant rains and flooding.

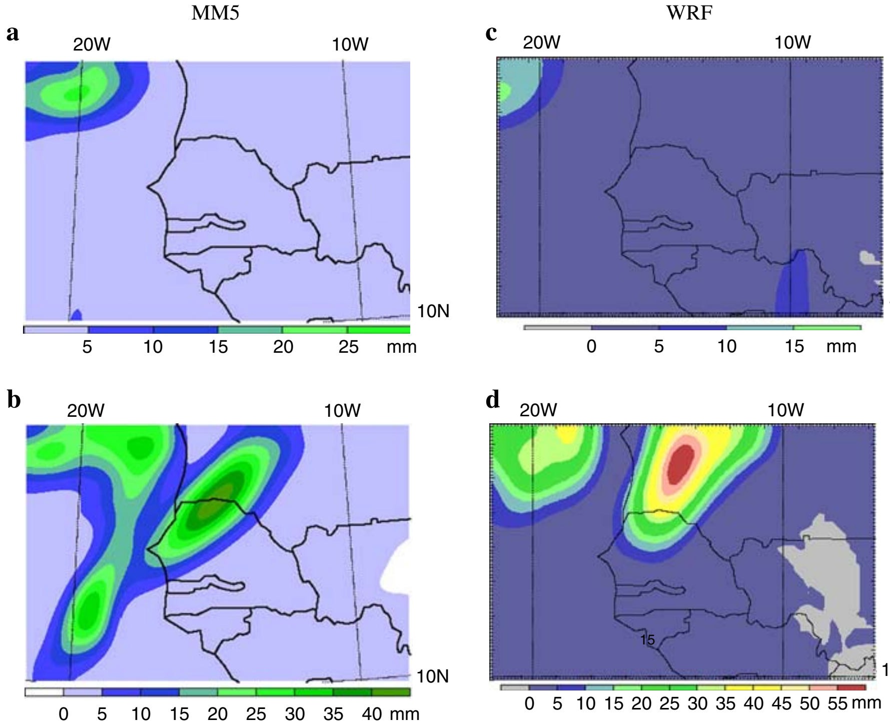

Fig. 4 MM5 and WRF simulations of total 24-h precipitation: **a** and **c**: 01/10/02, 00:00 UTC; **b** and **d**: 01/11/02, 00:00 UTC

Figure 5 shows the model-simulated and the gauge-recorded total rainfall from January 9 to 11, 2002. The highest rain amounts remained confined along the northern parts of the country. The rain gauge observations also indicated the same distribution patterns, with a general decrease southwestward. In general, there is a good agreement both in terms of the magnitude as well as spatial distribution of the modeled and observed rainfall for the study period. For example, Podor, which actually recorded 115.6 mm, according to MM5 (and WRF) simulations, received about 100 mm (and 80 mm) rains. Note that the gauge observations are point measurements, which are non-uniformly distributed over the region and have their own uncertainty (which could not be quantified). The model output agrees satisfactorily as regards the spatial patterns of the verification data, and both the simulated fields as well as observations showed a SW–NE axis of rainfall distribution.

4.2 Temperature

A rapid drop in temperatures accompanied the rains. On January 8, 2002, the temperatures across the region had values greater than 24°C (not shown). The following days, most of northern Senegal experienced a rapid decrease in temperatures. The lowest values were recorded on January 11 (Fig. 6). In the northern and western parts of the country, temperatures dropped below 20°C (68 F), which for this tropical region is a significant variation. The north experienced the lowest values,

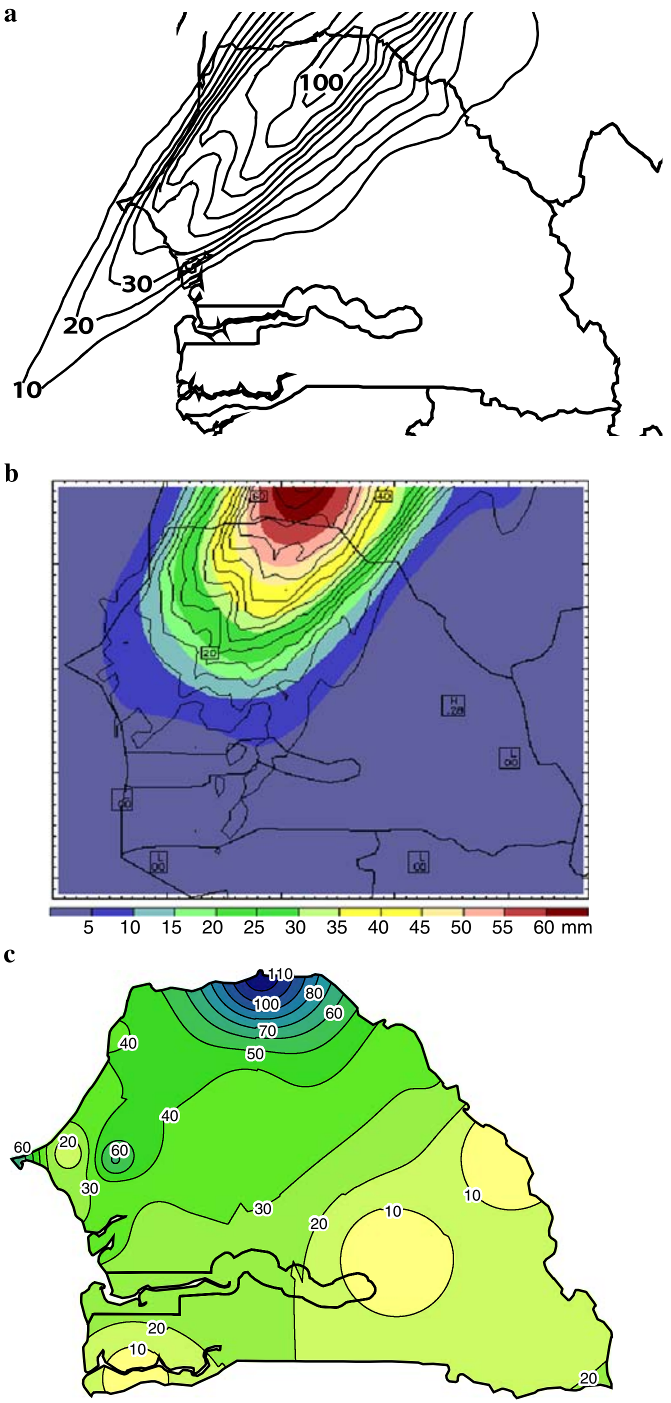

Fig. 5 Total precipitation (mm) from January 9 to 11, 2002: (**a**) MM5; (**b**) WRF; (**c**) rain gauge totals

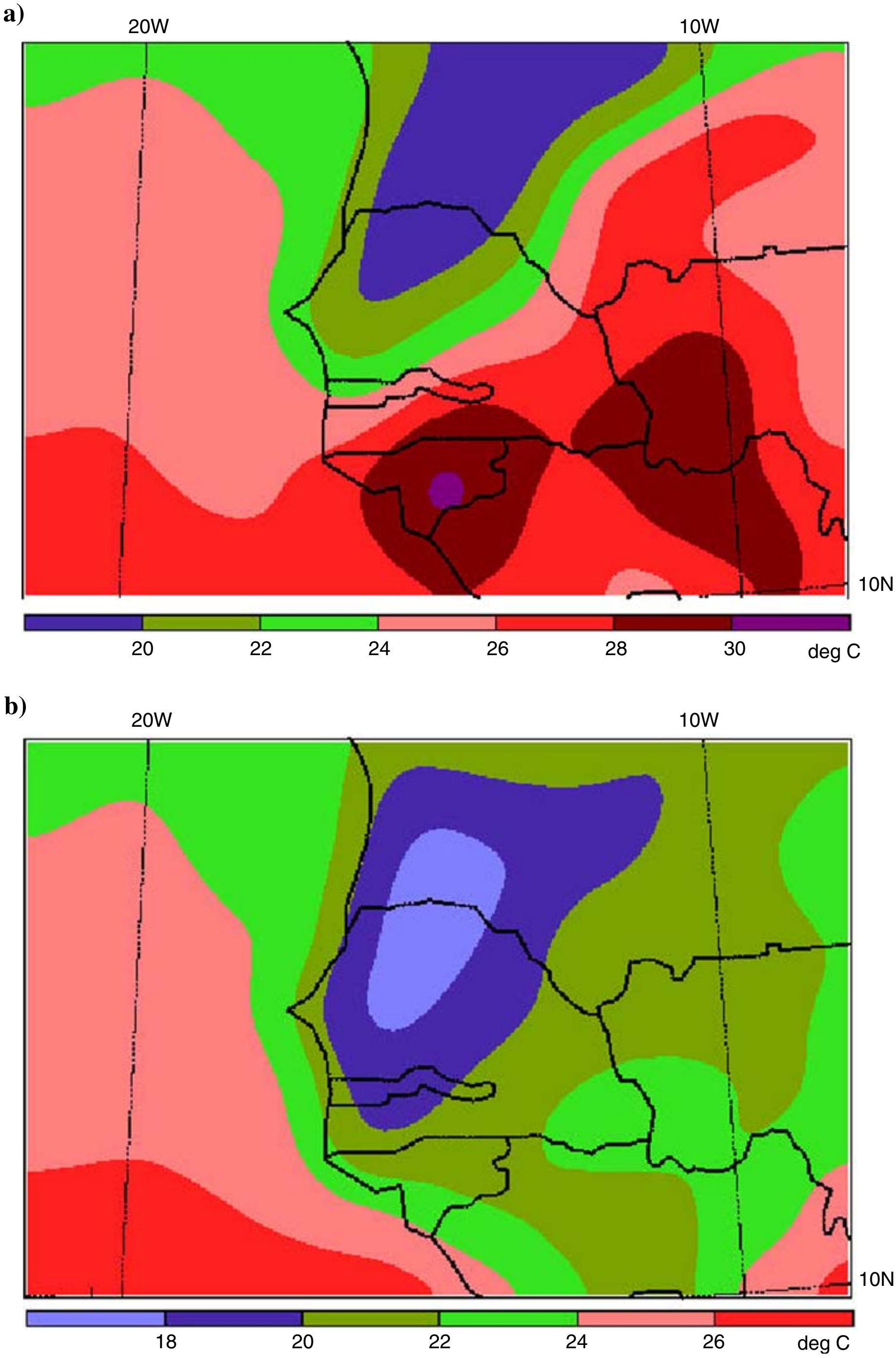

Fig. 6 MM5 simulation of temperatures: (**a**) 01/10/02—18:00 UTC; (**b**) 01/11/02—12:00 UTC

with fewer than 18°C (64.4 F). The spatial distribution of the temperature field is similar to that of the rainfall (varying along a NE–SW axis), indicating the same meteorological pattern accounted for this anomalous weather.

The changes in the daily minimum temperatures observed across Senegal on January 10 and 11 are shown in Fig. 7. A comparison of the modeled and observed daily mean temperatures for January 9 (Fig. 8) reveals that MM5 over-predicts the temperatures by about 2°C and WRF is closer to observations. For both models, the patterns of temperature variations throughout the study period are well simulated. The spatial patterns also show general agreement between the models and observations. The cold wave coming from the north is well expressed in the model's output and is consistent with observations.

4.3 Winds

The typical sea level pressure variation and the corresponding wind fields over Senegal are shown in Fig. 9. These fields coherently match the wind and pressure fields, with northerly winds at the surface and high-speed southwesterlies at the upper level. A high-pressure center is located in the north of Senegal, with a wedge expanding southwestward; on the adjacent ocean, a low-pressure system is located in the northwest of Senegal (Fig. 9a). The surface winds are oriented along the NE–SW axis over the continent. Over the adjacent ocean, the winds flow in a S–N direction (Fig. 9b) between the continental high pressure and the oceanic low. The surface winds increased from 6.2 m s^{-1} on January 8 to 16.5 m s^{-1} on January 11. At the upper level, i.e., 700 mb and above (Fig. 9c), the winds had a SW–NE direction throughout the 96-h simulation. The wind speed increased upward and a strong jet-like feature developed at the 500-mb level (Figs. 9c and 10).

The SW–NE axis, which appears to be a key feature of the meteorological situation throughout the study period, can also be seen in the visible satellite imagery. As shown in Fig. 11a, cloud band stretched from the Atlantic ITCZ to the Western

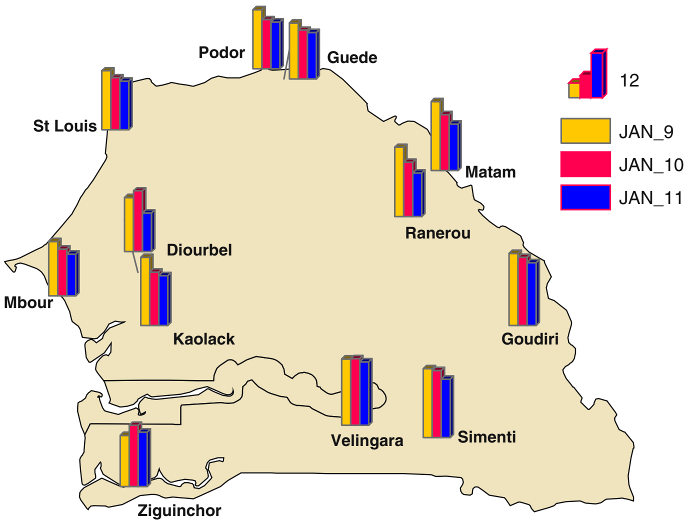

Fig. 7 Evolution of the mean daily minimum temperature (°C) during the 9–11 January period

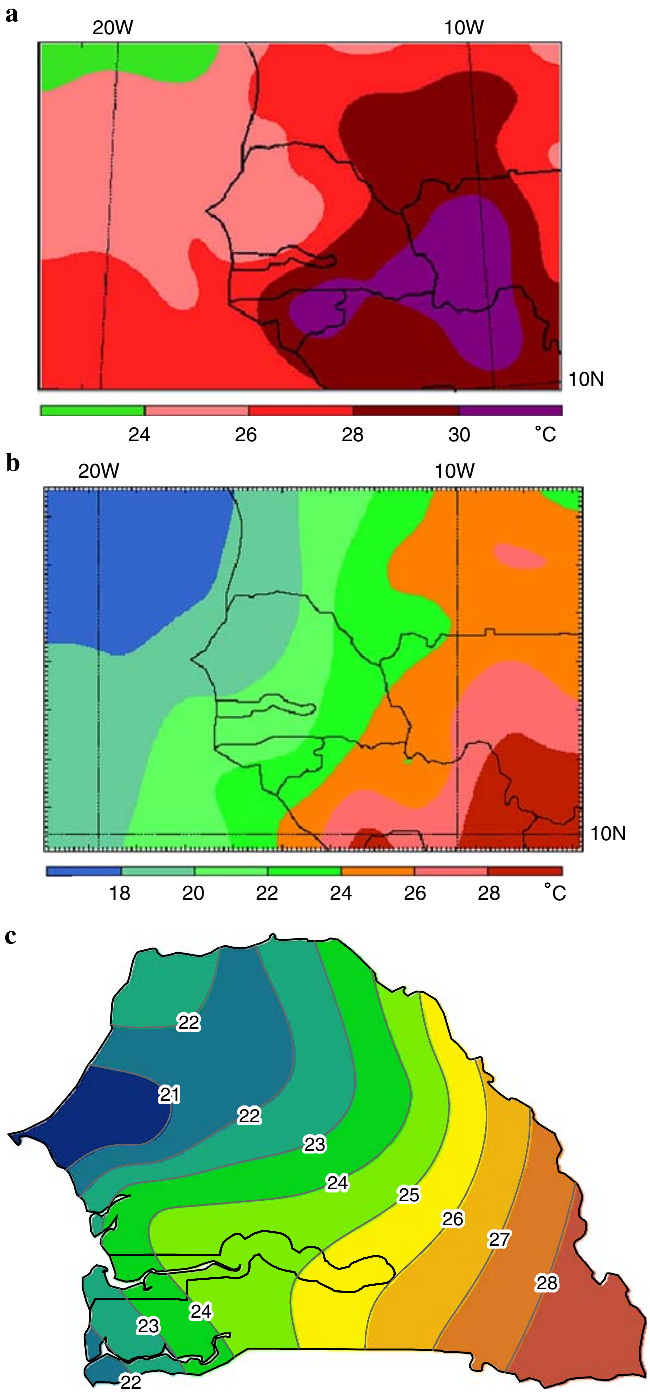

Fig. 8 Temperatures (°C) on January 9, 2002: (**a**) MM5 simulation at 18:00 UTC; (**b**) WRF simulation at 18:00 UTC; (**c**) daily mean temperatures. With respect to the spatial patterns, there is a good agreement between the simulations and the validation data

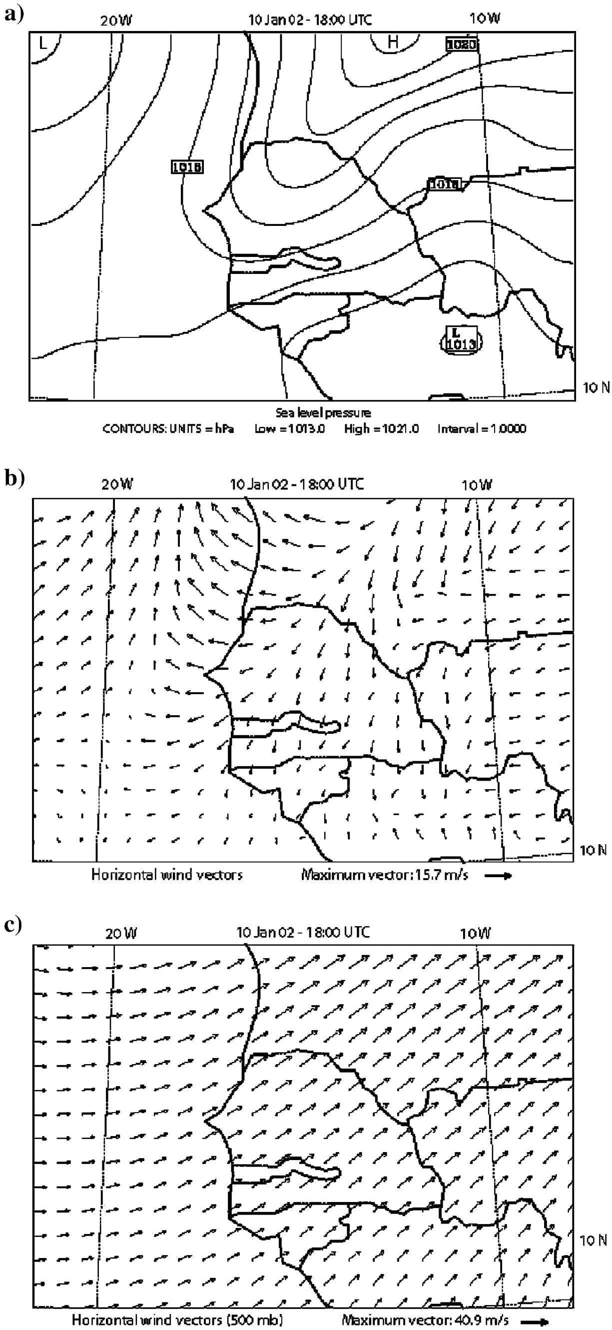

Fig. 9 Meteorological setup on January 10, 2002, at 18:00 UTC: (**a**) Sea level pressure; (**b**) Horizontal wind vectors at the surface level; (**c**) Horizontal wind vectors at the 500 mb level. Results shown are from MM5. The WRF run had similar patterns

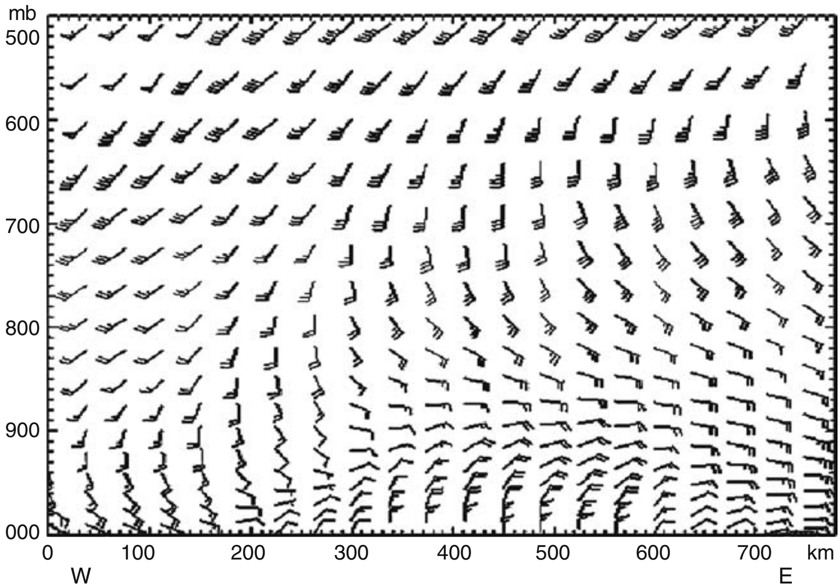

Fig. 10 Vertical cross section of the wind field at the latitude of Dakar (14°73′ N), 01/10/02, at 18:00 UTC. From the lower levels to the 500 mb level, a progressive shift of the wind direction from S–N to SW–NE is observed, along with an increase of the wind speed

Sahara on January 9. A cloud distribution indicative of an anti-clock (low pressure) circulation revealed the presence of a depression in the Atlantic Ocean over the Azores Islands area. On January 10, the two systems merged near the coast and the cloud bands covered most of the territory. The highest rainfall totals were recorded on this day (i.e. Saint-Louis: 39.7 mm; Podor: 35.7 mm; Diourbel: 36.6 mm).

The situation from January 9 to 11, 2002 was an extreme off-season rain event. The rains were caused by cloud bands oriented SW–NE and coming from the Atlantic ITCZ. Earlier studies have highlighted the presence of such large cloud bands originating from the ITCZ and heading for mid-latitudes in a SW–NE axis (e.g., De Felice and Viltard 1976; Thepenier 1981; Thepenier and Cruette 1981; De Brum Ferreira 1983; McGuirk and Ulsh 1990; Ziv 2001; Knippertz 2003). These cloud bands, also called tropical plumes (McGuirk 1988), preferentially develop in the area stretching from the tropical Atlantic to Europe and/or Asia (Iskenderian 1995). The presence of mid-latitude depressions picking up moisture from the ITCZ at the upper level causes an increase in cloud bands (Thepenier and Cruette 1981; McGuirk and Ulsh 1990; Ziv 2001; Knippertz 2004). In this case, Senegal, which lies in their trajectory, can experience off-season rains, a situation associated with a southward advection of cold air coming from the mid-latitudes. This cold air is believed to be a trigger of the convection over the Atlantic Ocean (Knippertz and Martin 2005). The SW–NE subtropical jet identified by long cloud bands plays a key role in the south/north moisture transport and can become an indicator for the potential of heavy inland rainfall from December to April over Senegal. This jet circulation at the upper level has been investigated in earlier studies (Dettwiller 1967) and is clearly shown in Figs. 10 and 11. Each of these features was well simulated by MM5 and WRF for this case.

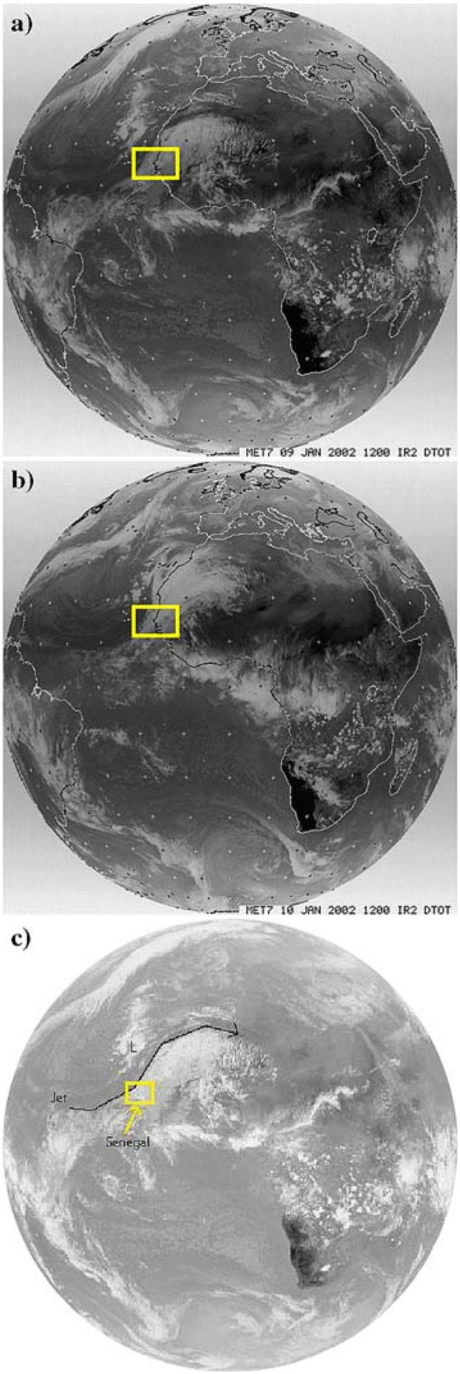

Fig. 11 Meteosat 7 imagery for (**a**) IR channel valid January 9, 2002 at 12:00 UTC; (**b**) IR channel valid January 10, 2002 at 12:00 UTC; and (**c**) Water Vapor channel for Jan. 9, 12:00 UTC. In the figures, the box shows the location of Senegal

Overall, the results for MM5 and WRF are qualitatively similar and lead to the same conclusions related to the evolution of the weather patterns and the ability of off-the-shelf models to be useful in tropical settings.

4.4 Applicability of dynamical models for hazard mitigation

The MM5 and WRF models (as well as other dynamical mesoscale models) have been routinely applied for weather forecasting and as part of a disaster mitigation tool in many countries. The real-time integration of these models requires large-scale lateral boundary conditions and initial conditions, which are now available in a near-real time basis from global operational forecast center such as US National Center for Environmental Prediction website (NCEP; e.g., http://www.nco.ncep.noaa.gov/pmb/products/gfs/), and can be requested from other agencies such as the UK Meteorological Office, and the European Center for Medium Range Weather Forecast (ECMWF). Through the operational centers both the analysis and forecast products are available, which can be integrated into the mesoscale models for providing initial as well as lateral boundary conditions for various real-time applications.

The global products are generally available at a coarse resolution (NCEP has 1° latitude × longitude resolution analysis and forecast). To capture the heavy precipitation events in the tropical region, which are orographically and convectively driven, high-resolution mesoscale models are required. For example, in our analysis of the Senegal heavy rain, the global products indicate the location of the low-pressure vortex and the moisture transport, while the MM5 and WRF model simulations show the timing, variability, and amounts of precipitation across the region. Similar results have been found for other regions such as for the heavy rain event in Mumbai, India in 2005 (Chang et al. 2005). Therefore, for applying the global products for specific regions, mesoscale models with regional analysis and data assimilation capabilities for better representation of the initial conditions and local forcings have to be adopted. The regional mesoscale models can also be effectively applied for dynamical downscaling by iteratively exploiting better representation of the orographic features and localized, intense atmospheric vortices resulting into heavy rainfall and other extreme weather conditions.

Gall (2006) has shown that the lead-time available for flash flood warning in the United States has increased from 52 min in 1998 to 65 min in 2005 mainly because of routine use of models such as WRF and MM5. Similarly, the Quantitative Precipitation Forecast (QPF) has been improved up to 72 h and this has implications for river discharge modeling and flood forecasting. For tropics such studies have not been documented, but adopting mesoscale models in tropical regions (such as Senegal) will assist in improving the skill of the forecast with longer lead times and thus enhance the overall lead time for disaster mitigation and applications.

5 Conclusion

A default configuration of the two modeling mesoscale systems (MM5 and WRF) was applied to simulate a high-impact heavy precipitation, low-temperature case in Senegal. The model results were compared with available observations and indicate an overall agreement. The MM5 and WRF analyses, in conjunction with satellite and surface observations, indicate that for Senegal (and West Africa), heavy off-season rainfall episodes can occur with the presence of a mid-latitude depression attracting moisture from the inter-tropical convergence zone. Thick cloud bands travel toward the northeast, carried by a southwesterly flow, which is well represented in the wind direction simulation at the level 500 mb. The rainfall experienced in northern

Senegal is well simulated by the models, with values and spatial distribution approaching the observations. The temperatures are also well simulated, and the drop in temperature can be linked with the surface wind circulation with the inland flow from the north bringing cooler temperatures. Even though wind observations were not available, the satellite and observed surface meteorology appear to be correctly represented by the model.

Both MM5 and WRF were able to simulate the weather patterns and could potentially become part of disaster mitigation. The simulations generally agree with the available validation data, and the difference between the values is not great. On the whole, though further tests are necessary to make a better assessment of the models' performances, one can be optimistic about the ability of the MM5 and WRF models to provide correct forecasts for tropical regions (Niyogi et al. 2002). The performance associated with these models can be further refined as the different model options (e.g., cloud physics, land surface scheme, etc.) are tested and customized over the region, making them efficient tools for disaster mitigation and prediction systems.

Tropical heavy rainfall events have localized feedbacks resulting into zones of moisture convergences and rain cells, which can lead to rapid flooding. These events cannot be appropriately resolved by large scale, coarse resolution global models in analysis as well as forecast. Our results demonstrate the application of high-resolution mesoscale models as a dynamical tool to effectively downscale global products and simulate convective and orographically driven heavy rainfall events. The model setup utilized in this study (for both MM5 and WRF) can be implemented with relatively limited computing resources (e.g. personal computers) to simulate localized processes. This scenario of low computational cost, easy access to global products, and the real time applicability of mesoscale models becomes an attractive dynamical tool which can be widely used in the developing countries for disaster mitigation applications.

Acknowledgements We would like to acknowledge the significant support of the Institute of International Education (IIE) with a Fulbright Fellowship to SF. We are also grateful to the following institutions: Météorologie Nationale, Dakar, Senegal, and Centre de Suivi Ecologique, Dakar, Senegal. This study benefited from NSF grant (ATM 0233780 Dr. S. Nelson), and the NASA-THP (NNG04GI84G Dr. J. Entin). We extend our gratitude to Moussa Yoro Thiam and Amadou Sene (Météorologie Nationale/ASECNA), who helped to gather the data. This paper also benefited from our discussions with the AMMA 2005 Dakar/Senegal Workshop participants.

References

Chang H, Niyogi D, Mohanty U, Routray A, Gupte M (2005) Impacts of land use changes on heavy precipitation over the Indian monsoonal regions. Proceedings of the American geophysical union fall meeting 2005, San Francisco, p A168

Chaboureau JP, Evan S, Roux F (2005) Numerical simulation of the 15–17, August 2004 West African mesoscale convective system. Proceedings of AMMA–African monsoon multidisciplinary analysis, Dakar 2005

Chapelet P, Asencio N, Muret M, Lafore P (2005) A first evaluation of models involved in the AMMA dry-run forecasting exercise in summer 05 monsoon. Proceedings of AMMA–African monsoon multidisciplinary analysis, Dakar 2005

De Brum Ferreira D (1983) Etude de la convection au dessus de l'Atlantique tropical au large de l'Afrique Occidentale, Linha de Accao de Geografia Fisica, Relatorio 1, 68 pp

De Felice P, Viltard A (1976) Aerojet subtropical d'hiver et nuages associes. La Météorologie, VI^{e} série 6

Dettwiller J (1967) Caractères du Jet Subtropical sur le Nord ouest de l'Afrique. Monographie de la Météorologie Nationale 58:29
Dhonneur G (1970) Structure continue de l'équateur météorologique sur l'Afrique Intertropicale. ASECNA, série I 29:60
Druyan LM (1987) GCM studies of the African summer monsoon. Climate Dyn 2:117–126
Druyan LM (1991) The sensitivity of sub-Saharan precipitation to Atlantic SST. Climatic Change 18:17–36
Dulac F, Chazette P, Gomes L, Chatenet B, Berger H, Vinicula Dos Santos JM (2001) A method of profiling the lower troposphere with coupled scatter and meteorological rawinsondes and first data from the tropical Atlantic off Sahara. J Aeros Sci 32:1069–1086
Fall S, Niyogi DS, Semazzi F (2006a) Mean climatology of Senegal. Earth Interactions 10 (Paper N 5):40 pp
Fall S, Semazzi F, Niyogi D, Anyah R, Bowden J (2006b) Spatiotemporal climate variability over Senegal and its relationships with global climate. Int J Climatol (in press)
Gall R (2006) NCAR Personal Communication
Grell G, Dudhia J, Stauffer D (1993) A description of the fifth-generation penn state/NCAR mesoscale model (MM5), NCAR Technical Notes, p 122
Iskenderian H (1995) A 10-year climatology of Northern Hemisphere tropical cloud plumes and their composite flow patterns. J Clim 8:1630–1637
Knippertz P (2003) Tropical-extratropical interactions causing precipitation in Northwest Africa: statistical analysis and seasonal variations. Mon Wea Rev 131:3069–3076
Knippertz P (2004) A simple identification scheme for upper-level troughs and its application to winter precipitation variability in Northwest Africa. J Clim 17:1411–1418
Knippertz P, Martin JE (2005) Tropical plumes and extreme precipitation in subtropical and tropical West Africa. Quart J Roy Meteor Soc 131:2337–2365
Lafore JP, Asencio N, Chapelet P et al (2005) The dry-run forecasting activities in summer 05 for AMMA: elaboration and test of the forecasting tools, methods and procedure. Proceedings of AMMA–African monsoon multidisciplinary analysis, Dakar 2005
Leroux M (1973) La dynamique des précipitations au Sénégal. Notes Africaines 140:105–108
McGuirk JP, Thompson AH, Schaefer JR (1988) An eastern Pacific tropical plume. Mon Wea Rev 116:2505–2521
McGuirk JP, Ulsh DJ (1990) Evolution of tropical plumes in VAS water vapor imagery. Mon Wea Rev 118:1758–1766
Michalakes J, Dudhia J, Gill D, Henderson T, Klemp J, Skamarock W, Wang W (2005) The weather research and forecast model: software architecture and performance. In: Zwieflhofer W, Mozdzynski G (eds) Proceedings of the eleventh ECMWF workshop on the use of high performance computing in meteorology. World Scientific, pp 156–168
Niyogi D, Xue YK, Raman S (2002) Hydrological land surface response in a tropical regime and a midlatitudinal regime. J Hydrometeorol 3:39–56
Rowell DP, Folland CK, Maskell K, Owen JA, Ward MN (1992) Modelling the influence of global sea surface temperatures on the variability and predictability of seasonal Sahel rainfall. Geophys Res Lett 19:905–908
Rowell DP, Folland CK, Maskell K, Ward MN (1995) Variability of summer rainfall over tropical North Africa (1906–92): Observations and modelling. Quart J Roy Meteor Soc 121:669–704
Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Wang W, Powers JG (2005) A description of the advanced research WRF version 2. NCAR Technical Note-468+STR, 88 pp
Thepenier RM (1981) Etudes climatologiques des bandes nuageuses pour l'ensemble de l'Hémisphère Nord, La Météorologie. VIe série 25:61–68
Thepenier RM, Cruette D (1981) Formation of cloud bands associated with the American subtropical jet stream and their interaction with mid-latitude synoptic disturbances reaching Europe. Mon Wea Rev 109:2209–2220
United Nations Office for the Coordination of Humanitarian Affairs-OCHA (2002) Situation report No. 1: Senegal–floods. Regional support office for West Africa, Dakar. Accessible from http://www.cidi.org/disaster/02a/ixl30.html
World Meteorological Organization (WMO) (2004) Workshop on development of scope and capabilities in emergency response activities. Geneva, Final Report, 30pp
WRF (2005) The weather research forecast model. Accessible from http://www.wrf-model.org
Ziv B (2001) A subtropical rainstorm associated with a tropical plume over Africa and the Middle-East. Theor Appl Clim 69:91–102