Long-term trend of pan evaporation measurements in Japan and its relevance to the variability of the hydrological cycle.

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1. Introduction

It is of great interest for engineers as well as scientists whether or not the hydrological cycle will change along with the prospective climate change and how large it is in its magnitude if it does. In a simple thought, raised temperature and increased water vapor in the air could cause the increase in the rainfall amount in a single storm event. The increased precipitation, and thus the increased soil wetness can be associated to the increase of the river discharge and the evaporation from the landsurface. In this way, global temperature rise is expected to cause an acceleration in the global hydrological cycle. On the other hand, activated cloud-precipitation system are associated with the increased amount of the cloud, and thus with the decrease in solar radiation, which is a negative feedback on the evaporation, and thus on the whole hydrological cycle.

Validation of the changing hydrological cycle through the analysis of measurements has been done mainly with precipitation over the land (e.g. Houghton et al., 2001). Evaporation, however, has not been investigated much since its long-term records are not widely available due to its difficulty in its direct measurements. Recently, pan evaporation, evaporation from a water-filled pan evaporimeter, has come to the light as an index of the "actual" evaporation, and efforts are ongoing to validate or invalidate the accelerating hydrological cycle.

2. Evaporation Paradox and Hydrological Cycle Change

The first to pay attention to the pan evaporation as an index of the changing hydrological cycle is Peterson et al. (1995), who investigated the measurements of pan evaporation over the past half century in the United States (US) and in the Former Soviet Union (FSU). They found decreasing trends of the pan evaporation in European/Siberian FSU and eastern/western US. They interpreted this decreasing trend as an indication of the decrease in the terrestrial evaporation, and claimed that this interpretation does not contradict to other observational facts, such as decrease in daily maximum air temperature during the summer and in degreed day in

Figure 1: Meteological stations subject to the analysis

Siberia/European FSU, and increase in river discharges.

Following Peterson et al. (1995), decreasing trends in past pan evaporation records has been reported from India(Chattopadhyay and Hulme, 1997) and Venezuela(Quintana-Gomez, 1997). The interpretation of the decreased pan evaporation by Peterson et al. (1995) is based on the notion that the pan evaporation is an indicator of the potential evaporation, that is, maximum possible evaporation from the landsurface. It is, however, a common knowledge among the hydrologists that some of potential evaporations, including pan evaporation, are negatively correlated with the "actual" terrestrial surface (e.g., Brutsaert and Stricker, 1979). This negative correlation, called "complimentary relationship", was used to interpret decreasing trend of pan evaporation by Brutsaert and Parlange (1998).

Brutsaert and Parlange (1998) pointed out that if the widely-observed pan evaporation decrease indicates an decrease in the terrestrial evaporation, it is inconsistent with the observed increase in the terrestrial precipitation: they called this as "Evaporation paradox". Using the complimentary relationship mentioned above, they explained that the decrease pan evaporation can be interpreted as an increase in the terrestrial evaporation, which does not contradict with the increasing precipitation. This hypothesis has been confirmed

by Lawrimore and Peterson (2000) and Golubev et al. (2001) using observational record at FSU and US.

This complimentary relationship, however, is mainly associated with drying and wetting of the landsurface, and the wetness of the landsurface does not solely control the evaporation. Roderick and Farquhar (2002) recently argued that the decreasing solar radiation associated with the increased cloud amount and aerosols may have caused the decrease in pan evaporation, and the discussion regarding the pan evaporation trend and the global hydrological change has been set back to the beginning. Ohmura and Wild (2002) summarized the problems and its solution on this issue.

Contribution to this "Pan evaporation" issue from the eastern Eurasia continent are limited so far. One of the few is by Xu (2001) who analyzed the data measured in China for about 20 years and reported that the past pan evaporation records showed an increasing trend in the arid region in China while decreasing trends are found in the humid region. She commented that this decreasing trend in the humid area of China together with the similar report in India (Chattopadhyay and Hulme, 1997) may be common to the monsoon climate system.

This paper, aiming to be another contribution from the eastern Eurasia, investigates the pan evaporation records observed in Japan, and discusses the implication of the result of its trend analysis.

3. Data

Data subject to the analysis in this paper is the daily pan evaporation and other meteorological variables measured at 13 meteorological stations (Figure 1)operated by Japan Meteorological Agency (JMA), and the data is distributed in CD-ROMs published by Japan Meteorological Business Support Center. Period of the analysis is from 1967 to 2000. Daily measurements are averaged over the four seasons (DJF, MAM, JJF and SON), the warm season (May to October) and the whole year period, and they are analyzed in terms of their interannual variability. Besides the pan evaporation, air temperature (AT), vapor pressure (VP), vapor pressure deficit (VPD), daily temperature range (DTR), precipitation (PR), sun duration (SD) and cloud amount (CA) are analyzed in order to investigate the controlling factors to the pan evaporation. All of the data are checked with its continuity using a statistical test.

4. Analysis

Long term trends of each meteorological variables are determined for each season in the linear regression analysis. The linear trend determined are tested in terms of its statistical significance using the single-sided t-test. Determined trend values together with the t-test results with the significance level of 99% and 95% are given in Tables 1 and Figure 2. It is shown in Figure 2(b) that statistically significant trend cannot be found in the precipitation records at most of the stations whereas increasing trends in the temperature (Figure 2(b)) are clear. This is partly attributable to large interannual variabilities in precipitation. Some reports (e.g., Houghton et al., 2001) have shown that while increasing trends in precipitation are clear most of the globe, those in north-eastern pacific region is obscure.

In contrast, decreasing trends in the pan evaporation (Tables 1 and Figure 2(c)) are clearly stated at the most of the stations analyzed during the most of the seasons. Closer investigation reveals that steady decreasing trends are found at Nemuro, Yonago, Shionomisaki, Fukuoka and Shimizu. Miyako, as well, shows a decreasing trend comparable in amount with these 5 stations, but the trend, especially in JJA, is not determined as statistically significant. This is probably due to the large variability of the summer climate in Miyako caused by a cold wind blow from the northeast called "Yamase". Thus, Miyako can be considered among stations that give stronger decreasing trend.

5. Discussion

A week increasing trend of the pan evaporation is found at Tokyo and Kagoshima, all of which are located in an urbanized area that have been urbanized during the last half century. In general, urbanization involves construction of buildings and paving of roads, and as both of them interferes evaporation from the landsurface, terrestrial evaporation tends to decrease. Therefore, pan evaporation trends in the urbanized/urbanising area should be taken separately from those in natural environment.

Linear trend of the pan evaporation is further investigated at 5 stations, namely Nemuro, Miyako, Wajima, Shionomisaki and Shimizu, which show a clear decreasing trend in multiple seasons. These stations are located in or near the rural town, and therefore are thought to be relatively free from the effect of the urbanization.

At all of the 5 stations, air temperature shows clear increasing trend (Figure 2(a)) while precipitation does not (Figure 2(b)). In the northern stations, Nemuro, Miyako, and Wajima, a decreasing trend of the sun duration, therefore that of the solar radiation, is observed, whereas trend is weak in the southern stations (Figure 2(d)). Vapor pressure deficit (VPD) has increasing trend at the stations Wajima, Shionomisaki and Shimizu, while no trend was detected in Nemuro and Miyako

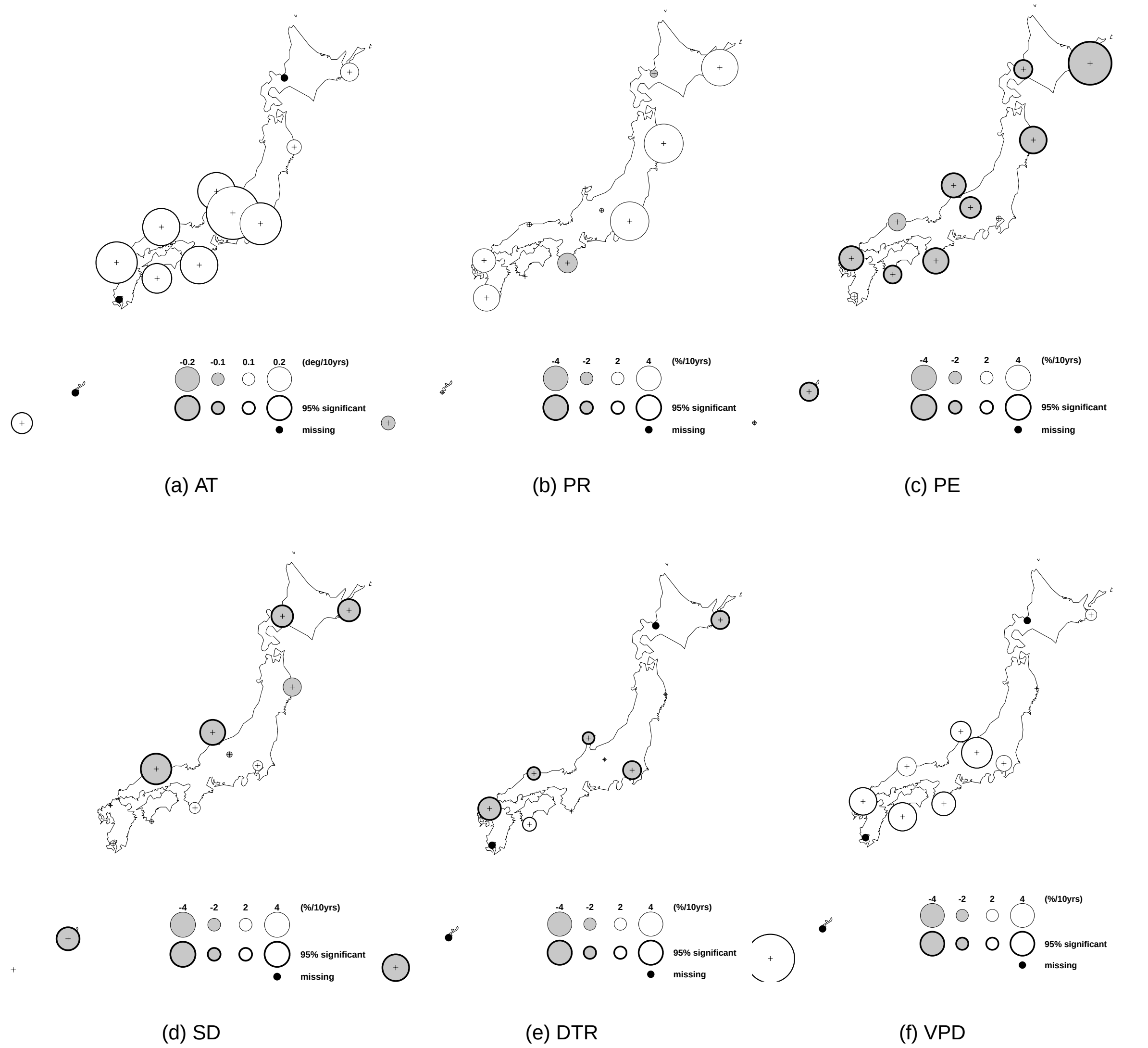

Figure 2: Linear trend of air temperature (AT), precipitation (PR), pan evaporation (PE), sun duration (SD), daily temperature range (DTR) and vapor pressure deficit (VPD) in the warm season. White circles and gray circles indicate increasing and decreasing trend, respectively. The size of the circles indicates the magnitude of the trend while the thick edge of the circles indicates the increasing/decreasing trend with the 95% significance level.

(Figure 2(f)).

From these observations it can be inferred that the decreasing solar radiation associated with the increasing cloud amount largely affect the pan evaporation trends in the northern stations and that the increasing VPD in Wajima, Shionomisaki and Shimizu may have large influence on the decreasing pan evaporation. Associated with the former observation, Possible effect of decreasing solar radiation on pan evaporation as well as on the terrestrial evaporation was already mentioned by Roderick and Farquhar (2002), who implies that decreasing pan evaporation indicates decreasing terrestrial evaporation. In the meantime, increasing VPD in the southern 3 stations implies increasing terrestrial evaporation. If increase in terrestrial evaporation and decrease in pan evaporation concur, it is a validation of the interpretation by Brutsaert and Parlange (1998) with “complimentary relationship”. These notions are also supported by a detailed correlation analysis and the stepwise multiple linear regression if interannual variations of meteorological variables(Asanuma et al., 2004).

6. Conclusion

Pan evaporation measured at 13 stations in Japan over 35 years are investigated in conjunction with its long term trend of the climate/hydrological system. It was found that the decreasing trend of the pan evaporation prevails over most of Japan. This decreasing pan evaporation can be considered as a common characteristics in Monsoon Asia (Xu, 2001).

Further investigation showed that this decreas-

Table 1: Linear trend (mm/year) of the pan evaporation normalized with the long term average. The values in **underlined bold face** and those in **bold face**, respectively, are increasing/decreasing trends with the significance level of 99%, and 95% determined by t-test. The numbers in the parenthesis are the standard deviation.

Station	All	Warm	MAM	JJA	SON	DJF
Sapporo	-	**-2.9** (1.6)	-	-1.7 (2.0)	-	-
Nemuro	-	**-6.8** (1.6)	-	**-7.8** (2.0)	-	-
Miyako	-	**-4.3** (2.1)	-	-4.1 (2.9)	-	-
Wajima	-	**-3.9** (1.7)	-	-3.5 (2.3)	**-4.2** (1.7)	-
Matsumoto	-	**-3.3** (1.5)	-	-2.6 (2.1)	-3.8 (2.3)	-
Tokyo	2.4 (1.5)	0.8 (1.7)	0.3 (1.7)	0.5 (2.4)	**5.7** (2.0)	-
Yonago	-2.2 (1.7)	-2.8 (2.0)	-2.7 (1.6)	-3.0 (2.6)	-2.0 (1.9)	-
Shionomisaki	**-4.0** (0.9)	**-4.1** (1.1)	**-3.7** (1.6)	**-4.6** (1.4)	**-3.6** (1.2)	**-4.5** (1.9)
Fukuoka	**-5.5** (1.4)	**-3.8** (1.8)	**-3.6** (1.8)	-3.8 (2.4)	**-6.3** (1.6)	-
Kagoshima	1.1 (1.3)	1.2 (1.4)	1.9 (1.8)	-0.4 (1.6)	3.1 (1.8)	-
Shimizu	-2.1 (1.3)	**-2.9** (1.4)	-1.1 (1.6)	**-3.7** (1.7)	**-2.4** (1.3)	-2.1 (1.7)
Ishigakijima	-1.6 (1.3)	-0.6 (1.5)	**-4.1** (2.3)	0.3 (1.9)	-1.5 (1.4)	-2.6 (2.2)
Naha	**-2.8** (1.3)	**-2.9** (1.5)	**-3.6** (1.9)	-3.3 (2.0)	**-2.6** (1.5)	1.0 (1.9)

ing trend in pan evaporation is probably caused by the decreasing solar radiation in the northern region, while it is associated with the increasing VPD in the southern region. Therefore, it can be concluded that the decreasing pan evaporation trend in Japan indicates decreasing and increasing terrestrial evaporation in the northern and southern region, respectively.

Results of this paper suggests that different interpretation of the pan evaporation should be applied in a different climate system and that analyses of other meteorological variables should be accompanied with the interpretation, especially when a trend of the solar radiation is expected.

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