GEOGRAPHICAL REPORTS
OF TOKYO METROPOLITAN UNIVERSITY 44 (2009) 95-102

SEASONAL METEOROLOGICAL VARIATIONS IN SOUTHERN MALI, WEST AFRICA PART 2: SEASONAL VARIATION OF UPPER AIR AND TEMPORAL SURFACE METEOROLOGICAL VARIATIONS IN 2002

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Abstract Local meteorology observations in southern Mali, West Africa were performed from 2001 to 2004. Daily precipitation data over 4 years reveal common seasonal variations, allowing the seasons to be resolved into pre-rain, early rain, break in rain, late rain and dry seasons. These seasonal cycles are closely connected with seasonal changes in surface and upper-air meteorological parameters. The diurnal variations in surface meteorological observation data also reveal a strong relationship between the daytime hour and precipitation frequency and amount, including early morning rain, a dry daytime period, and evening rain.

Key words: West Africa, Mali, rainy season, seasonal variation, upper air meteorological data, diurnal variation

1. Introduction

The semiarid regions of West Africa have suffered major drought and famine twice since the 1970s. Famine occurred in the Sahel from 1972 to 1974 and from 1983 to 1985. The recent unstable climate conditions attributed to global warming have heightened the importance of meteorological study in semiarid areas. We selected the experimental sites in Mali, and deployed suitable meteorological equipment for hourly observations from 2001 to 2004. The seasonal variations of surface meteorological observation data have been presented in Part 1 (Kanno *et al.* 2008, hereafter designate as 'Part 1'). In this report, upper air meteorological data analysis and the relationship with seasonal variation, and the diurnal change of surface meteorological data will be discussed.

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2. Data and methods

The year 2002 has been selected as a study case for analysis of seasonal variation description of Kanno *et al.* (2008), and then upper air meteorological data in same year were chosen for investigation. Although upper-air meteorological data were observed at Bamako International Airport, a large proportion of observations were missed in 2002. Upper-air observation data recorded in 2002 at Niamey, Niger are therefore used in the analysis. The Niamey station is located 3° in latitude (approx. 330 km) north of Diou, but is the nearest upper-air observation station other than the Bamako station. Data are averaged in each pentad (5-day mean). A maximum of 10 upper-air observations are available (5 days, twice daily observation, 00Z and 12Z), although there are some missing observations through the year. In the case of missing data, residual data were averaged. No upper-air observation data are available for the 72nd and 73rd pentads in 2002.

Surface meteorological observation was performed at Diou station (see Fig. 2 in Part 1). Meteorological observations of air temperature, air pressure, relative humidity, *RH* solar radiation, precipitation, wind direction and wind speed were made at 1 h intervals and stored by a data logger. Air temperature, air pressure, relative humidity, and wind direction are instantaneous values, while wind speeds are 10 min means prior to the hourly data log. The meteorological parameters are taken from contiguous data from 2002 for use in the analysis of diurnal change.

3. Results

Seasonal variations in the vertical atmospheric structure at Niamey

Time series of the vertical structure of potential temperature (θ) and *RH* obtained from upper-air observation data at Niamey in 2002 are shown in Fig. 1, the corresponding wind trace is shown in Fig. 2, and the equivalent potential temperature (θe) is shown in Fig. 3.

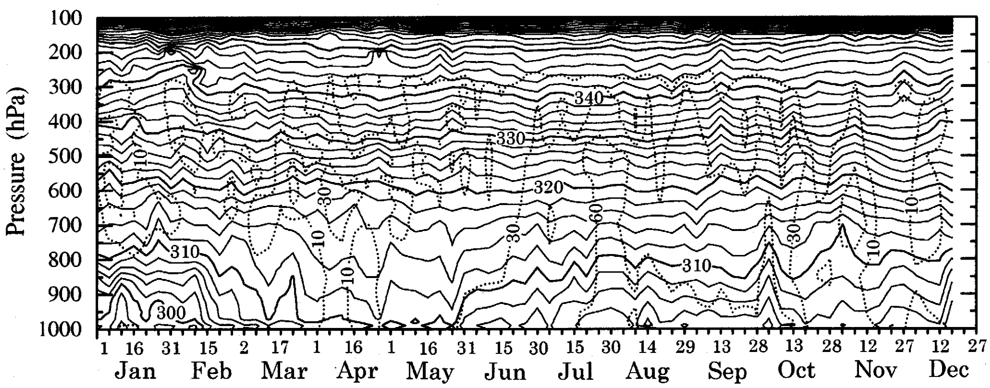

Fig. 1 Time-height cross-section of potential temperature and relative humidity at Niamey, 2002 as pentad mean values. Dot lines denote relative humidity (units: percent).

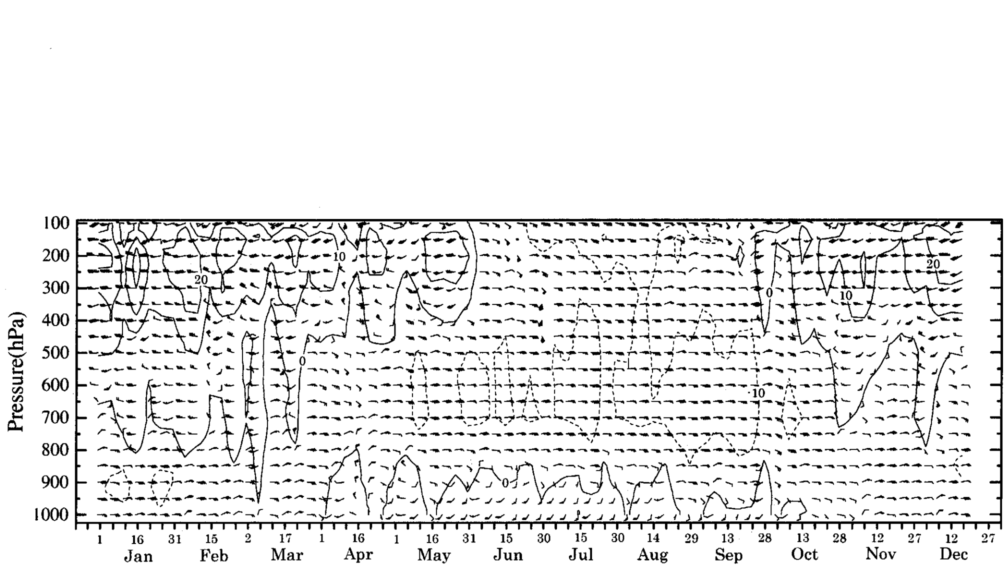

Fig. 2 Time-height cross-section of wind at Niamey, 2002. Contours denote wind speed of u-component (units: m/s).

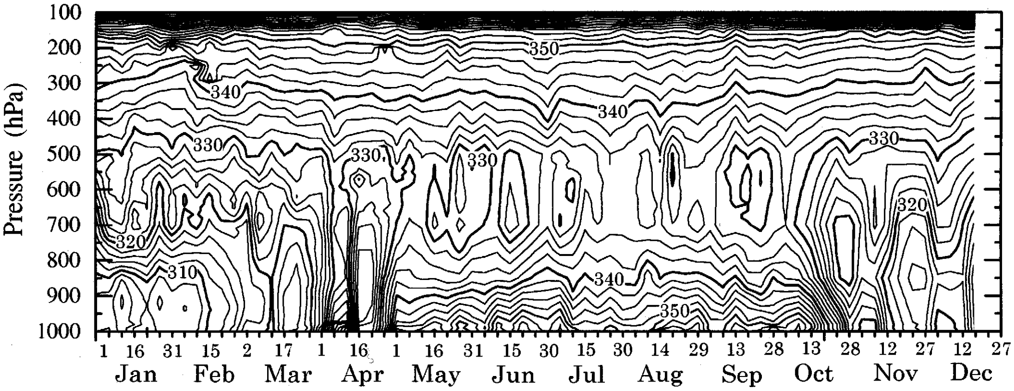

Fig. 3 Time-height cross-section of equivalent potential temperature at Niamey, 2002.

The θ-*RH* field reveals the formation of dry and very cold air of at levels below 800 hPa from January to mid-February (Fig. 1). This cold air dome disappears in March followed by a rise in temperature and an increase in θ near the ground to the largest annual value from late April to May. From the end of May, θ falls in the lower layer and *RH* rises to greater than 30%. The relative humidity rises again in mid-July to over 60%, simultaneous with the break and the beginning of the late rainy season. The region of 60% relative humidity briefly reaches the 500 hPa level and then persists in the lower layer until early October, corresponding well with the period of the late rainy season. The difference between the early and late rainy seasons can therefore be clearly recognized in the humidity field. Around mid-October, the relative humidity drops discontinuously and θ increases, almost simultaneously with the end of rainy season.

In the vertical wind field (Fig. 2), an upper westerly wind can be seen to prevail from January to May, centered around a core at approximately 200 hPa and having a wind speed sometimes exceeding 20 m/s. An easterly wind prevails in the lower layer until late March, forming a wind shear between the westerly and easterly winds at a level of 500–700 hPa. From early April, the westerly wind extends into the lower layer, simultaneous with the beginning of the pre-rainy season. This lower-layer westerly wind prevails until early October, while the upper westerly wind ends in late May and turns easterly. This wind direction change corresponds to an increase in *RH* to over 30% in the lower layer. These results suggest a large-scale air mass alternation in this period.

During the rainy season, an easterly wind prevails in the middle layer (500-700 hPa), corresponding to the tropical easterly jet stream reported to occur at the same level by Barry and Chorley (1987). When the rainy season ends, the upper westerly wind returns, the middle easterly wind weakens, and the lower westerly wind ceases. Consequently, the rainy season can be characterized by the combination of a lower westerly wind and a middle easterly wind in the vertical wind field.

The time series of equivalent potential temperature (θe) shows cold and stable stratification from January to February (Fig. 3). The stratification in March and April are semi-stable, but from May to September (including the rainy season), high θe in the lower layer and low θe at 500–700 hPa cause fully unstable stratification. From the vertical wind field (Fig. 2), this instability can be attributed to the contrast in air mass between the lower layer westerly wind and middle layer easterly wind. From October stratification becomes stable again.

Seasonal changes in surface and upper meteorological parameters

The seasonal changes in surface and upper meteorological parameters are arranged in Fig.4. As description of Kanno *et al.* (2008), based on 4 years of precipitation data, seasons and sub-seasons can be defined as follows. The period from October to March, characterized by little rain, can be defined as the dry season. Early to mid-April marks the first rains, and is followed by a period without continuous rain from late April to early May. This period from early April to early May is defined as the pre-rainy season. From mid-May until early July, rains are frequent, and this period is denoted the early rainy season. Around mid-July, rain stops briefly, defined as the break in the rainy season, followed by frequent rain until late September, constituting the late rainy season.

At the end of the dry season, certain surface meteorological parameters underwent a distinct transition (Fig. 4). The daily range of temperature, inter-day variation in humidity and solar radiation, and wind direction all changed markedly at this transition. In the upper-air fields, the relative humidity dropped simultaneously with the change in mid- and low-level wind direction. The period of the dry season and pre-rainy season can therefore be regarded as an important seasonal change. After the pre-rainy season, the early rainy season begins (mid-May) without an accompanying change in meteorological parameters.

Around the break in the rainy season, relative humidity at the surface drops briefly, while that in the upper atmosphere increases to over 60% (surface to 500 hPa). In the late rainy season, the surface temperature displays a small inter-day variation, while surface solar radiation undergoes large inter-day variations at low values and the relative humidity at the surface and in the lower atmospheric layer remains high. Therefore, the break period and subsequent late rainy season are characterized by a distinct seasonal change at the surface and in the upper-air field. Around the end of the late rainy season (beginning of the dry season), certain meteorological parameters change, including surface solar radiation, surface relative humidity, lower-layer stratification, and vertical wind profiles.

<table>
<tr><td colspan="2"></td><td colspan="9">Dry Season</td><td colspan="4">Pre Rainy Season</td><td colspan="6">Early Rainy Season</td><td>Break</td><td colspan="7">Late Rainy Season</td><td colspan="9">Dry Season</td></tr>
<tr><td colspan="2">month</td><td colspan="3">January</td><td colspan="3">February</td><td colspan="3">March</td><td colspan="3">April</td><td colspan="3">May</td><td colspan="3">June</td><td colspan="3">July</td><td colspan="3">August</td><td colspan="3">September</td><td colspan="3">October</td><td colspan="3">November</td><td colspan="3">December</td></tr>
<tr><td colspan="2">ten days period</td><td>early</td><td>mid</td><td>late</td><td>early</td><td>mid</td><td>late</td><td>early</td><td>mid</td><td>late</td><td>early</td><td>mid</td><td>late</td><td>early</td><td>mid</td><td>late</td><td>early</td><td>mid</td><td>late</td><td>early</td><td>mid</td><td>late</td><td>early</td><td>mid</td><td>late</td><td>early</td><td>mid</td><td>late</td><td>early</td><td>mid</td><td>late</td><td>early</td><td>mid</td><td>late</td><td>early</td><td>mid</td><td>late</td></tr>
<tr><td rowspan="7">Surface observation at Dion, Mali</td><td>Precipitation 2001-2004</td><td colspan="9">few rains</td><td colspan="2">first apparent rains</td><td colspan="2">no continuous rains</td><td colspan="6">frequent rains</td><td>interruption</td><td colspan="7">frequent rains</td><td colspan="9">few rains</td></tr>
<tr><td>temperatures in 2002</td><td colspan="9">large diurnal range</td><td colspan="11">small diurnal range
temperatures gradually decrease</td><td colspan="7">small interdiurnal variation</td><td colspan="9">diurnal range increases</td></tr>
<tr><td>Relative humidity in 2002</td><td colspan="6">around 20%</td><td colspan="3">large intradiurnal variations</td><td>blief increase</td><td colspan="9">gradually increase</td><td>drops</td><td colspan="9">keeps around 60-80%</td><td colspan="7">gradually decrease</td></tr>
<tr><td>Mixing ratio in 2002</td><td colspan="6">around 2g/kg</td><td colspan="3">large intradiurnal variations</td><td>blief increase</td><td colspan="6">gradually increase</td><td colspan="13">keeps around 16 g/kg</td><td colspan="7">gradually decrease</td></tr>
<tr><td>Solar radiation in 2002</td><td colspan="9">small interdiurnal variation</td><td colspan="10">large intradiurnal variation with about 20MJ mean value</td><td colspan="6">large interdiurnal variation with small solar radiation</td><td colspan="2">over 20MJ again</td><td colspan="9">small interdiurnal variation and gradually decreases</td></tr>
<tr><td>Wind direction in 2002</td><td colspan="5">NE</td><td colspan="4">unsettled</td><td colspan="21">SW</td><td colspan="2">unsettled</td><td colspan="4">NE</td></tr>
<tr><td rowspan="5">Upper air observation at Niamey, 2002</td><td>Stratification in lower layer (θ and θe)</td><td colspan="6">very stable</td><td colspan="6">stable but changing in short periods</td><td colspan="15">unstable</td><td colspan="9">from unstable to stable</td></tr>
<tr><td>Relative humidity</td><td colspan="9">lower than 10% below 800hPa</td><td colspan="6">generally exceeds 10%</td><td colspan="4">generally exceeds 30%</td><td colspan="2">over 60% up to 500hPa</td><td colspan="7">over 60% below 800-900hPa</td><td colspan="3">gradually decreasing</td><td colspan="5">lower than 10% below 800hPa</td></tr>
<tr><td>Wind (upper)</td><td colspan="15">strong weaterly</td><td colspan="11">easterly</td><td colspan="3">westerly</td><td colspan="7">strong westerly</td></tr>
<tr><td>Wind (middle)</td><td colspan="8">westerly</td><td colspan="7">easterly</td><td colspan="12">strong easterly</td><td colspan="9">easterly and westerly</td></tr>
<tr><td>Wind (lower)</td><td colspan="9">easterly</td><td colspan="19">westerly</td><td colspan="8">easterly</td></tr>
</table>

Fig. 4 Seasonal variations in upper and surface meteorological parameters. Surface meteorological parameters are same as in Fig.8 description in Kanno *et al.* (2008).

Diurnal variations in precipitation and surface pressure

As meteorological parameters were observed at an hourly time interval, the observation data can be used for analysis of diurnal variations. Figure 5 shows the time series of accumulated hourly mean pressure (a), precipitation per rain event (b), hourly rain frequency (c), and hourly precipitation (d) for the period from May to October. From 0100 to 0800, rain occurs frequently but the hourly precipitation is generally low, except for the activity at 0300 (2 large events of 36.7 mm and 26.9 mm). From 0900 to 1400, the frequency of precipitation drops to below 10 occasions, and the hourly accumulated precipitation becomes low. These results show that there are distinct dry periods during the day. From 1500 to 1900, both the rain frequency and precipitation increase. From 2000, precipitation decreases but the frequency does not. Evening rain

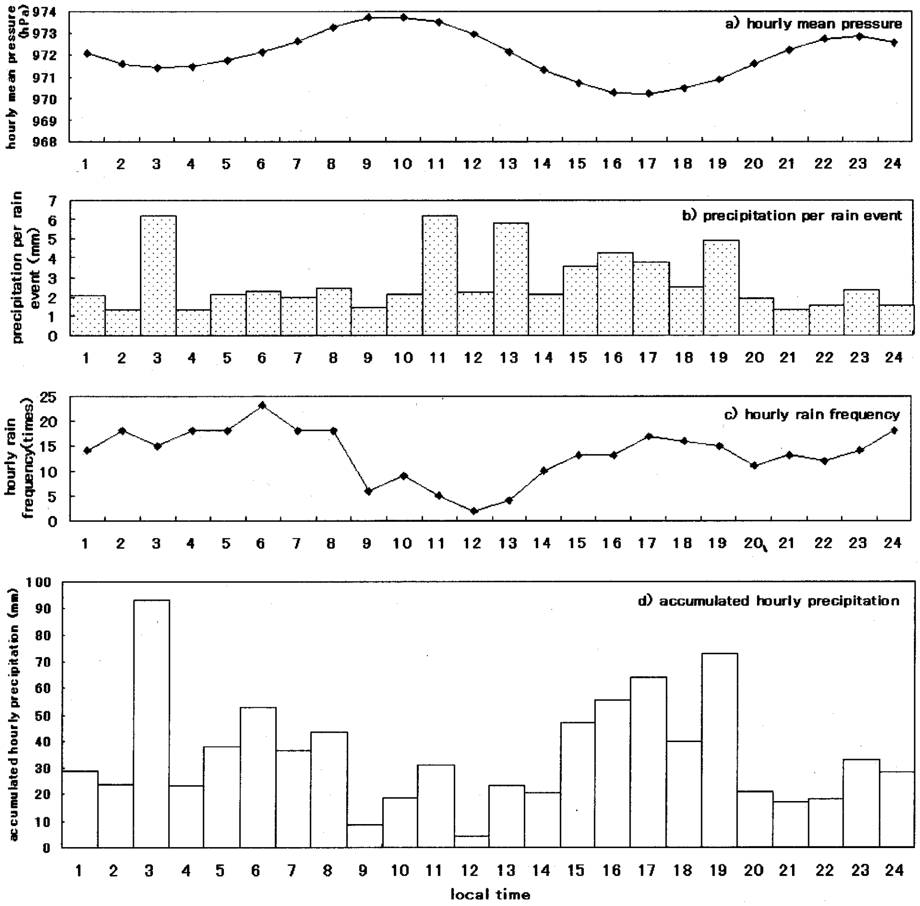

Fig. 5 Time-variations of (a) hourly mean pressure, (b) precipitation per rain event, (c) hourly rain frequency, and (d) accumulated hourly precipitation. Data are calculated for each hour from May 1 to October 31 in 2002.

(1500–1900) is therefore characterized by relatively high precipitation per event in comparison with morning rain, indicating that evening rains are mainly produced by convective, cumulonimbus storms, whereas morning rains are produced by stratus cloud.

The surface pressure displays an obvious diurnal variation, which can also be seen in the time series for individual days. There are two peaks in surface pressure during the day, consistent with the general diurnal variation of atmospheric pressure. It is noteworthy that the peak pressure in the morning occurs at nearly the same time as the beginning of the daytime dry period, while the following minimum corresponds to the evening rain period. The diurnal pressure variation thus appears to affect the timing of rains, that is, morning high pressure suppresses daytime rain, while evening low pressure leads to convective rain. Diurnal variation in surface pressure is probably the most important feature in low-latitude areas, suggesting that more hourly observations should be conducted in the tropics.

4. Conclusion

The seasonal cycles in southern Mali can thus be defined based on surface and upper-air meteorological observation data for the period from 2001 to 2004. The diurnal variations in pressure and precipitation were also revealed by hourly meteorological observations. The temporal and seasonal variations represent basic information that can be used to enhance our understanding of the Mali climate and reduce the climate risks for agriculture. Although research on global climate changes is also important for forecasting weather in West Africa, the present results for the local climate are very useful for reducing the climate risks in local agricultural areas.

Under the recent unstable climatic conditions attributed to global warming, improvement in stable agriculture production has become increasingly important. Although this report presents a case study for just one small village, the basic results concerning the seasonal and daily changes are expected to be applicable to semiarid areas all over the world. Further observations in this manner will be useful for building a better understanding of local climates.

Acknowledgements

The Mali climatic risk reduction project was a collaborative effort of the Japan International Research Center for Agricultural Sciences (JIRCAS), Tsukuba, Japan; the Institut d'Economie Rurale (IER), Mali; and the National Agricultural Research Center for the Tohoku Region, Morioka, Iwate, Japan. Funding was provided by the Fluidity Program of the Ministry of Education, Culture, Sports, Science and Technology, Japan; and JIRCAS. The Compagnie Malienne du Développement du Coton (CMDT) provided valuable background information and assistance in village and farmer selection. We express our appreciation to these institutions for their support. Finally, we wish to thank all the farmer-collaborators and the leadership of the villages of Niessoumana and Diou who were our partners in this work.

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