Analysis of meteorological measurements made over three rainy seasons in Sinazongwe District, Zambia.

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1. Introduction and method: Meteorological observations in 2009/2010

Local meteorological observations have been made in the Sinazongwe District, Zambia, from September 2007. Detailed analysis of observations from the 2007/08 rainy season was reported in Kanno and Saeki (2009), and that of the 2008/09 rainy season was summarized in Kanno et al. (2010). In this paper, we summarize the characteristics of the 2009/10 rainy season and compare these to the 2007/08 and 2008/09 rainy seasons.

Two meteorological observation stations (weather stations) were installed at Siachaya Village (site ***C***; high elevation, 1090 m) and Sianemba Village (site ***A***; low elevation, 515 m). The stations were powered by a solar-charged battery and installed in a wide open area devoid of vegetation in the center of each village. Meteorological observations of air temperature, air pressure, relative humidity, solar radiation, precipitation, wind direction and wind speed were made at 30 min intervals and stored by a data logger. Wind direction was recorded as instantaneous values, whilst the other meteorological elements were recorded as mean values over a 30 min period (the 30 min prior to the time of data logging). Equivalent potential temperature and absolute humidity were calculated from air temperature, relative humidity and air pressure.

Separate to these observation stations, a total of 48 rain gauges were installed at sites ***A*** and ***C*** as well as at an additional location in Kanego and Chanzika villages (Site ***B***; mid elevation, 720-986 m), with 16 gauges at each site. Precipitation data was recorded at 30 min intervals and automatically stored in the data logger, and hourly and daily precipitation means were calculated from this data.

In the 2009/2010 season, the condition of the rain gauges was generally poor, especially at site ***A***. Some data loggers were broken and others recorded zero in the middle of the rainy season (the cause being that the water hole in the rain gauge was clogged with mud). Consequently, the number of rain gauges with data over the whole rainy season was: 4 at site ***A***, 7 at site ***B***, and 10 at site ***C***, respectively. The number of data loggers that collected data over the whole measurement period varied in each of the three rainy seasons at each station. We therefore interpolated the precipitation at missing data points using the precipitation data at the nearest three gauges and these interpolated time series were then used to calculate the mean precipitation data.

2. Temporal variation of precipitation at each site

Precipitation data recorded by the weather stations for the three rainy seasons, 2007/08, 2008/09, and 2009/10, were compared for sites ***A*** and ***C***. Figure 1 shows the accumulated daily precipitation at the two weather stations. In the 2007/08 rainy season, there was a lot of rain in December, and in 2009/10 season, there was much rain around late February to early March, and 2008/09 experienced a stable increasing rate of precipitation throughout the rainy season. At site ***A***, the difference in the accumulated precipitation between the 2007/08 and 2008/09 rainy seasons was very large until mid February. However, much precipitation fell in late February and the difference in the total amount of precipitation over these two rainy seasons was not large: 1437-1258 = 179 mm. Interestingly, the time variation in precipitation differed amongst the three rainy seasons, and the accumulated precipitation over time in the 2008/09 rainy season shows a constant increasing rate. At site ***C***, the variation in precipitation over time in each of the three years was similar to site ***A***, but the precipitation difference between the 2007/08 and 2009/10 rainy seasons were smaller than at site ***A***. This indicates that the volume of precipitation in the highlands (site ***C***) is more stable over a rainy season than the lowlands.

Figure 2 shows the daily and accumulated precipitation for the three rainy seasons at site ***A***. Precipitation was averaged over the 16 rain gauges, which comprised a combination of observation and interpolated data. The difference in precipitation between the first and third rainy season precipitation was distinct until early March. The maximum accumulated precipitation difference was 1030 mm on February 1. In the 2009/10 rainy season, precipitation suddenly increased in early and late March. Interestingly, there was a distinct break with almost no rain for ten days in mid February 2010. After this break, over 1000 mm of precipitation was observed in a short period and the total amount of precipitation for the season reached nearly the same value as in the 2007/08 rainy season. In the other two rainy seasons, there was not much rain after late February, and the dry spell and rain late in the season in 2010 are distinct inter-seasonal variations. These may have importance for understanding the nature of precipitation variations in the 2009/10 season.

Figure 3 shows the daily and accumulated precipitation for each of the three rainy seasons at site ***B***. Whilst the nature of the temporal variations for each of the three rainy seasons were similar to those at site ***A***, the difference between the seasons was a little lower than at site ***A***. The precipitation graph for Site ***C*** is shown in Fig. 4. The maximum difference between two rainy seasons was 680 mm, which is the smallest difference amongst the three sites. Also, the total amount of precipitation was nearly the same in each of the three years at site ***C.*** The dry period in mid February 2010 can be seen distinctly at all three sites.

Next, we consider the causes responsible for the precipitation differences amongst the three rainy seasons. Interestingly, in spite of the time variations, the total amount of precipitation in each of the three rainy seasons was the nearly the same at sites ***B*** and ***C***, and in 2007/08 and 2009/10 rainy seasons, were almost the same at site ***A***. Major events in

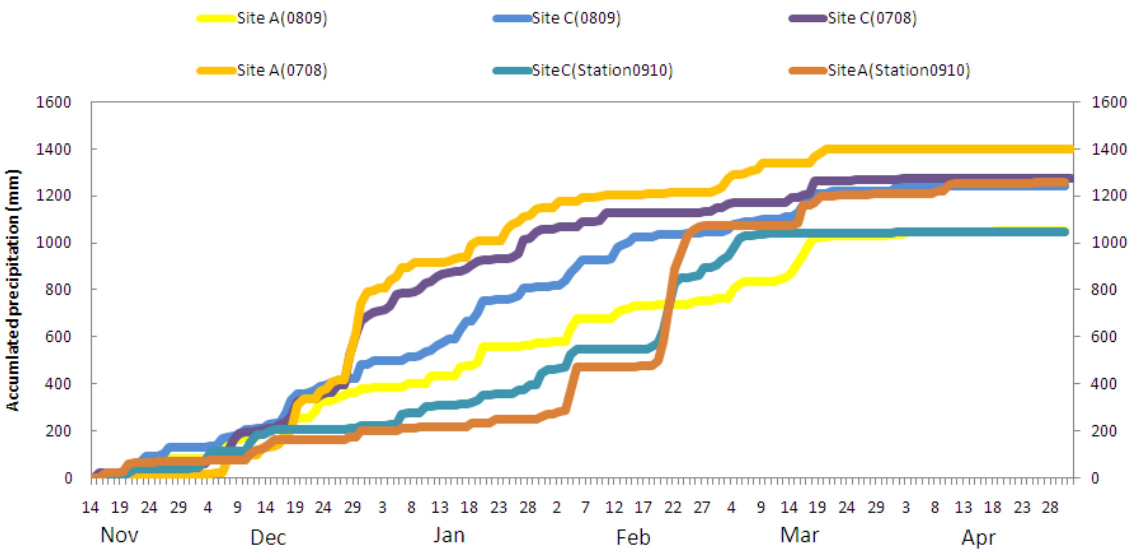


Fig. 1 Daily accumulated precipitation (mm) at sites *A* and *C* from November 14 to April 30 for the three rainy seasons (2007/08, 2008/09, and 2009/10). Data were observed by meteorological weather stations.

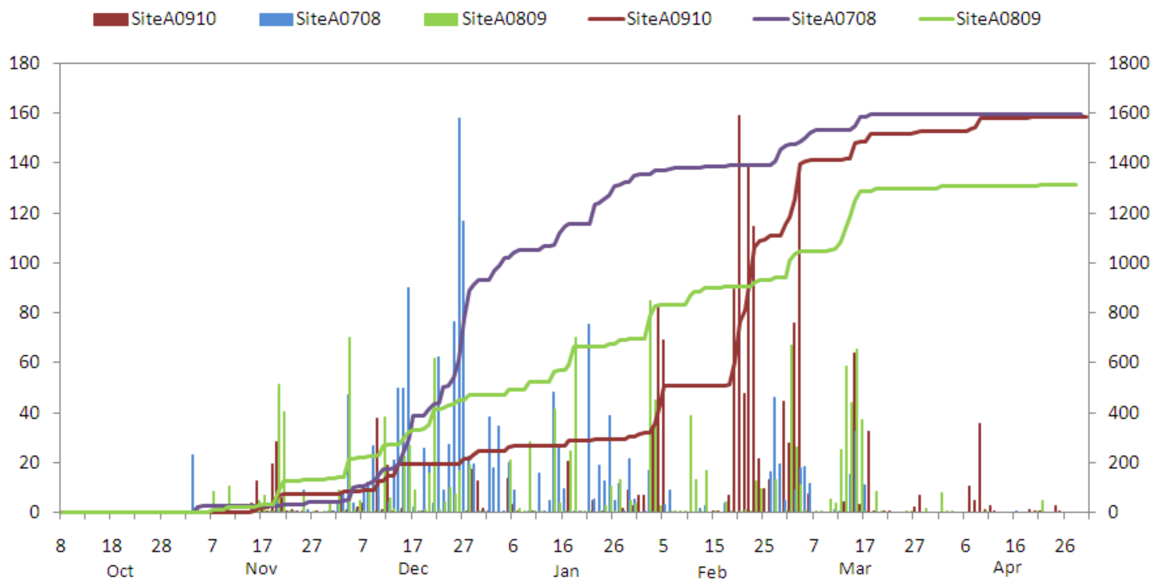


Fig. 2 Daily mean and accumulated precipitation (mm) at site *A* from November 1 to April 30 for the two rainy seasons (2007/08 and 2008/09). Precipitation was averaged over the 16 rain gauges.

regards to the global atmospheric field occurred during these periods. An *El Nino* event occurred from Spring 2007 to Summer 2008 and a *La Nina* event occurred from Summer 2009 to Spring 2010 (seasons for the northern hemisphere). These events affect global weather conditions, causing, for example, unusual rainfall and flooding, drought and forest fires, warm winters, cool summers.

So, the difference in the timing of rainfall in the two rainy seasons was possibly affected by these *El Nino* and *La Nina* events, and we now have measurements for three different cases: *El Nino*, *La Nina*, and the common (2008/2009 season) year.

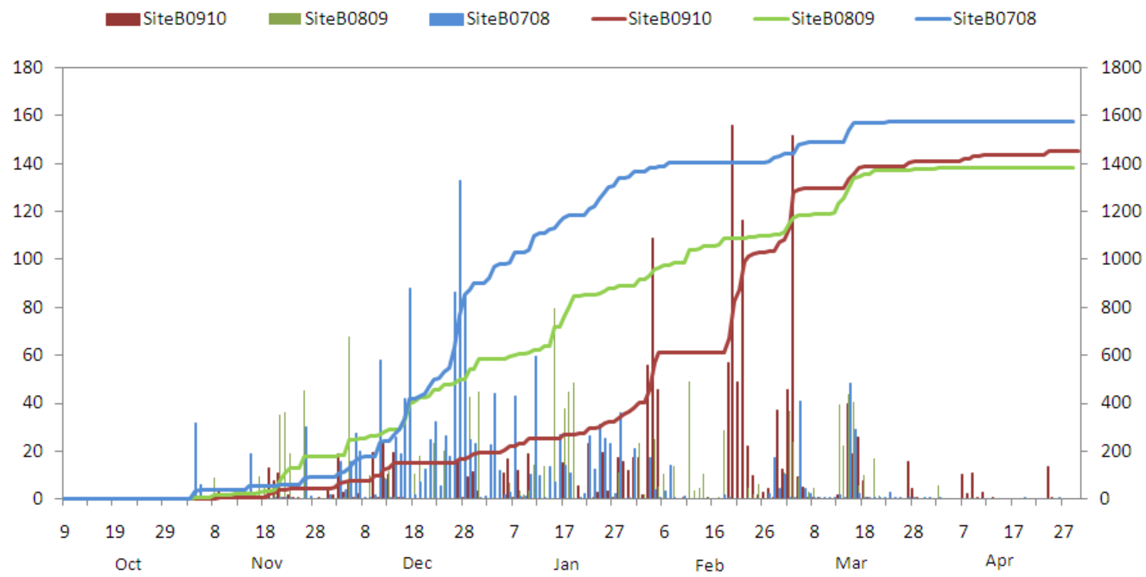


Fig. 3 As in Fig. 2 except for site *B*.

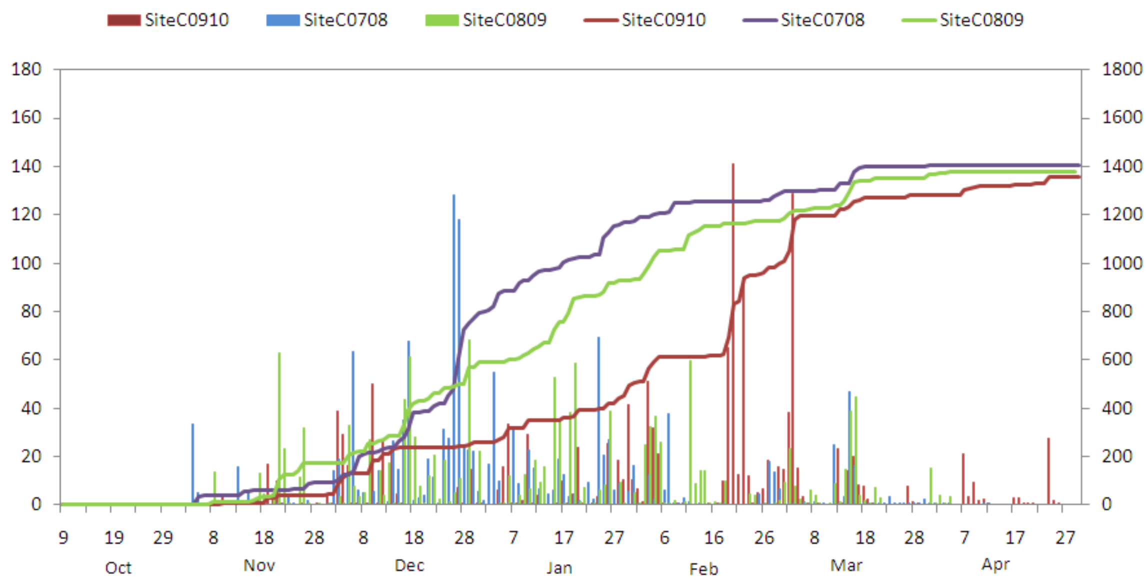


Fig. 4 As in Fig. 2 except for site *C*.

Distinct diurnal variations are present in the hourly precipitation values in the 2009/10 rainy season (Fig. 5), with high precipitation occurring between 1700 and 0200 hours at all sites. In comparison to the previous two rainy seasons, the two peaks in rainfall at 2100-2200 and 2400-0100 at site ***A*** are unique features. In the morning, site ***A*** has an indistinct peak around 0500, site ***B*** has a distinct peak at 0600 and ***C*** has a peak at 0700-0800. It seems that the morning rain moves from site ***A*** (lowland) to site ***C*** (highland). In the daytime from 1000 to 1500, there was little rain at each of the three sites. In a comparison of the three rainy seasons, there was little daytime rain observed in the 2008/09 and 2009/10 seasons; however, in the 2007/08 rainy season, distinct daytime rain was observed. Since the 2007/08 rainy season was an *El Nino* year, the atmospheric circulation may have been different from the other two rainy seasons. In conclusion, midnight rain around 2000-0100 was common in all three rainy seasons, but daytime rain was observed only in the 2007/08 rainy season, which may be attributable to the *El Nino* phenomenon occurring at this time.

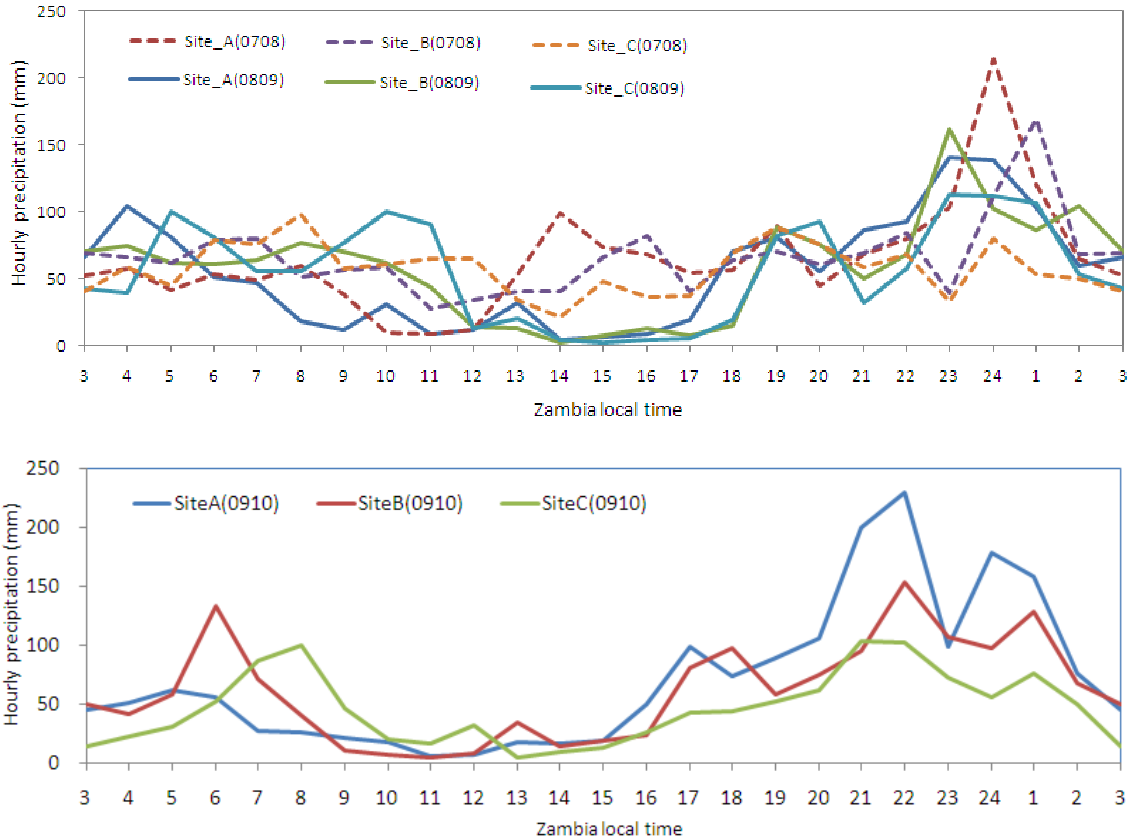


Fig. 5 Hourly precipitation (mm) from November 1 to April 30 for three rainy seasons (upper: 2007/08 and 2008/09, lower: 2009/10) at sites *A*, *B* and *C*.

3. Meteorological observation station data

In this section, daily and hourly variations of meteorological parameters other than precipitation at site ***A*** are discussed. The analysis period is from September 2007 to August 2010, and the annual features will be discussed. Analysis of data from site ***C*** was not conducted due to poor data recovery owing to instrument failure.

3.1. Temperature and humidity

Figure 6 shows the time variation of temperature and relative humidity at site ***A***.

Temperatures reach a maximum value from October to December, just before and following the onset of the rainy season. In the rainy season (from November to March), temperatures gradually decrease, and after the rainy season, this rate of decrease becomes large and temperatures fall until June-July.

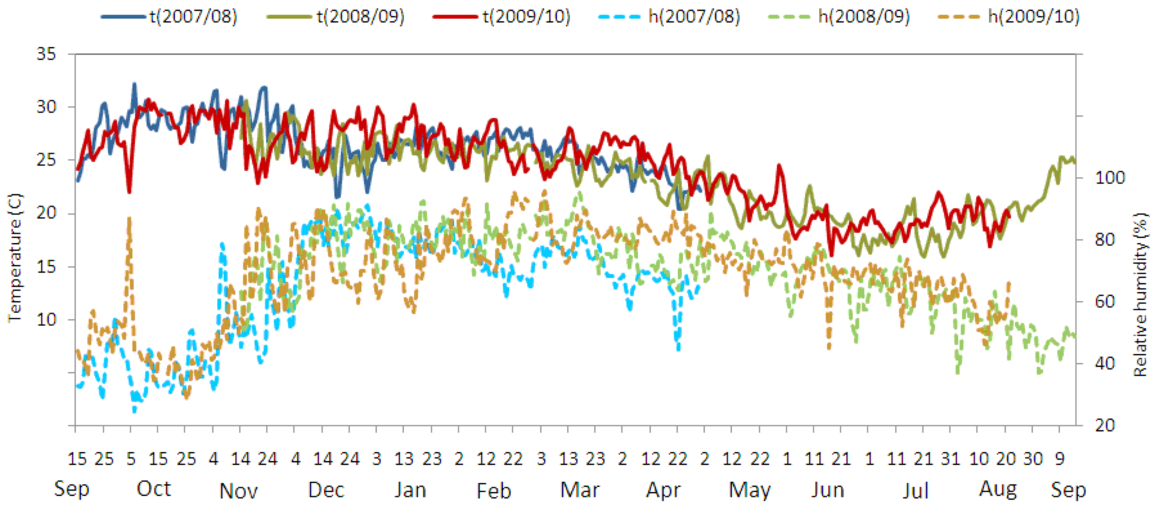


Fig. 6 Time series of temperature (t) and relative humidity (h) at site *A* in three rainy seasons (2007/08, 2008/09 and 2009/10).

Relative humidity shows minimum values of around 30-40 % from September to October, and then rises rapidly with the beginning of the rainy season. After December, humidity is maintained at 60-80 % until April, and then gradually decreases. The relative humidity was distinctly lower around December to January in the 2009/10 rainy season (*La Nina* year) than for the other two rainy seasons, during which period there was little rain. Also, the relative humidity from late March to April 2010 maintained higher values than during the other two rainy seasons. On the other hand, humidity from February to April in 2007/08 season (*El Nino* year) was lower than the other rainy seasons, and there was a little rain after February 2008. Consequently, humidity showed different temporal variations in the *El Nino* and *La Nina* years, which indicates that the difference in precipitation between those seasons may have been produced by large atmospheric variations.

3.2. Equivalent potential temperature and mixing ratio

Figure 7 shows the time variation of equivalent potential temperature (θe) and mixing ratio (x) over the three rainy seasons. These values simultaneously rise in early November, indicating the arrival of the air mass that produces the rainy season around this period. Therefore, in spite of the interannual variations in precipitation, the air mass movement may occur at nearly the same time in each of the three years. On the other hand, a distinct difference is seen in the period from late March to April, whereby θe and x in 2007/08 and 2008/09 seasons rapidly drop at the end of the rainy season, but in 2009/10, they maintain a high value, same as that in the rainy season, until April. These differences might be produced by the large-scale atmospheric variations peculiar to the *La Nina* year.

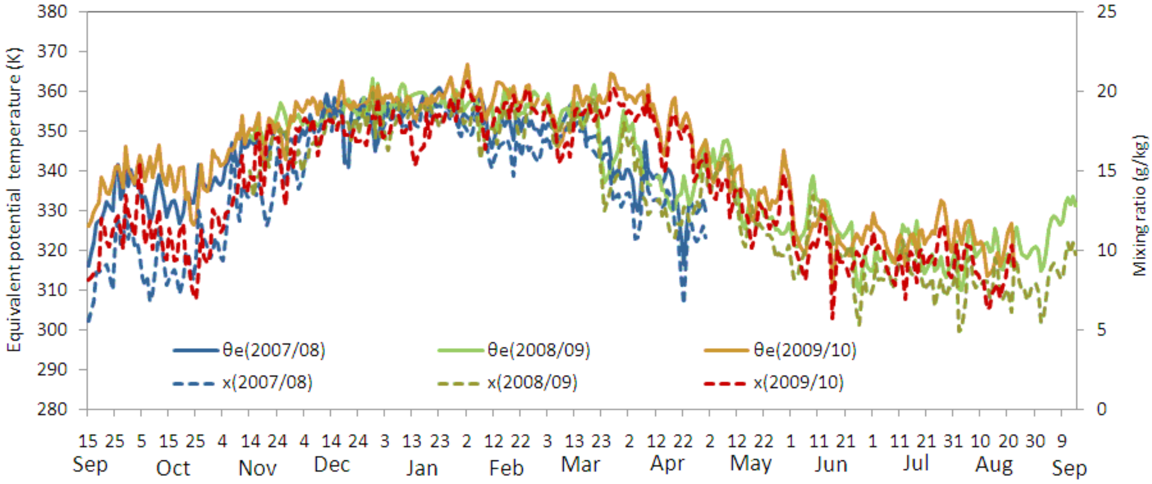


Fig. 7 Time series of equivalent potential temperature (*θe;* K) and mixing ratio (*x*; g/kg) at site *A* in three rainy seasons.

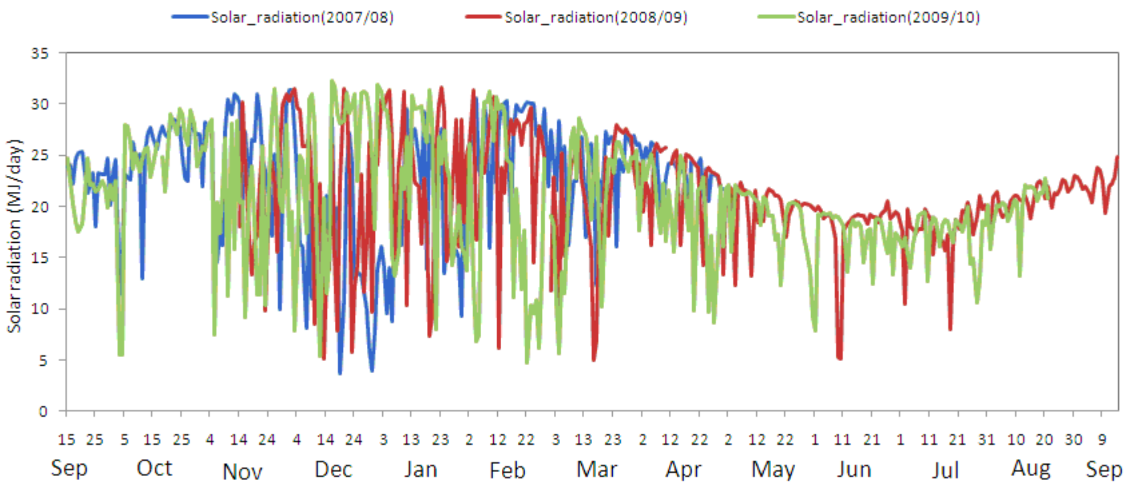


Fig. 8 Time series of daily solar radiation (MJ) at site *A* for three rainy seasons.

3.3. Solar radiation

Figure 8 shows the time series of daily solar radiation over each of the three rainy seasons. The value on a clear day indicates the annual cycle in solar radiation: the maximum values were observed in the rainy season from December to February, and the minimum were around June and July. In the rainy season, the values of solar radiation in each of the three years indicate the characteristic inter-seasonal change. Around mid December and late January, all values dropped simultaneously, likely coinciding with cloudy and rainy weather. On the other hand, solar radiation in 2007/08 fell in early January, but did not in the other two years. Also, solar radiation was low around late February 2010. These differences might coincide with the precipitation differences in the *El Nino* and *La Nina* years, respectively. We thus identify that these climate events affect a range of meteorological elements.

4. The relation between the dry spell and the large-scale atmospheric field in the 2009/10 rainy season

As discussed in Section 2, the time series of precipitation show unique features in each rainy season. In this section, we focus on the dry period in the 2009/10 rainy season and analyze the contemporaneous moisture field, and then consider the relation between them. The data used in this section is NCEP/NCAR reanalysis data (Kalnay et al., 1996).

Figure 9 shows the surface precipitable water distribution over southern Africa from January 27 to February 5, 2010. At our observation sites, about 200 mm of rain fell in this period. The high precipitable water area is shaped like a band from the equatorial Indian Ocean to the southern part of the African continent, and around the equator on the western side of Africa, which are part of the ITCZ. Also, there is another band-like area from the southeastern coast to the western equatorial coast through the southern part of Zambia. The value at our site is ca. 37-38 kg/m^2. Therefore, the rain experienced in this period may have been brought by this moisture band. Surface precipitable water for the period from February 6 to 15 is shown in Fig. 10. In this 10 day period, there is no rain and it is recognized as a clear break in the rainy season. The band-like area across the African continent seems to be interrupted, and the value at our site is ca. 30 kg/m^2. Surface precipitable water from February 16 to 25 is shown in Fig. 11. In this period, a lot of rainfall over 500 mm was experienced. The band-like moist area extended from the Indian Ocean to our site. The value around our site is ca. 40 kg/m^2 and this may have been sufficient to produce much rain.

Consequently, the break in the 2009/10 rainy season was associated with the variation in the large-scale moisture field, that is, the inter-seasonal variation of the ITCZ. Therefore, it is possible that the variation in precipitation at the three study sites is a local phenomenon, but that the global atmospheric variation also affects them. A numerical meteorological model experiment using the global objective analysis data as input should be effective for the analysis of the variation in the distribution of local precipitation.

5. Numerical simulation experiments

In this section, a numerical meteorological model was used for the simulation of the spatial distribution and temporal variation of local precipitation at the study site. The model used in this study was the Weather Research & Forecasting Model (WRF) ver. 3.2. The input data sources were as follows: the objective analysis data were NCEP/NCAR reanalysis data, the vegetation data were supplied via the MODIS (MODerate resolution Imaging Spectroradiometer) product, soil data were from the World Soil Resources Map Index, and the topography data were sourced from U.S. Geological Survey's GTOPO30.

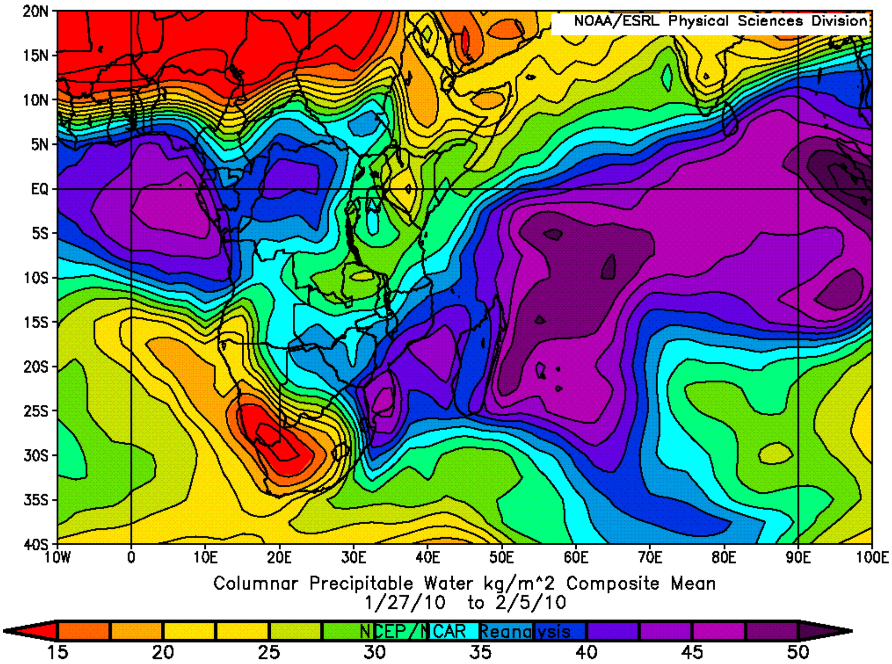


Fig. 9 Surface precipitable water distribution over southern Africa from January 27 to February 5, 2010.

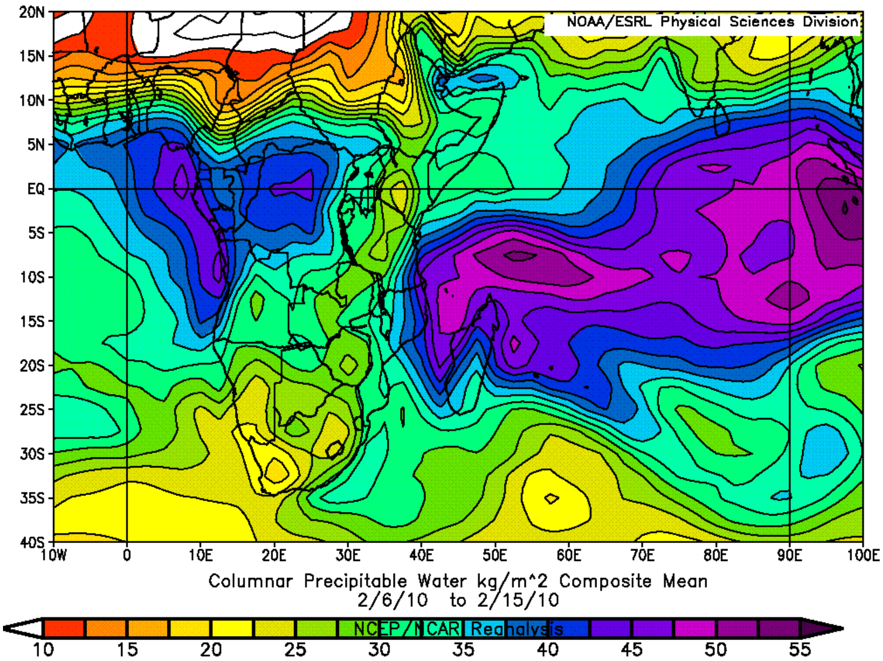


Fig. 10 As in Fig. 9 except from February 6 to 15, 2010.

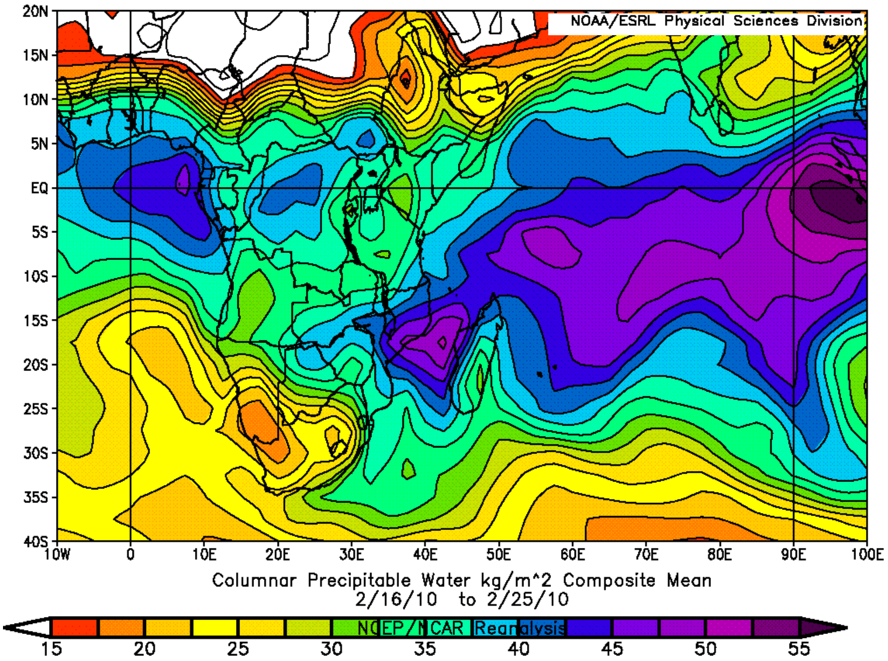
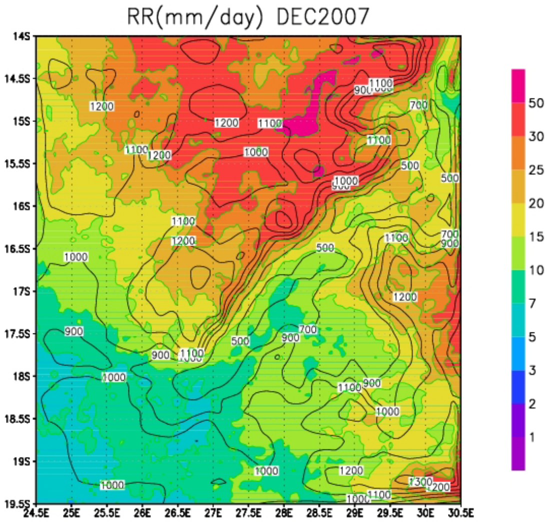


Fig. 11 As in Fig. 9 except from February 16 to 25, 2010.

Figures 12, 13 and 14 show the daily mean distribution of precipitation in December in 2007, 2008 and 2009, respectively. As already mentioned, a lot of rain fell in December in 2007 and little rain in 2009 at our sites. The results of the model simulation agree with these observations. In 2007, much precipitation was seen in the simulation results around the northern highland area and our site experienced relatively high precipitation extending from the north along the southwestward-facing slope. In 2008, precipitation was less than in 2007, and in 2009, there was the least precipitation of the three years in the vicinity of our sites.

Figures 15, 16 and 17 show the daily mean distribution of precipitation in February 2008, 2009 and 2010, respectively. According to the observations at our sites, precipitation was low in 2008 and high in 2010. The simulated distribution of precipitation in 2008 shows few rainfall areas around 16.5-18.0ºS latitude (Fig.15), and around our sites, precipitation was the lowest of the three rainy seasons. On the other hand, in February 2009 and 2010, a large precipitation area was located in the northern area, and the precipitation was highest in 2010 of the three rainy seasons around our sites (Figs.16 and 17).

Consequently, the numerical model was found to well simulate the observed distribution of precipitation in the three rainy seasons. Thus, the other simulated meteorological elements should be useful for gaining an understanding of the factors producing these weather variations. We are continuing the simulation of further meteorological elements over a longer time range, and these will be presented in a subsequent report.



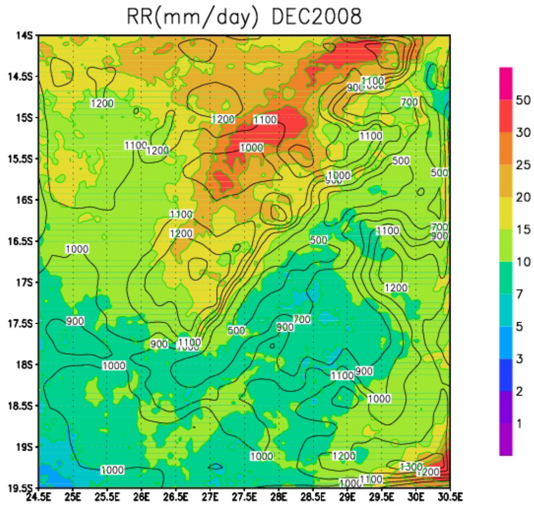


Fig. 12 Daily mean precipitation distribution in December in 2007 in Sinazongwe District, Zambia. The colorscale indicates the amount of precipitation, lines and numerals in the figure are the contour line and value. The contour interval is 100 mm.

Fig. 13 As in Fig. 12 except for 2008.

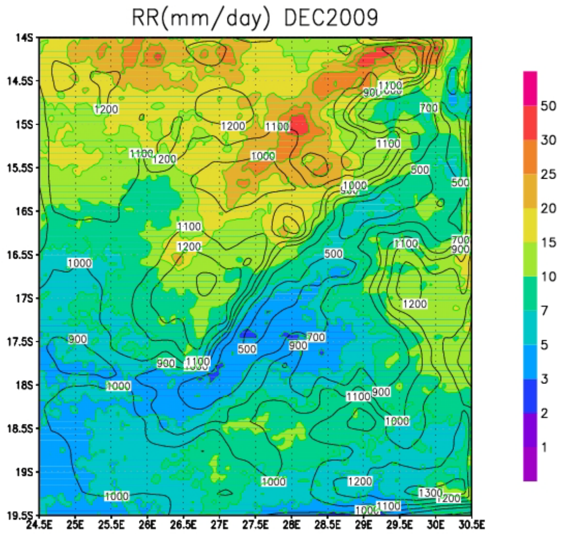


Fig. 14 As in Fig. 12 except for 2009.

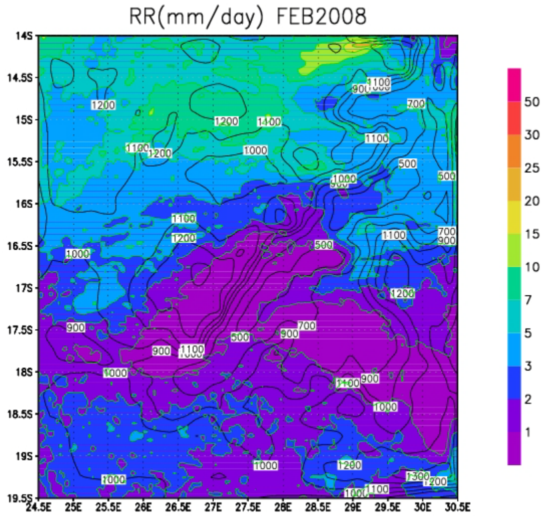


Fig. 15 Daily mean precipitation distribution in February in 2008 in Sinazongwe District, Zambia.

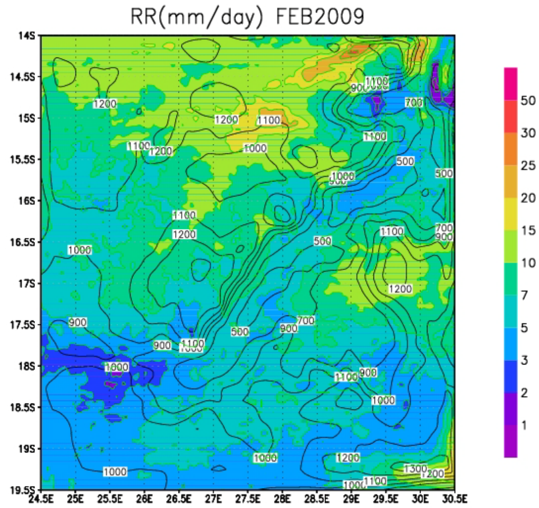


Fig. 16 As in Fig. 15 except for 2009.

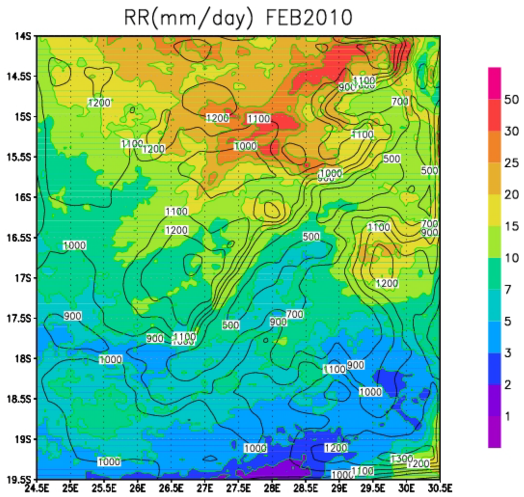


Fig. 17 As in Fig. 15 except for 2010.

6. Conclusions

Local meteorological observations were made at three research sites in the Sinazongwe District, Zambia, from September 2007 onward. The observation data were analyzed and compared over three rainy seasons: 2007/08, 2008/09, and 2009/10. The results of this analysis are summarized as follows:

1) The time series of precipitation over the three rainy seasons show distinct variations: the early stage of the 2007/08 rainy season experienced a lot of rain, but the late stage of the 2009/10 season experienced much rain. Since the 2007/08 rainy season occurred in an *El Nino* phase and the 2009/10 rainy season occurred in a *La Nina* phase, these differences were possibly produced by the differences in large scale circulation.

2) Hourly accumulated precipitation showed distinct diurnal variations, with high

precipitation between 1700 and 0200 hours at all sites throughout the three rainy seasons. In the 2009/10 rainy season, morning rain seems to have moved from the lowlands to highlands. In the 2007/08 season, there was distinct precipitation in the daytime, which may be related to the *El Nino* event.

3) Temporal variations in temperature showed a common seasonal change, but those in relative humidity showed variable characteristics. Exemplifying the difference between the *El Nino* and *La Nina* years, humidity around December to January of the 2009/10 rainy season (*La Nina* year) was distinctly lower than in the other two seasons. Also, humidity from late March to April 2010 maintained a higher value than the other two seasons. On the other hand, humidity from February to April in 2007/08 season (*El Nino* year) was lower than the others.

4) The temporal variations of equivalent potential temperature and mixing ratio show a simultaneous rise around early November, which indicates that the air mass producing the rainy season arrives around this period. In the 2009/10 season, these parameters maintain a high value until April, same as in rainy season. These differences may be produced by the large-scale variations peculiar to the *La Nina* year.

5) Around mid December and late January, solar radiation dropped in all years, which likely coincides with cloudy and rainy weather. Solar radiation fell in early January 2007/08, but not in the other two years, and in late February 2010, solar radiation was low. These differences might coincide with the temporal differences in precipitation in *El Nino* and *La Nina* years, respectively.

6) According to the large-scale precipitable water analysis, the break in the 2009/10 rainy season was likely affected by the variation of the large scale moisture field, that is, the inter-seasonal variation of the ITCZ. It is possible that the variations in precipitation at three sites are local in nature, but also affected by the variation in global atmospheric circulation.

7) The numerical meteorological model was found to well simulate the distribution of precipitation over the three rainy seasons. Thus, other simulated meteorological elements should be useful in providing an understanding of the factors producing these weather variations, and this will be investigated in a subsequent study.

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