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Analysis of Meteorological Measurements made over Three Rainy Seasons and Rainfall Simulations in Sinazongwe District, Southern Province, Zambia

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Abstract

Zambia has frequently been affected by abnormal weather and droughts. Our research focused on the type of meteorological data required to assist farmers' efforts to avoid the risks associated with these weather conditions. We conducted local meteorological observations from September 2007 to August 2010 at three sites in Sinazongwe District, Zambia. The three rainy seasons of this period coincided in sequence with La Niña (normal) and El Niño conditions. The mean annual precipitation for the three years of our study exceeded 1200 mm, which was considerably more than the regional annual average rainfall from 1970 to 2000 of around 800 mm per year. We used detailed analyses of intra-seasonal variations in other meteorological elements to attempt to explain the high precipitation. Local circulation dominated in our research area, while heavy rain induced by convection in the afternoon and night might account for precipitation exceeding the norm. We numerically simulated meteorological conditions over the past decade to determine whether the annual precipitation observed since September 2007 indeed exceeded the norm. Intra-seasonal variations in precipitation, such as high rainfall in December during the 2007/2008 rainy season, a gradual increase in cumulative precipitation through 2008/2009, and high rainfall in February in the 2009/2010 rainy season were possibly controlled by El Niño – Southern Oscillation. Our results suggest that annual variations in precipitation are common in this area and that the precipitation we observed did not necessarily exceed the norm.

Discipline: Agro-meteorology

Additional key words: El Niño, ENSO, ITCZ, La Niña, Local climate

Introduction

There has recently been growing concern about the increasing frequency of extreme climatic events and the impacts of global environmental changes. This concern is particularly serious for arid and semi-arid areas of Africa, where it is predicted that rain-fed agriculture will be severely damaged by climate change (Hassan 2010). In sub-Saharan Africa, food insecurity and famine due to drought are the most significant weather-related concerns. Two major famines in the Sahel (1972–1974 and 1983–1985) have been well studied using many approaches,

including meteorological approaches. Several researchers have also sought to understand the rainfall variability causing famines (Folland et al. 1986, Fontaine & Janicot 1996, Hastenrath 1990, Lamb 1983, Lamb & Pepler 1992). Le Barbe *et al.* (Le Barbe et al. 2002) used high-resolution data to investigate rainfall variability in West Africa and determined the spatial extent and temporal variation of rainfall on intra-seasonal and decadal time scales. Indeed, the recent climate variability attributable to global warming has heightened the importance of meteorological studies in semi-arid areas. However, in comparison with developed countries, meteorological observation networks in developing countries are scarce, particularly arid and semi-arid

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Africa, and the range of parameters observed is limited. Accordingly, for local climate studies, agriculture, and social–ecological systems in these regions, it is sometimes necessary for researchers to obtain their own meteorological data to supplement the broad regional data available from other sources.

Our study provides a rare example of local meteorological data being gathered concurrently in a drought-prone semi-arid region of Zambia. Zambia is within the Southern Africa geographic region, and covers 752,615 km² bounded by latitudes 8 to 18°S and longitudes 22 to 34°E. Most of Zambia is a plateau between 950 and 1500 m above sea level and both the climate and vegetation are sub-tropical. According to the Köppen climate classification system, northern Zambia is classified as *Cw* (humid mesothermal, winter dry period) and southern Zambia as *Bs* (dry climate, summer dry period). According to Jain (Jain 2006), Zambia experiences three distinct seasons: a warm wet season from November to April, during which 95% of annual precipitation falls; a cool dry winter season from May to July with mean temperature from 15 to 27 °C; and a hot dry season from August to October with an average maximum temperature of 27 to 32 °C. Annual rainfall varies from more than 1200 mm in the north to about 700 mm in the central region and less than 700 mm in the south.

The Zambian climate is mainly controlled by air-mass alternations (Toulmin 2010). During the dry season (May to October), Zambia is covered by a continental tropical (cT) air mass. Around November, the Inter-Tropical Convergence Zone (ITCZ) moves south from the equatorial region, leading to the inflow of a maritime tropical (mT) air mass that introduces the rainy season, which lasts until April. Because the ITCZ enters Zambia from the north, and because southern Zambia is near the southern limit of its influence, the precipitation decreases southward.

Because Zambia lies at the western end of the ITCZ, precipitation during the rainy season can be unstable; meaning droughts sometimes occur. According to the Zambia Vulnerability Assessment Committee (VAC 2006) and Lekprichakul (Lekprichakul 2007), there have been five Zambian droughts over the past 18 years (1991/1992, 1994/1995, 1997/1998, 2000/2001, and 2004/2005), during which time the yields of crops such as maize suffered due to dry weather damage. Without the drought years, the onset date of rainy season is crucial for Zambia's agriculture, whereupon the relationships among these dates, ITCZ, Angola heat low and ENSO were investigated (Hachigonta et al. 2008). The climate risk for local agriculture due to climate change was also thoroughly discussed (Stern & Cooper 2011). Conversely, Jain (Jain 2006) showed that annual mean temperatures have risen in Zambia in recent years and that the precipitation varies considerably within the country. Since the increased mean temperature in

November and December and reduced mean precipitation in January and February have caused farm revenue to decline, future climate research in Zambia should focus on both variations in weather and climate change.

This study aimed to use meteorological observations to investigate local climate change in Sinazongwe District, Zambia, and help reduce the risks posed to farmers by future climate change. We used collected meteorological data, which was then compared to precipitation estimated by meteorological numerical simulation. A numerical simulation was used to calculate the local precipitation last decade and analyze estimated normal values and temporal variations. They reveal the quantitative value before the period we start the local meteorological observation and also allow us to consider whether our observation data are received under normal or abnormal conditions.

Methods

We collected meteorological data at three sites (A, B, and C; Fig. 1) in Sinazongwe District, Zambia, from September 2007 to August 2010. Meteorological observation instruments (weather robots) were installed at Sianemba Village (site A: low elevation, 515 m; 17°05' S, 27°31' E) and Siachaya Village (site C: high elevation, 1090 m; 16°59' S, 27°20' E). The weather robots were powered by solar-charged batteries and installed in wide open areas devoid of vegetation near the center of each village. At sites A and C, observations of air temperature and relative humidity (CS215-Lx temperature and relative humidity sensor with a 41303-5A radiation shield; Campbell Scientific Inc., Logan, UT, USA), precipitation (CTK-15PC tipping-bucket rain gauges; Climatic Inc., Tokyo, Japan), and wind direction and speed (034B-Lx wind set, Campbell Scientific Inc.) were performed at 30-min intervals and recorded by a data logger (CR1000, Campbell Scientific Inc.). Wind direction was recorded as instantaneous values, while the other meteorological data (except precipitation) were recorded as 30-min means (the 30 min before data logging). Only a rain gauge (CTK-15PC) was installed at site B (Kanego Village: middle elevation, 798 m; 17°06' S, 27°19' E) with a pulse data logger (HIOKI Inc., Nagano, Japan). The observed monthly precipitation is calculated by adding the daily total precipitation for each month, while annual precipitation is the total from October to April, because there is almost no rain during the dry season and we removed the rain gauge from the fields during this period to protect it from dust and other damage.

The Weather Research & Forecasting Model (WRF) ver. 3.2 was used to simulate the weather over the study area from 2000 to 2010, thus including the period of our meteorological observations. The input data sources for the modeling were as follows: three-hourly interval meteorological

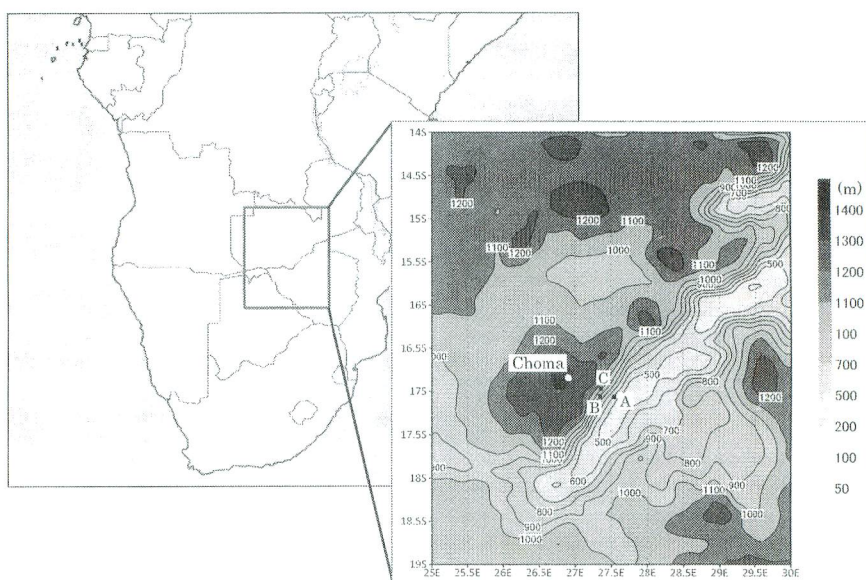


Fig. 1. Regional location map and topographical map of study area showing locations of meteorological observation sites A, B, and C of this study, and Choma, the national meteorological station; topographic contours are from GTOPO30

data (temperature, sea surface temperature, soil temperature, soil moisture, wind, absolute humidity, relative humidity, solar radiation, and standard pressure level heights) were from the National Center for Environmental Prediction (NCEP) reanalysis data set (Kalnay 1996), vegetation data were from the Moderate Resolution Imaging Spectroradiometer (MODIS) dataset, soil data were from the World Soil Resources Map Index of the National Resources Conservation Service (NRCS), and topographic data were from GTOPO30 (USGS web-site).

Results

1. Temporal variations in precipitation

(1) Comparisons of individual site precipitation for the three rainy seasons

Daily and cumulative precipitation at site A during the three rainy seasons (Fig. 2) show that rainfall in the 2007/2008 rainy season was high in December, in the 2009/2010 season rainfall was high from late February to early March, and in 2008/2009 it was relatively evenly distributed throughout the season. The difference in cumulative precipitation between the 2007/2008 and 2009/2010 rainy seasons was significant until mid-February. However, rainfall was high in late February 2010 and there was little difference (78 mm) in the total precipitation between these two rainy seasons. Interestingly, although temporal variations in precipitation at site A differed among the three rainy

seasons, the differences in total precipitation among the three seasons were less than 257 mm.

Comparison of the 2007/2008 and 2009/2010 rainy seasons at site A showed that the maximum difference in cumulative precipitation was 1047 mm on 31 January. In the 2009/2010 rainy season, precipitation increased suddenly in late February. Interestingly, there was a distinct break of almost no rain for ten days in mid-February 2010, which was followed by more than 1000 mm of precipitation in a short period, resulting in total precipitation for the 2009/2010 rainy season slightly exceeding that of the 2007/2008 season. In the 2007/2008 and 2008/2009 rainy seasons, there was little rain after late February.

The dry spell and late rain in 2010 showed distinct inter-seasonal variations at site A. It appears that there was a pause in the southward movement of the ITCZ in 2009/2010 such that its full effect at site A was delayed. Accordingly, the southward movement of the ITCZ was likely an important control on variations in precipitation during the 2009/2010 rainy season.

At site B, although the temporal variations in each of the three rainy seasons resembled those at site A, the greatest difference in cumulative precipitation among the three seasons (1002 mm on 28 January) was smaller than at site A (Fig. 3).

At site C, the temporal variations in precipitation over the three seasons resembled those at sites A and B, but the difference in cumulative precipitation between the

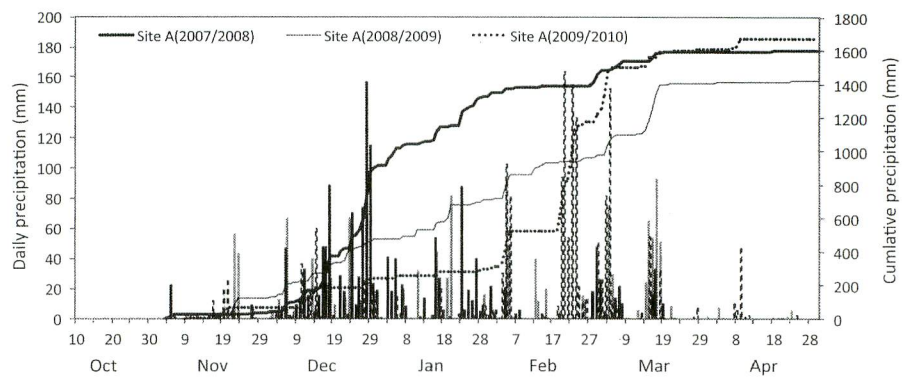


Fig. 2. Comparison of daily and cumulative precipitation at site A from 10 October to 30 April for the rainy seasons 2007/2008, 2008/2009, and 2009/2010. Bars indicate daily precipitations as the same style of cumulative precipitation

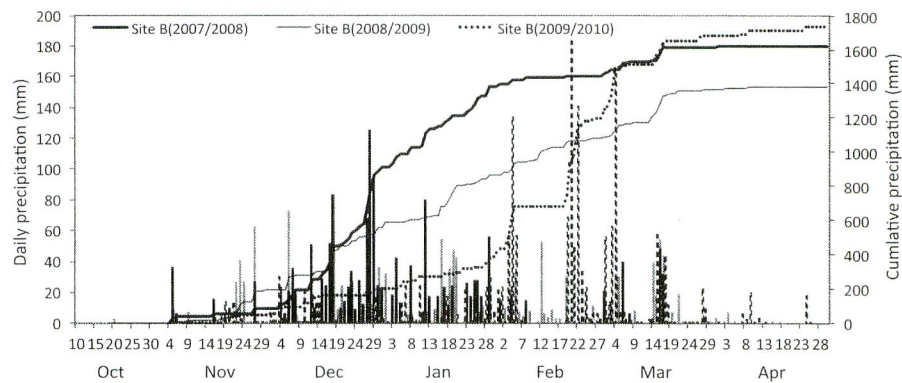


Fig. 3. Comparison of daily and cumulative precipitation at site B from 10 October to 30 April for the rainy seasons 2007/2008, 2008/2009, and 2009/2010

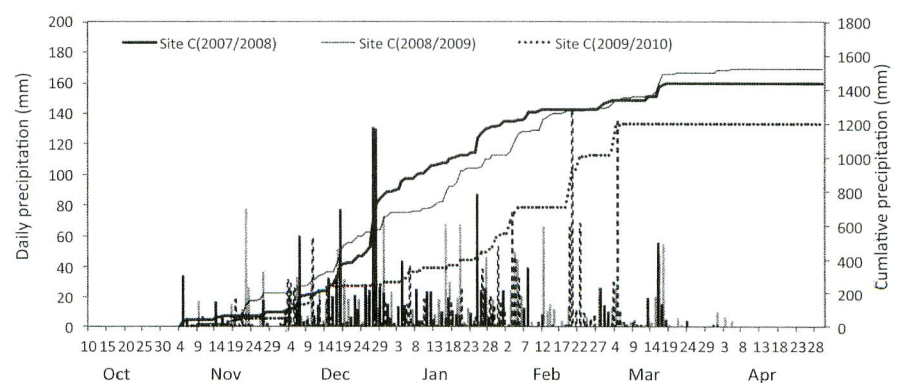


Fig. 4. Comparison of daily and cumulative precipitation at site C from 10 October to 30 April for the rainy seasons 2007/2008, 2008/2009, and 2009/2010

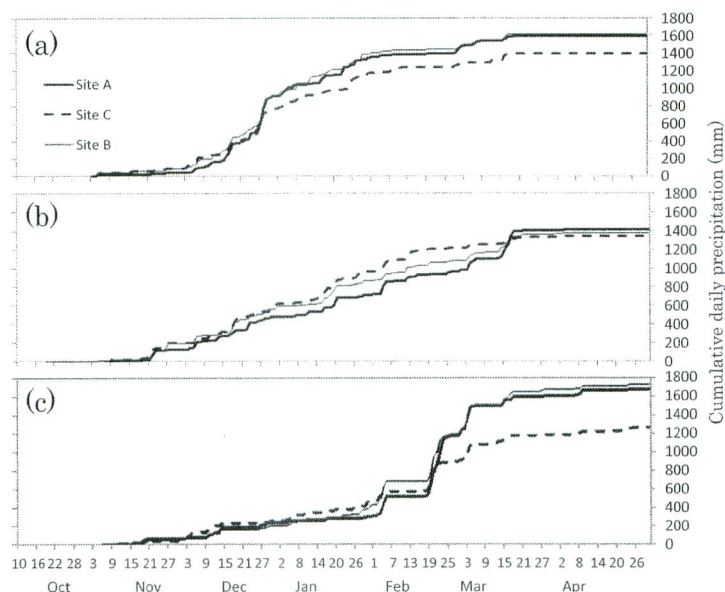


Fig. 5. Comparisons of daily cumulative precipitation at sites A, B, and C from 10 October to 30 April for the rainy seasons a) 2007/2008, b) 2008/2009, and c) 2009/2010

2007/2008 and 2009/2010 rainy seasons (723 mm on 27 January) was smaller than that at other sites (Fig. 4). Temporal variations in cumulative precipitation at site C in 2007/2008 and 2008/2009 showed similar increasing trends, but precipitation in the 2009/2010 season was lower and showed different patterns of variation than in 2007/2008 and 2008/2009.

(2) Comparison among sites of precipitation for each rainy season

The time series of cumulative daily precipitation for each rainy season at sites A and B show similar patterns (Fig. 5), although they differ from that of site C. At site C, total precipitation in 2007/2008 exceeded that of the two subsequent seasons. In 2008/2009, total precipitation was only marginally lower at site C, but in 2009/2010 it was considerably lower and showed more complex variations than in the preceding seasons: cumulative 2009/2010 rainfall at site C was highest until mid-February, but lowest from late February onwards.

These different patterns of precipitation indicate that rain-bearing systems at low (site A), intermediate (site B), and high (site C) elevation sites differ, and, in particular, the pattern at high elevation differs considerably from the others. Although the difference in altitude between sites B and C is less than 300 m, the pattern of rainy season precipitation clearly differs between them. Differences in dominant local topography (e.g. slopes, hills, valleys, or mixed geographical features) might account for the differences in pre-

cipitation for these two sites.

(3) Diurnal variations in precipitation

Distinct diurnal variations in mean hourly precipitation were evident in the 2008/2009 and 2009/2010 rainy seasons (Fig. 6). In 2008/2009, most rain fell overnight (1800 to 0600; local time, GMT +2) and there was little rain from late morning through the afternoon (1100 to 1700). In 2009/2010 there was little rain in the middle of the day (1000 to 1500) and considerable rain from afternoon to the following morning (1600 to 0800). In 2007/2008, despite a prominent peak of precipitation at around midnight at site A, there were no distinct diurnal variations.

Comparisons among the three sites show that site A (low elevation) had distinct overnight peaks and site C (high elevation) showed relatively small diurnal variations. These observations suggest that local convection dominated at the lower elevation on the plain (site A) and produced more precipitation than at the hilltop (site C), especially during the 2009/2010 rainy season.

2. Other meteorological data

Here, we discuss daily and hourly variations in meteorological parameters other than precipitation over the period from September 2007 to August 2010. Our discussion mainly focuses on site A, because instrument failure at site C affected data recovery there. However, wind data from site C were usable from 2009 onward and are thus included in our current discussion.

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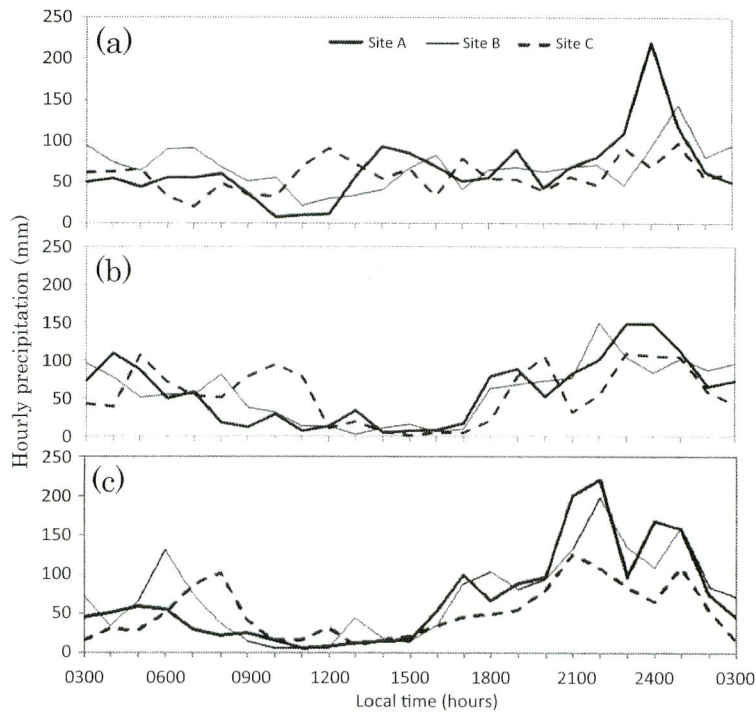


Fig. 6. Comparisons of total hourly precipitation at sites A, B, and C from 10 October to 30 April for the rainy seasons a) 2007/2008, b) 2008/2009, and c) 2009/2010

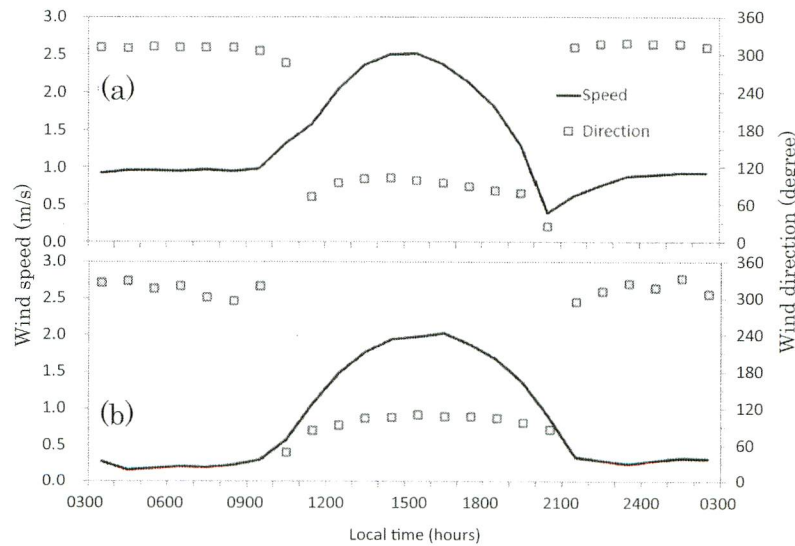


Fig. 7. Daily variations in hourly means of wind speed and wind direction at site A for the 2009/2010 dry season (upper panel, 1 Jun. to 31 Oct.) and rainy season (lower panel, 1 Nov. to 31 Mar.). Wind speed was calculated as an arithmetic mean and wind direction as a vector mean; we first separated the east–west (u) and north–south (v) components and then computed hourly averages. W_s , wind speed; W_d , wind direction

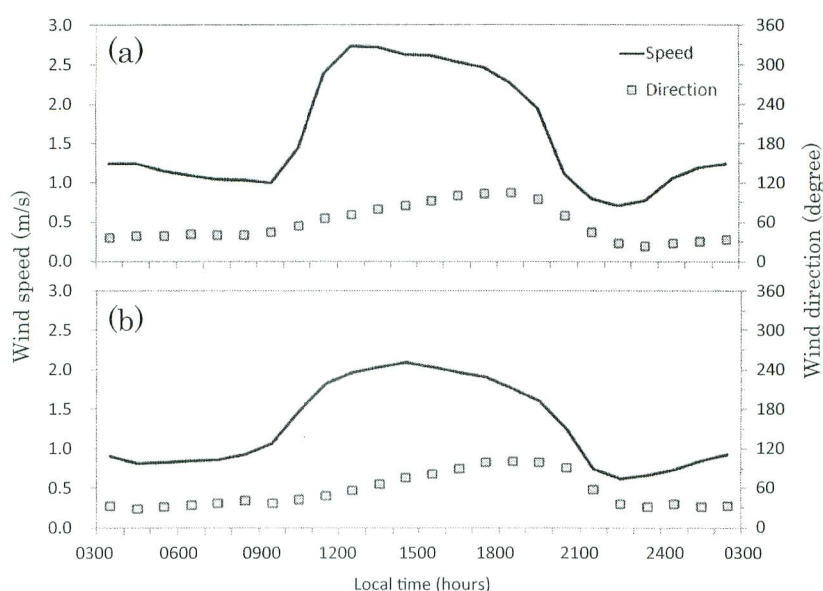


Fig. 8. Daily variations in hourly means of wind speed and wind direction at site C for the 2009/2010 dry season (upper panel, 1 Jun. to 31 Oct.) and rainy season (lower panel, 1 Nov. to 31 Mar.). Wind speed was calculated as an arithmetic mean and wind direction as a vector mean. Ws, wind speed; Wd, wind direction

(1) Diurnal variations in wind speed and direction

Similar clear diurnal variations emerged in wind direction and speed in both the dry and rainy seasons at site A (Fig. 7). At night the wind direction was stable at around 300–350° (north-westerly) during both seasons and wind speed was low, at around 1 m/s in dry season and under 0.5 m/s in rainy season. However, during the day, wind direction changed to around 100° (easterly) and wind speed increased; peaking in the early afternoon. Because site A is on the western shore of Lake Kariba, these diurnal variations are indicative of lake-breeze circulation; a north-westerly mountain wind blows from the hills at night and a stronger easterly lake breeze blows from Lake Kariba during the day. Because lake-breeze circulation is generated by differences in surface pressure between the land and lake, the weaker winds of the rainy season can be attributable to small thermal differences due to weak solar radiation during the day and radiative cooling at night.

Conversely, diurnal variations in wind speed differ on the hill top (site C, Fig. 8) from those near the lake (site A, Fig. 7). Wind speeds at site C show diurnal variations resembling those at site A, but easterly winds prevail at site C through both the dry and rainy seasons, unlike at site A. It is therefore apparent that local lake-breeze circulation is restricted to the areas of low elevation on the plain.

(2) Seasonal variations in wind speed and direction

We considered seasonal variations in wind speed and direction overnight and during the day by selecting two rep-

resentative times: 0400 (night) and 1300 (day).

From June to September at site A, wind speed and direction at night were relatively stable at around 1 m/s and 300° (Fig. 9). From October to early December however, wind direction was unstable and wind speed frequently exceeded 2 m/s; then, from mid-December onward, wind speed decreased. These data suggest that local circulation prevailed at site A at night from June to September. Synoptic disturbances at the beginning of the rainy season affected the wind, weakening the effect of local circulation during the rainy season.

At site C, there were no clear seasonal variations in wind speed or wind direction at night (Fig. 9). Wind speed oscillated above and below 1 m/s from the dry season to the end of the rainy season and wind direction varied considerably, but was dominantly around 30°.

At site A, daytime wind speed increased from June to mid-November and then abruptly weakened around the transition from dry to rainy season (Fig. 10). Daytime wind direction at site A was less variable than wind speed.

At site C there was a change of daytime wind direction at the start of the rainy season (Fig. 10). Namely, until mid-November, the daytime wind direction was stable at around 100° but became clearly unstable at the beginning of the rainy season. These observations indicate that the major variations in daytime wind direction and speed correspond to the change from dry to rainy season.

(3) Temperature and relative humidity

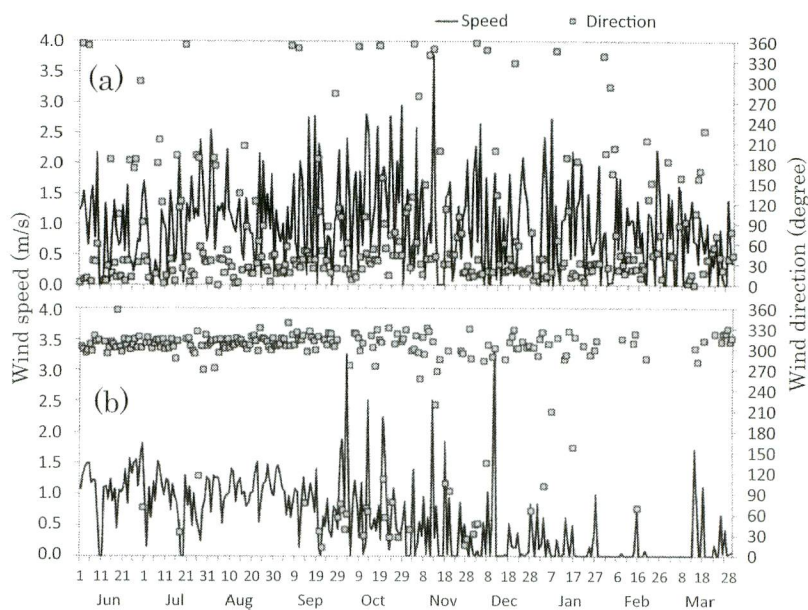


Fig. 9. Daily variations in hourly means of wind speed and wind direction at 0400 local time from 1 June, 2009 to 31 March, 2010 at site A (lower panel) and site C (upper panel). Wind speed was calculated as an arithmetic mean and wind direction as a vector mean. Ws, wind speed; Wd, wind direction

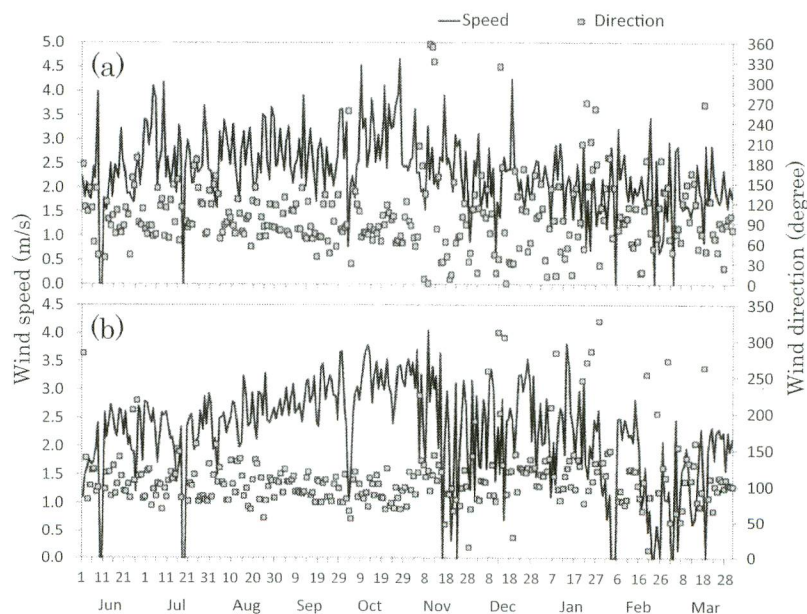


Fig. 10. Daily variations in hourly means of wind speed and wind direction at 1300 local time from 1 June, 2009 to 31 March, 2010 at site A (lower panel) and site C (upper panel). Wind speed was calculated as an arithmetic mean and wind direction as a vector mean. Ws, wind speed; Wd, wind direction

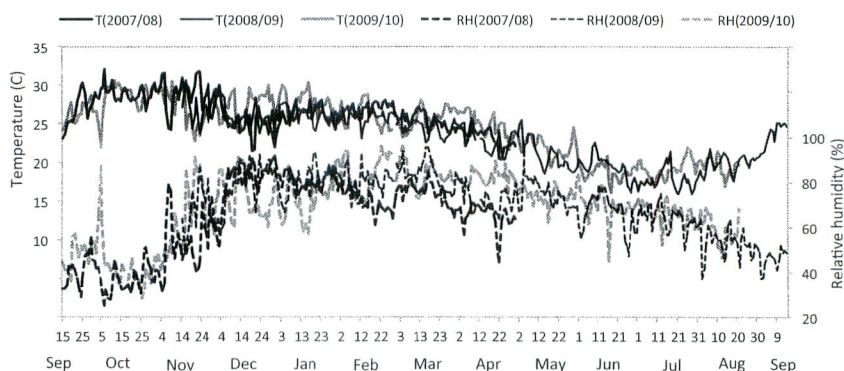


Fig. 11. Time series of daily means of temperature (T) and relative humidity (RH) at site A for 2007/2008, 2008/2009, and 2009/2010

Temperature and relative humidity data at site A (Fig. 11) are complete for the three rainy seasons (November–March), but data from May to October 2008 are missing owing to failure of the data logger. Temperatures at site A peaked from October to December, immediately before and after the onset of the rainy season, but decreased gradually during the rainy season. At the end of the rainy season, the rate of temperature decrease accelerated and temperatures fell continuously until June.

At site A, relative humidity was lowest (30–40%) from September to October, and then rose rapidly at the onset of the rainy season (Fig. 11). The resulting high humidity (60–80%) was maintained from December to April and then gradually decreased. From December to January of the 2009/2010 rainy season, when there was little rain, relative humidity at site A was distinctly lower than in the same periods of 2007/2008 and 2008/2009. Similarly, relative humidity from late March to April 2010 exceeded the figure during the same periods of the other rainy seasons. Conversely, relative humidity at site A from February to April of the 2007/2008 season was lower than in the other rainy seasons, and there was little rain at site A from February to April 2008.

Clearly, relative humidity showed different temporal variations during the three rainy seasons, indicating that differences in precipitation among those seasons may reflect large-scale atmospheric variations, such as spatial or temporal differences in the southward movement of the ITCZ.

3. Numerical simulations

The distribution of simulated daily mean precipitation in the study area in December 2008 (Fig. 12) shows significant precipitation in the highlands in the north of the study area and extending along the south-east-facing slope bordering the highlands. The precipitation generally decreases gradually from north to south, which accords with the pre-

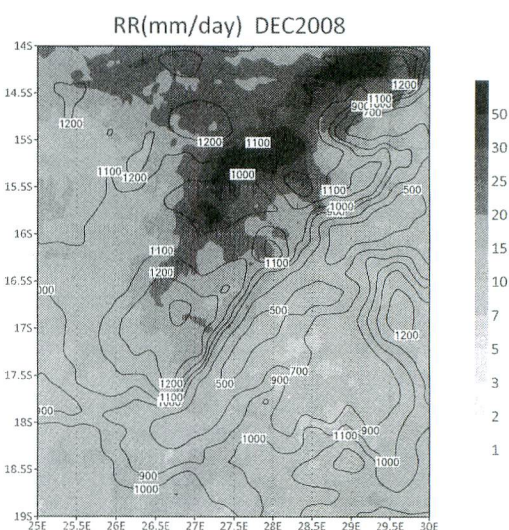


Fig. 12. Simulated distribution of daily mean precipitation in the study area for December 2008. The color scale indicates precipitation; topographic contours are from GTOPO30

cipitation distribution of Jain (Jain 2006).

Although we observed meteorological data from both sites A (beside Lake Kariba) and C (upper hills), we focus here on site C. This is because its higher elevation makes it more susceptible to prevailing winds, hence it would be expected to provide more representative simulations than site A, and also because the positions of site C and the Choma station are similar. The time series of observed and simulated daily mean temperature and relative humidity at site C during the 2009/2010 rainy season (Fig. 13) generally match well, apart from sudden drops in observed temperature (e.g. in early October). Simulated relative humidity matched observed data well in the dry season (from May to

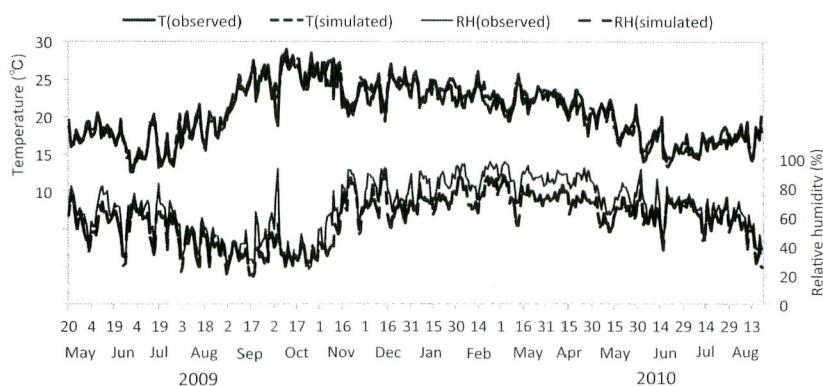


Fig. 13. Time series of observed and simulated temperature (T) and relative humidity (RH) at site C during the 2009/2010 rainy season

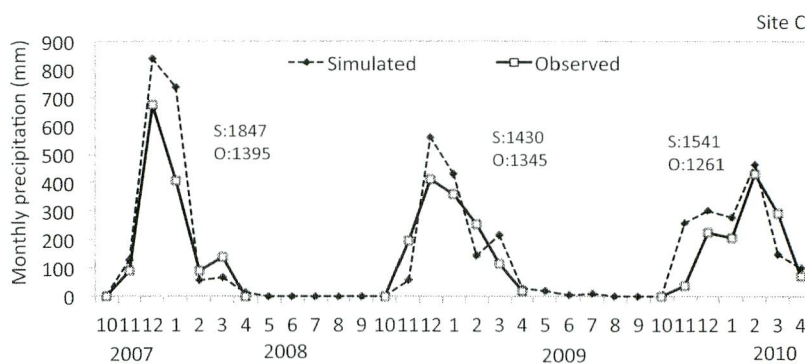


Fig. 14. Monthly observed (O) and simulated (S) precipitation from 2007 to 2010 at site C

October). However, relative humidity during the rainy season tended to be under-estimated, suggesting that simulating humidity was more difficult than temperature in this area.

Although our simulation of monthly precipitation over the three rainy seasons at site C (Fig. 14) considerably over-estimated precipitation in some instances (e.g. January 2007 and November 2009), the differences for other months were generally around 100 mm, and seasonal variations were well simulated. The total simulated precipitation for each rainy season exceeded the observed precipitation (Fig. 14): by 452 mm in 2007/2008, 85 mm in 2008/2009, and 280 mm in 2009/2010 respectively. Accordingly, we need to take this over-estimation into account when evaluating seasonal and annual variations in precipitation.

Discussion

1. Observational data

Although we expected our meteorological observations to show similar trends in the three rainy seasons, our data

revealed different intra-seasonal variations among the seasons. Peak precipitation occurred early in 2007/2008, at the usual time in 2008/2009, and late in 2009/2010, but total precipitation among the three seasons was similar. These intra-seasonal differences may be related to the timing of the southward movement of the ITCZ. The 2007/2008 rainy season was during a La Niña year, the 2008/2009 season was a normal year, and the 2009/2010 season was during an El Niño year (Japan Meteorological Agency web-site). Needless to say, El Niño – Southern Oscillation (ENSO) is known to strongly affect global and African weather (Farmer 1988, Janowiak 1988, Lindesay et al. 1986, Nicholson 1886a, Nicholson 1886b, Nicholson & Entekhabi 1987, Nicholson & Palao 1993, Nicholson 1993, Nicholson & Kim 1997, Ropelewski & Halpert 1987, Ropelewski & Halpert 1989, Semazzi et al. 1988, Van Heerden et al. 1988, Wolter 1989). Also, in Africa, the southward movement of the ITCZ is restricted under El Niño conditions (Toulmin 2010) such that areas at the southernmost limit of its annual migration are deprived of rain. Accordingly, the intra-sea-

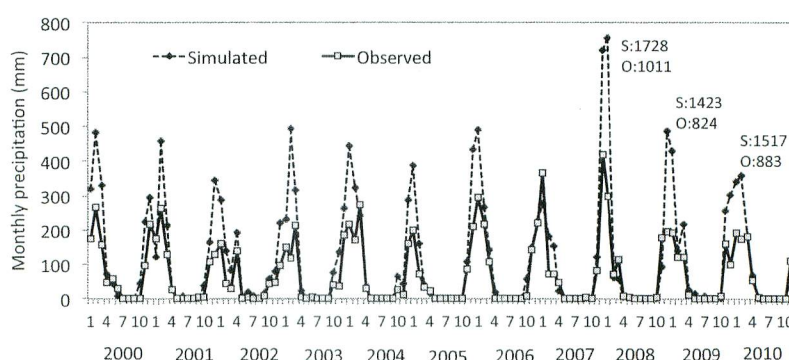


Fig. 15. Monthly observed (O) and simulated (S) precipitation from 2000 to 2010 at the Choma national meteorological station

sonal variation of precipitation that we observed during the 2009/2010 rainy season may reflect the effect of El Niño on the southward migration of the ITCZ. La Niña has the opposite effect on global climate, meaning the peak of precipitation in December of the 2007/2008 rainy season might reflect the influence of La Niña. Of course, our observation periods were too short to confirm the relationships between annual variations and the ENSO and we may have observed the data to discuss these relationships in a local context.

At each of our sites, the annual precipitation observed was above 1200 mm, which exceeded the climatological norm (average rainfall from 1970 to 2000 from precipitation distribution map in Jain (Jain 2006)) up to 600 mm. At Choma, the national meteorological station closest to our study area, the observed rainy season precipitation exceeded the climatological norm (1981–2010 mean) of 766 mm in 2007/2008 (1011 mm), 2008/2009 (824 mm), and 2009/2010 (883 mm), but was lower than that recorded at each of our sites in the same seasons. Choma is on a plateau at an elevation of about 1400 m, some 90 km north-west of our study area (Fig. 1). In terms of meteorological phenomena, the distance separating Choma from our study sites is insignificant and cannot in itself explain the differences in precipitation. Our observation sites lie on the south-east-facing slope below the plateau, and local circulation dominates at the lowest site (A, beside the lake). The clear diurnal variations in precipitation at our sites (Fig. 6) suggest that strong afternoon convection produced heavy afternoon rain and that differences in topography among our three sites affected precipitation. Accordingly, local meteorological observations are important and necessary to gain an understanding of the local climate.

2. Correction of over-estimated precipitation data

Although our simulation of data for the period 2000 to 2010 over-estimated rainy season precipitation at Choma

meteorological station, seasonal variations were modeled reasonably well (Fig. 15). We corrected for this over-estimation by calculating the percentage annual deviations of the simulated data from the simulated 10-year mean and adding these amounts to the observed 10-year mean (Fig. 16). The corrected model matched the observed data well, except for the rainy seasons of 2000/2001 (243 mm higher) and 2003/2004 (240 mm lower). Since these two deviations were within 30% of the 10-year average (825 mm), we considered them reasonable. We also think that the virtually flat deviation from each year precipitation might reflect the peculiar bias of the WRF model, and then the deviation percentage variation possibly indicates the nearly accurate temporal trend.

We then applied the same method to determine annual deviations from the 10-year mean at sites A, B, and C from 2000 to 2010. Figure 17 shows significant fluctuations from the 10-year mean. Rainfall far exceeded the 10-year mean in 2000/2001, and was considerably lower in 2004/2005 (a drought year in Zambia) and 2006/2007. Since the estimated precipitation amounts were less than these large deviations in our observed years, we could confirm that three rainy seasons from 2007 to 2010 might not be unusual. The difference between our sites and Choma might be attributable to differing topological effects such as strong night rain produced by the local atmospheric circulation.

3. Importance of acquiring local scale precipitation

Although the annual precipitation we observed from 2007 to 2010 at our three sites considerably exceeded the climatological norm, the corrected 10-year simulation data suggest that the annual rainfall was not unusual. Moreover, heavy rain in December during the 2007/2008 rainy season produced severe flooding at site A (Fig. 2). It is therefore clear that regional seasonal means of precipitation provide insufficient data to assess the possible impacts of localized

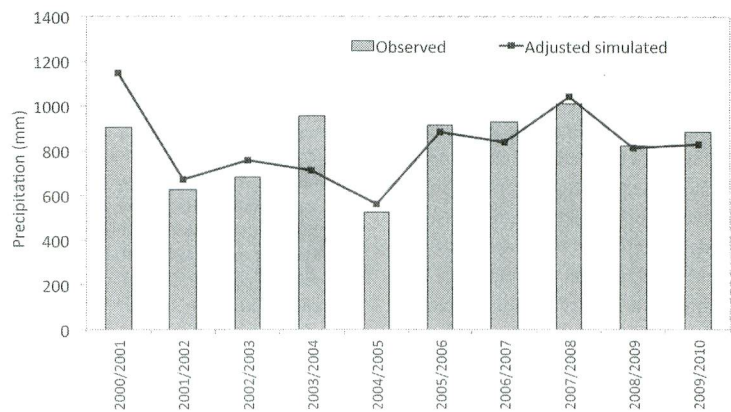


Fig. 16. Annual observed and simulated precipitation from 2000 to 2010 at Choma national meteorological station after correction for over-estimation. Annual precipitation is measured from July to June. See text (section 4.3) for details of the correction method

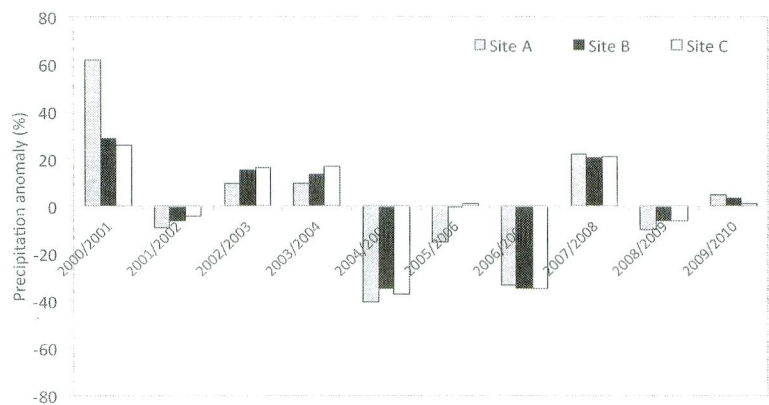


Fig. 17. Deviations from 10-year mean (2000–2010) of corrected simulated annual precipitation at sites A, B, and C

short-term heavy rain on human activities; the acquisition of monthly data on a local scale is crucial.

Conclusion

We compared local meteorological observations at three sites in the Sinazongwe District, Zambia over three rainy seasons: 2007/2008, 2008/2009, and 2009/2010.

There were distinct differences in the patterns of observed precipitation over the three rainy seasons: high rainfall early in the 2007/2008 rainy season and late in the 2009/2010 season. The differences peaked at the lowest site (A) and were smallest at the highest site (C). Annual precipitation at all three sites exceeded 1200 mm, considerably more than the climatological norm of about 800 mm. Hourly cumulative precipitation showed distinct diurnal

variations: rain during the afternoon and night and dry periods from morning to noon. Also wind speed and wind direction at the lowest site showed distinct lake-breeze circulation throughout the year. These variations may be attributable to unstable stratification conditions in response to heating by strong solar radiation. Precipitation exceeding the climatological norm at the three sites may reflect local climatic conditions.

The three rainy seasons from 2007 to 2010 corresponded in turn with La Niña, normal, and El Niño conditions. The intra-seasonal variations in precipitation (e.g. high rainfall in December of the 2007/2008 rainy season and in February of the 2009/2010 rainy season) appeared driven by ENSO. Temporal variations in temperature, wind and humidity appeared markedly sensitive to large-scale atmospheric movements, such as ENSO and the southward

movement of the ITCZ. If the relationships we inferred between ENSO and local weather in Zambia are correct, it may be possible to use them to provide forecasts of intra-seasonal differences in precipitation to assist agricultural water management.

Our numerical simulations of temperature and relative humidity agreed well with data observed at meteorological stations. Although the simulated total precipitation in the study area tended to exceed the observed data, seasonal variations were simulated relatively well. Our 10-year numerical simulation results suggest that the study area was characterized by considerable variability of annual precipitation and that the high precipitation we recorded during the three rainy seasons did not exceed the climatological norm.

Our results show that, because of the local variability of the climate in southern Zambia, the spatial coverage of existing meteorological stations is too sparse to use in local meteorological studies. Moreover, seasonal mean data are insufficient to predict the short-term anomalous weather patterns that affect decision-making in agriculture, such as which crops to plant and when to plant them. Accordingly, local observations obtained at close spatial density and with short temporal sampling are required for meteorological research on a local scale.

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