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Effect of Atmospheric Pressure on Evaporation in Central Ethiopia

Shinji SUZUKI*[1], Masku DERESSA[2], Atsushi SANADA[3], Kenji NAKAMURA[4], Fumio WATANABE[1] and Satoru TAKAHASHI[1]

Abstract: The authors have implemented a meteorological observation in the Oromia State, central Ethiopia. The region is located at the Great Rift Valley and classified as semi-arid area. Generally, the area is exposed to intense solar radiation, moderate wind, and low relative humidity resulting in high driving force of evaporation. Further, the authors suggest that low atmospheric pressure associated with high elevation would accelerate the evaporation ratio since water is vaporizable when the atmospheric pressure is reduced. The current study aims to monitor annual change in the atmospheric pressure and analyze the effect of it on the evaporation ratio in central Ethiopia. The evaporation ratio was computed by the Bowen ratio energy balance method. The atmospheric pressure in central Ethiopia was almost constant throughout a year ranging from 83.9 to 84.5 kPa independent of air temperature and rainfall. Taking into account the actual atmospheric pressure measured at the experimental field, the evaporation ratio computed by the Bowen ratio energy balance method was 4.5% larger than that calculated under the standard atmosphere. Although this difference (4.5%) would seem small, this would cause considerable error (i.e. underestimation) when the amount of evaporation is assessed cumulatively for longer period (ex. months or years). The results of the current study also suggest that highlands in arid lands have a high potential to dry due to its low atmospheric pressure. This implies fragility of eco-systems in other similar environments and accounts in part for difficulty to reestablish forests in highlands of the arid lands once the forests are cleared.

Key Words: Heat budget, Highlands, Meteorology, Semi-arid region, Water resource

1. Introduction

Crop production systems in central Ethiopia are mostly under rainfed condition. Although the mean amount of annual rainfall is still much for crop growth (400 to 800 mm), the crop production systems often suffer from severe drought stress resulting in unstable food security. Further, the forest area in the country, which was reported as 40 to 65% in hundreds years ago, decreased down to 2.2% over the past 60 years due to consumption as a fuel and expansion of arable land (Berry, 2003; EFAP, 1994; Hawando, 1997). Hence unstable agricultural production in the region is exacerbated by these severely degraded natural resources. The draught stress is in part due to erratic and fluctuated rainfall distribution patterns in the region, while it is of great importance to clarify reasons of causing draught in the region in order to consider more suitable measures to mitigate degradation of natural resources and improve crop productivity. The author's previous work (Suzuki *et al.*, 2009a) reported that the area is exposed to intense solar radiation, moderate wind, and low relative humidity resulting in high driving force of evaporation from soil surface. Further, the region is characterized in high altitude (more than 1,500 m Alt.) indicating low atmospheric pressure. Depressions of the atmospheric pressure would affect diffusion coefficient of gas including vapor. The psychrometric constant is a function of the atmospheric pressure (see eq. (5) in Materials and Methods), which is used when an evaporation ratio is calculated by energy balance methods. Therefore, the authors suggest that low atmospheric pressure associated with high elevation would accelerate the evaporation ratio. The current study aims to monitor annual change in the atmospheric pressure and analyze the effect of it on the evaporation ratio in central Ethiopia after verifying an instrument used.

2. Materials and Methods

The experimental field is located at Adami-tulu Agricultural Research Center, Oromia region of central Ethiopia (N 7° 52', E 38°43', Alt. 1,650 m). The region is located in the Great Rift Valley. Rainy season is during June to September, and dry season is other months. Soil texture of the experimental field was Loamy Sand. The maximum air temperature becomes over 30°C during Feb. to May and the minimum air temperature decreases below 10°C during Dec. to Feb. with a mean daily temperature through a year ranging from 18 to 23°C. A mean annual solar radiation is considerably large

* Corresponding Author: s4suzuki@nodai.ac.jp

Tokyo University of Agriculture, 1-1-1, Sakuragaoka, Setagaya, Tokyo, 156-8502, Japan.

1) Faculty of Regional Environment Science, Tokyo University of Agriculture, Japan
2) Adami Tulu Agricultural Research Center, Oromia, Ethiopia.
3) Faculty of International Agriculture and Food Studies, Tokyo University of Agriculture, Japan
4) NTC International, Co., Japan

(22 MJ m^{-2} d^{-1}) and a mean annual rainfall ranges from 600 to 800 mm (Suzuki *et al.*, 2009b). The experimental field is 70 m × 70 m and the surface is flat with sparse shrub. Although the experimental field is covered with local vegetation with a height of around 0.3 m in rainy season, the vegetation withers and dies in dry season. In the center of the experimental field, a flat and bare observation site (10 m × 10 m) was established.

The atmospheric pressure was measured using a pressure gauge (U20-001-01, Onset Computer Co.) at the observation site from Jan. 2009 to Jan. 2010 with 20 minute intervals. In addition, air temperature at a height of 1.73 m above the ground and rainfall were measured using a Temperature/RH smart sensor (S-THB-M002, Onset Computer Co.) and a rain gauge smart sensor (S-RGB-M0002, Onset Computer Co.), respectively. Data of the air temperature and the rainfall were recorded by the HOBO Weather Station (Onset Computer Co.) with 10 minute intervals. The atmospheric pressure and the air temperature were averaged for 24 hours. Daily summations were derived for the rainfall.

Since the U20-001-01 was originally designed to measure water level, a validity of the U20-001-01 to measure the atmospheric pressure was tested by comparison with two high precision air pressure sensors, namely; a digital barometer (PTB210, VAISALA) and a handy manometer (PG-100 -102VP, NIDEC Copal Electronics Co.). A comparison with the PTB210 was conducted at a meteorological station operated by the National Agricultural Research Center for Hokkaido Region (N 42°53', E 143°04', Alt 93 m), located in the central part of Tokachi District, Hokkaido, Japan. The U20-001-01 was set close to the PTB210 and the data of the atmospheric pressure was recorded from Oct. 2009 to Jan. 2010 with 10 min intervals. The data were averaged for 24 hours. Although the atmospheric pressure was suggested to be lower than 90 kPa in central Ethiopia, the atmospheric pressure measured at the National Agricultural Research Center for Hokkaido Region ranged from 97 kPa to 101 kPa (see Result and Discussion). Therefore the accuracy of the U20-001-01 to measure the atmospheric pressure lower than 95 kPa was tested at a laboratory of the Setagaya Campus of Tokyo University of Agriculture, Japan (N 35°38', E 139°38', Alt 57 m) using a system shown in **Figure 1**. By changing *H* in Figure 1, decreased air pressure was established and measured by the U20-001-01 and the PG-100-102VP with 1 min intervals.

In order to measure the evaporation ratio from bare soil surface at the observation site of central Ethiopia, following measurements were undertaken from 9th Dec. 2009 to 7th Jan. 2010, namely; a ground heat flux and a net radiation were monitored using a heat-flux plate (HFT-1.1, REBS) installed at a depth of 0.02 m and a domeless net radiometer (NR-Lite,

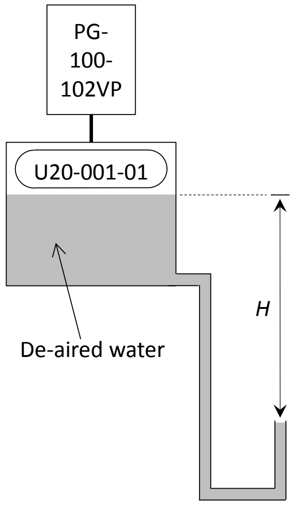

Fig. 1. Schematic diagram of the experiment to verify the accuracy of the water level logger (U20-001-01) by comparison with PG-100-102VP.

Kipp & Zonen) at a height of 0.72 m, respectively (Suzuki *et al.*, 2011). Both temperature and relative humidity were monitored at two heights (0.30 m and 0.50 m above the ground surface) using the S-THB-M002 and the HOBO Weather Station with a solar radiation shield (RS3, Onset Computer Co.). These data were recorded with 10 min intervals. Daily summations were derived for the ground heat flux and net radiation. Daily averages were obtained for the temperature and the relative humidity.

The evaporation ratio (E, mm d^{-1}) was computed by the Bowen ratio energy balance method as follows;

$$E = \frac{R_n - G}{l(1+\beta)\rho_w} \qquad (1)$$

where Rn is the net radiation (J m^{-2} d^{-1}), G is the ground heat flux (J m^{-2} d^{-1}), ρ_w is the density of water (=1,000 kg m^{-3}), and l is the latent heat of water (J kg^{-1}) given as;

$$l = 2.501 \times 10^6 - 2.361 \times 10^3 \cdot \left(\frac{T_1 + T_2}{2}\right) \qquad (2)$$

T_1 and T_2 are the temperatures (˚C) at each height. β is the Bowen ratio which can be calculated as;

$$\beta = \gamma \frac{(T_1 - T_2)}{(e_1 - e_2)} \qquad (3)$$

where e_1 and e_2 are the vapor pressures (kPa) at each height and derived from (Campbell and Norman, 1998);

$$e_i = 0.611 exp\left(\frac{17.502 T_i}{T_i + 240.97}\right)\frac{RH_i}{100}$$
$$i = 1 \text{ and } 2 \qquad (4)$$

where RH_i is the relative humidity (%) at each height. γ is the psychrometric constant (kPa K^{-1}) and calculated as;

$$\gamma = \frac{C_p P}{0.622 l} \qquad (5)$$

where C_p is the heat capacity of air at constant pressure (J kg^{-1} K^{-1}) written by (Ham, 2005 p541);

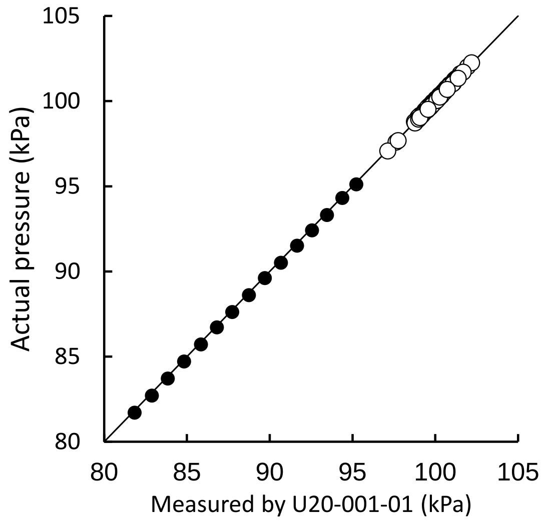

Fig. 2. Comparison of the atmospheric pressures between data measured by U20-001-01 and actual data measured by PTB210 (open) and PG-100-102VP (closed). r^2 and RMSE are coefficient determination and root mean square error, respectively.

$$C_p = 1004.7\left\{\frac{0.522(e_1 + e_2)}{2P} + 1\right\} \qquad (6)$$

P is atmospheric pressure (kPa). In many cases, γ is literally considered as a constant (=0.066 kPa K^{-1}) (Meyer, 1999; Dingman, 2002). This is because the γ is often dealt with under the standard atmosphere (101.3 kPa and 15°C). However, the γ is not strictly a constant, but a function of P. In the current study, the evaporation ratio was calculated substituting the atmospheric pressure measured at the observation site for eq. (5) and compared with the evaporation ratio calculated when P=101.3 kPa (i.e. standard atmospheric pressure).

3. Results and Discussion

The air pressure measured by the U20-001-01was remarkably agreed with the data measured by both the PTB210 and the PG-100-102VP (**Fig. 2**). The coefficient of determination (r^2) and the root mean square error (RMSE) were 0.9998 and 0.067 kPa, respectively (Fig. 2). The result ensures validity of the U20-001-01 to measure the atmospheric pressure in central Ethiopia with noticeable precision.

The atmospheric pressure in central Ethiopia was almost constant throughout a year of 2009 ranging from 83.9 kPa to 84.5 kPa independent of air temperature and rainfall (**Fig. 3**). Low atmospheric pressure observed in central Ethiopia is of course resulting from high altitude of the region, however, it is of note that the atmospheric pressure in central Ethiopia is considerably smaller than the standard atmospheric pressure by more than 15%. There were two rainfall events during the observation period of the evaporation ratio (21 mm for 11th to 12th Dec. 2009 and 18 mm for 29th to 30th in Dec. 2009) (Fig. 3). The evaporation ratio calculated in the current study showed more than 4.0 mm d^{-1} after the two rainfall events, and immediately decreased down to 2.5 mm d^{-1}. This indicates that the evaporation ratio increases only when soil has much water after rainfall, while the evaporation ratio is impeded soon due to decreases in the soil water content. A mean evaporation ratio during the observation period was 2.4 mm d^{-1} (**Fig. 4**). Further, the evaporation ratio calculated using the atmospheric pressure measured at the observation site (actual evaporation ratio; E_a) was always higher than the evaporation ratio calculated when P=101.3 kPa ($E_{P=101.3\,\mathrm{kPa}}$). The E_a was 4.5% larger than the $E_{P=101.3\,\mathrm{kPa}}$ in average (Fig. 4). Although the difference between E_a and $E_{P=101.3\,\mathrm{kPa}}$ (4.5%) would seem small, this would cause considerable error (i.e. underestimation) when the amount of evaporation is assessed cumulatively for longer period (ex. months or years).

4. Conclusion

The current study quantitatively revealed how small the atmospheric pressure in central Ethiopia is compared with the standard atmosphere. The results of the current study suggest that assessments of the amount of evaporation in central Ethiopia by the Bowen ratio energy balance method would result in underestimation without taking into account the depression of the actual atmospheric pressure. The results of the current study also suggest that highlands in arid lands have a high potential to dry due to its low atmospheric pressure. This implies fragility of eco-systems in other similar environments and accounts in part for difficulty to reestablish forests in highlands of the arid lands once the forests are cleared.

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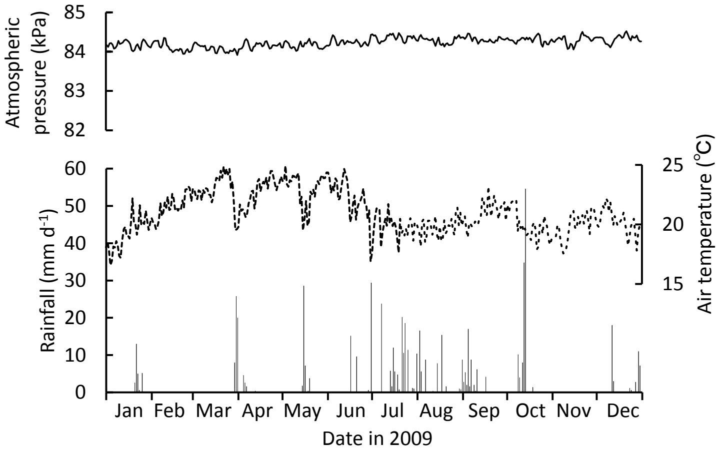

Fig. 3. Changes in atmospheric pressure associated with air temperature and rainfall in central Ethiopia.

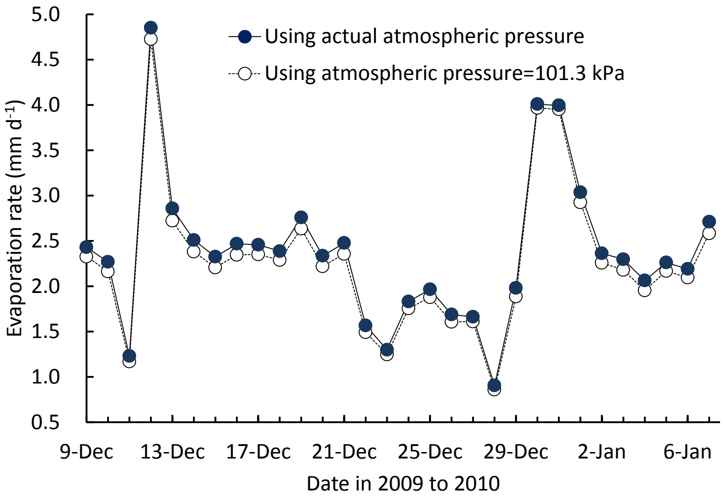

Fig. 4. Changes in evaporation ratios calculated using standard atmospheric pressure (open) and atmospheric pressure measured at central Ethiopia (closed).

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