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DIURNAL CYCLE OF SURFACE WIND AND ITS SEASONALITY AT MANILA, PHILIPPINES, FROM 1890 TO 1900

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Abstract This study investigates the diurnal cycle of surface winds and their seasonal differences in rescued data containing the hourly wind direction (WD), wind speed (WS), and daily rainfall at Manila, the Philippines, from 1890 to 1900. The seasonal differences in the diurnal cycle of surface wind were largest between the rainy season (June to September) and the dry season (January to April). In the driest month (February), the appearance ratios of SW–WNW and E–SE winds were highest from 09 to 15 local time (LT) and from 16 to 24 LT, respectively. This diurnal cycle of WD became unclear from May to September. Particularly, during the August–September, the appearance ratio of SSW–WSW winds remained high for most of the day. These seasonal changes in diurnal WD cycle might be closely related to the full development of the SW monsoon. In October when the rainy season started to withdraw, the diurnal cycle of WD observed in February reappeared. The WS in all months was higher during the daytime than during the night, peaking from 15 to 16 LT in August and at 13 LT in December. The WS fell to below 1 m/s from 01 to 07 LT during the dry season.

Keywords: surface wind, diurnal cycle, seasonal difference, Manila, data rescue

1. Introduction

The Philippines holds the old meteorological observation records in Southeast Asia. The first observatory was established in Manila (Fig. 1a) by the Spanish Jesuits in 1865 (Udias 1996; Udias 2003). At the beginning of the 20th century, the meteorological observation was taken over by the U.S. administration. The Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) was then established around the late 1940s.

The historical weather records before the establishment of PAGASA are essential for clarifying the climate and long-term climate changes around the Philippines. However, preparation of these records in digitized format has been hindered by influences of World War II and digital records are scarce (Page *et al.* 2004). In our efforts to rescue these data, we found pieces of the historical weather records in paper medium in the libraries of different countries such as the U.K., the Netherlands, Spain, Canada, Hawaii, and Japan (Akasaka 2014). We then digitized some meteorological factors in these data and investigated the climatological features in and around the Philippines (e.g. Kubota and Chan 2009; Akasaka 2020).

Some factors in the old meteorological data were observed on an hourly basis from around the

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1890s. Such high temporal-resolution data are valuable because hourly meteorological data for the late 19th century were difficult to obtain. Nevertheless, they have been under-utilized in climatic research of the Philippines. The present study aims to clarify the diurnal cycle of surface winds and its seasonal differences at Manila from 1890 to 1900 based on the hourly surface wind direction (WD), wind speed (WS), and daily rainfall data obtained by data rescue. The results will facilitate discussion on the climatological characteristics of the Asian monsoon and their changes on the centennial scale.

2. Data and Methodology

The weather records from 1890 to 1900 are included in the monthly bulletins "*Observatorio Meteorologico de Manila*", written in Spanish and published by Manila Observatory. These bulletins were found mainly in the library of the Japan Meteorological Agency. From the weather records, we digitized the hourly surface WD, WS, and daily rainfall at Manila (Fig. 1a) from January of 1890 to December of 1900. The data in October of 1891 and June of 1893 are missing. The detailed observation environment and observation instruments are largely unknown but the location information (latitude and longitude of the station) is available. Akasaka (2020) compared the annual and seasonal diurnal WD and WS cycles at Manila during the 1890–1900 and 2013–2015 periods. They confirmed very similar characteristics of the cycles in both periods. Therefore, using the old surface wind data, we analyze the climatic characteristics of the diurnal surface wind cycle during the late 19th century. This study newly adds the hourly WS, including the calm (zero wind) data, and clarifies the annual and monthly characteristics of the diurnal WD and WS changes at Manila. The relationship between the seasonal transition in the diurnal cycle of surface winds and the seasonal march of rainfall is then investigated in detail.

To investigate the annual and seasonal diurnal cycles of WD and WS, we calculated the appearance ratio of each WD and the mean WS at each time within each month of the 1890–1900 period. We also counted the number of calm (WS = 0 m/s) times in each month, which are reported in the monthly bulletins, along with their appearance ratio. To clarify the seasonal differences in the diurnal cycles of WD and WS, we calculated the monthly and annual rainfalls and the number of rainy days from the daily rainfall data. Here, we use the rainfall data because the seasons at Manila are characterized by changes in monthly rainfall rather than by changes in monthly temperature. As the numbers of monthly and annual rainy days, we counted the numbers of days on which the rainfall exceeded 0.5 mm in each month and year, respectively.

3. Annual Characteristics of Diurnal Cycles of Wind Direction and Wind Speed

Figure 1b shows the diurnal cycles in the appearance ratio of WD and the mean WS from 1890 to 1900. The appearance ratio of the SSW–W winds was high (>10%) from 09 to 19 local time (LT). The WSs in these WDs exceeded 3 m/s throughout the day except from 09 to 10 LT. The mean WS along each WD (excluding the NW, NNW, N, NNE, and NE winds) was higher from 11 to 17 LT. The mean WS also showed a distinct diurnal cycle, being higher during 14–16 LT and lower during 24 LT and 01–07 LT (Fig. 2). The frequencies of calm distinctly decreased after 08 LT and fell below 10% from 10 to 16 LT. As Manila is located along the west coast of Luzon Island (Fig. 1a), the higher ratio of SSW–W winds and increase in WS during the daytime

likely correspond to sea breezes.

During the night-time, the WS was relatively low (<3 m/s) in all directions except SSW–W. The frequencies of E–ESE and NNE–NE winds increased from 17 to 23 LT and from 04 to 08 LT, respectively (Fig. 1b). Additionally, the frequencies of calm exceeded 30% from 24 to 8 LT. The high frequencies of E–ESE and NNE–NE winds and the lower WS during night-time might correspond to land breezes, which are generally weaker than sea breezes.

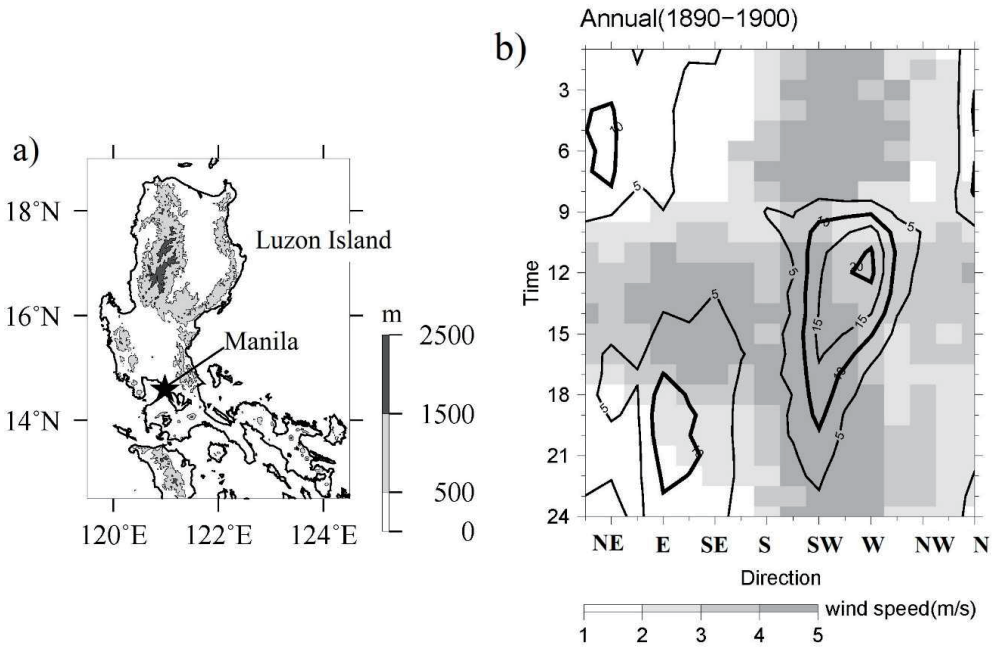

Fig. 1 Location of Manila, diurnal cycle of appearance ratio of WD, and mean WS at Manila during the 1890–1900 period: (a) location of the Manila observation site; (b) annual appearance ratio of WD and annual mean of WS at each time of the day. In (b), the contour intervals are separated by 5% and the gray shadings indicate the mean WS along each WD.

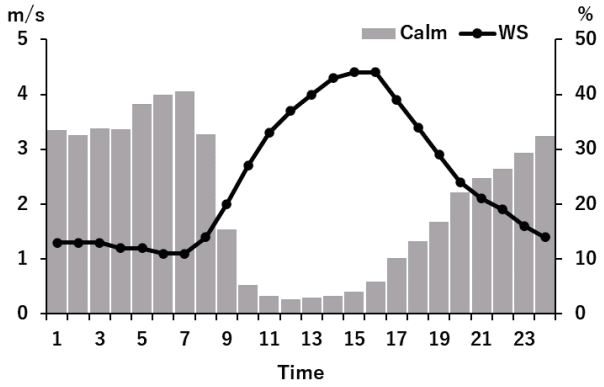

Fig. 2 Diurnal cycles of mean WS and appearance ratios of calm at Manila during 1890–1900.

4. Diurnal Cycles of Wind Direction and Wind Speed During the Rainy and Dry Seasons

Seasonal Changes in Monthly Rainfall and Number of Rainy Days

This section focuses on the seasonal changes in the monthly rainfall characteristics, which are closely related to the seasonality of WD and WS. The mean annual rainfall amount and number of annual rainy days at Manila during the 1890–1900 period were 1945.6 mm and 148.5 days, respectively. Manila has distinct wet and dry seasons lasting from June to September and from January to April, respectively. During the dry season from 1890 to 1900, the average monthly rainfall ranged from 6.3 to 25.7 mm (Fig. 3a) and the mean total rainfall amount and number of rainy days ranged from 24.1 to 165.6 mm and from 9 to 38 days, respectively (Fig. 4). The driest month was February. The mean and standard deviation (SD) in the number of monthly rainy days was also lowest in February (Fig. 3b).

The mean monthly rainfall and number of rainy days began increasing in May. According to Akasaka *et al.* (2007), who studied the relationship between the seasonal marches of pentad rainfall and the wind field at the 850 hPa level in the Philippines from 1961 to 2000, the rainy season usually starts in the middle of May. The monthly rainfall amounts increased from June to September and the SD was larger during the June to August period than during the dry season. The highest monthly rainfalls, expressed as outliers in Fig. 3a, appeared in July of 1899 and August of 1900 (Fig. 3a). The seasonal rainfall amount (number of rainy days) from June to September accounted for 61.0%–81.4% (46.5%–63.3%) of the annual rainfall amount (number of rainy days) from 1890 to 1900 (Fig. 4). The larger rainfall variations from June to August are suggested to be closely related to the inter-annual variations in the SW monsoon, which characterize the rainy season at the west coast of the Philippines. The number of rainy days notably rose in May whereas the monthly rainfall clearly increased in June. Both the monthly rainfall and number of rainy days distinctly decreased in October and the decrease continued to January.

Based on Figs. 3 and 4, we focused on the diurnal WD and WS cycles in February, May, August, October, and December. The results are presented in the next section.

Seasonal Differences in Diurnal Cycles of Wind Direction and Wind Speed

In February, the driest month, the frequency of SW–WNW winds was highest from 09 to 15 LT (Fig. 5a). Within this period, the appearance ratio of W winds exceeded 20%. In contrast, the 16–24 LT period showed higher frequencies of E–SE winds, particularly from 19 to 21 LT. It can be said that the diurnal cycles of WD and WS are clarified in February. From 11 to 17 LT, the WS of the E–SE winds exceeded 4 m/s, higher than the sea breeze (SW–WNW winds) during the daytime. According to Akasaka *et al*. (2007), the E–SE winds prevailing during the dry season follow the direction of the trade wind. The duration of higher appearance ratio was shorter for the SW–WNW winds and longer for the E–SE winds than in Fig. 1b. These characteristics continued until April (Figure not shown).

When the rainy season began in May, the diurnal cycles of WD and WS greatly changed (Fig. 5b). The frequencies of NNE–SE winds largely dropped to below 5% and the time over which the SSW–WNW winds exceeded 10% was extended. SW winds became evident, especially from 09 to 20 LT. The time over which the WSs exceeded 4 m/s was also greatly extended and the WSs of the SSW–W winds increased throughout the day. Although the appearance ratio of WSW wind exceeded 20%, the higher ratio WD gradually moved from WSW to SW toward July.

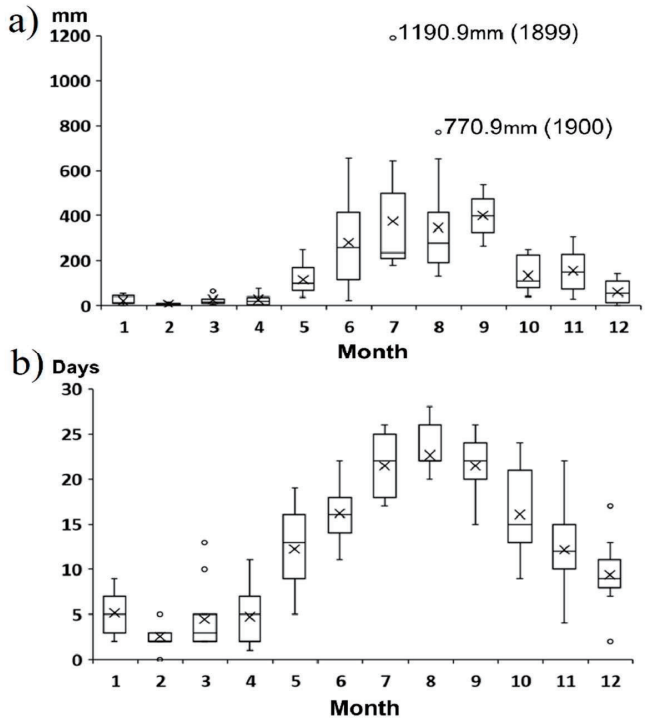

Fig. 3 Boxplots of monthly rainfall (a) and number of rainy days (b) at Manila during the 1890–1900 period. The upper and lower ends of the box indicate the third and first quartiles, respectively. Horizontal lines and cross marks indicate the median and mean values, respectively. The whiskers extend from the quartiles to the maximum and minimum values. Circles denote the outliers exceeding 1.5 times the interquartile range in each month.

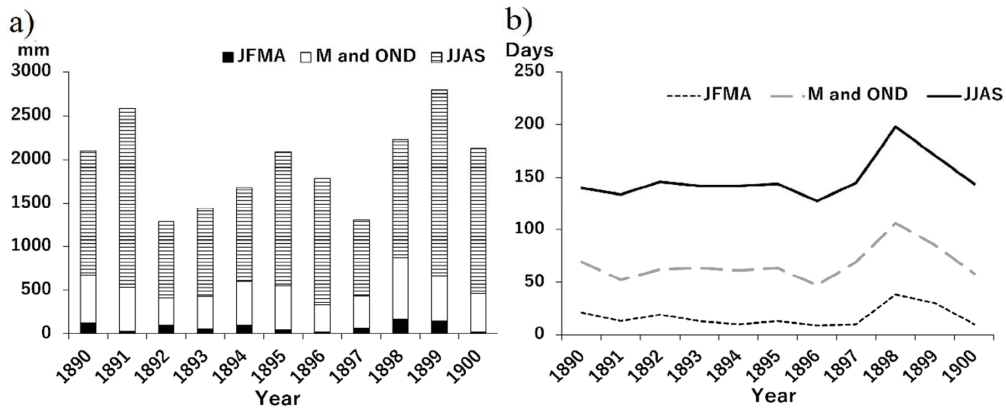

Fig. 4 Stacked bar and line charts of seasonal rainfall amounts (a) and number of seasonal rainy days (b) at Manila during the 1890–1900 period. JFMA: January, February, March, April; M: May; OND: October, November, December; JJAS: June, July, August, September.

In August, the characteristics of the diurnal WD and WS cycles were similar to those in July and September (Fig. 5c). The appearance ratio of the SSW–WSW winds exceeded 20% from 11 to 20 LT and the WSs of these winds exceeded 4 m/s throughout the day. That is, the diurnal WD and WS cycles became unclear during the period of continuously prevailing SSW–SW winds (July to September). This period thus corresponds to the developmental period of the SW monsoon. Therefore, both the monthly rainfall amount and number of rainy days were large during the July–September period (Fig. 3).

The diurnal cycle of WD greatly changed in October. The appearance ratio of the SSW–WSW winds obviously declined although the speeds of those winds remained high (Fig. 5d). Meanwhile, the appearance ratio of the NNE–NE winds rose during the night-time. These changes were suggested to indicate the reoccurrence of the diurnal WD and WS cycles, which is significantly connected to the withdrawal of the rainy season with an abrupt decrease of the monthly rainfall amount in October (Fig. 3a). According to Matsumoto *et al.* (2020), this period corresponds to the beginning period of the NE monsoon around Manila.

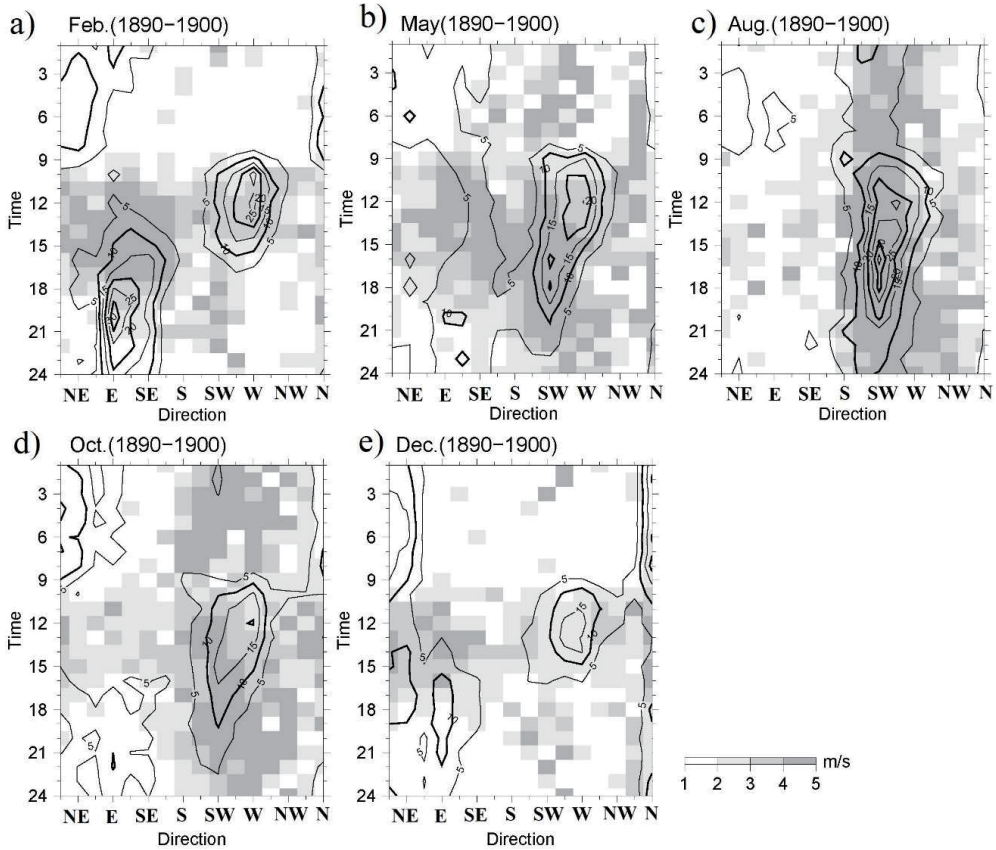

Fig. 5 Monthly appearance ratios of WD and mean WS at Manila during February (a), May (b), August (c), October (d), and December (e) of 1890–1900. Same as Fig. 1b but showing the monthly appearance ratios of WD and mean WS.

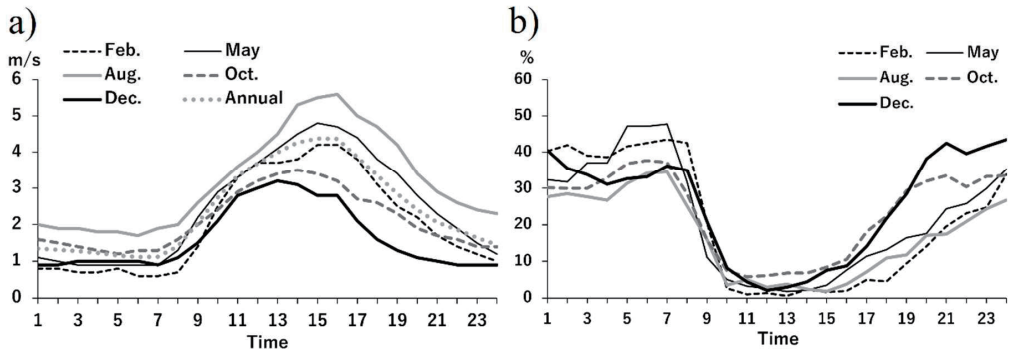

Fig. 6 Diurnal changes in mean WS (a) and appearance ratios of calm (b) at Manila during February, May, August, October, and December of 1890–1900.

In December, the characteristics of the diurnal WD and WS cycles were similar to those in February (c.f. Figs. 5a and e). However, the appearance ratios of both the WD and WS dropped from those in February. Notably, the duration in the appearance ratio of the SW–W winds above 10% was four hours shorter than in October. The mean WS during the day was weakest at this time. In contrast, the appearance ratio of the N–NE and E winds exceeded 10% during the night-time. This period corresponds to the onset of the dry season (Fig. 3a).

Figure 6 shows the seasonal differences in the mean WS and the appearance ratio of calm. The peak daytime WS and the wind strength differed in each month (Fig. 6a). The earliest and latest WS peaks appeared at 13 LT in December and at 16 LT in August, respectively. The WSs at these peak times were 3.2 m/s in December and 5.6 m/s in August. The night-time WS was also higher in August than in December and was lowest from 01 to 08 LT in February. Meanwhile, the appearance ratios of calm were high from 19 to 24 LT in December and low from 10 to 16 LT in February and August (Fig. 6b). Interestingly, the appearance ratio of calm was higher from 01 to 07 LT in February than in December.

5. Conclusion

The diurnal WD and WS cycles at Manila from 1890 to 1900 distinctly differed between the rainy and dry seasons. The annual diurnal cycle of WD showed high appearance ratios of SSW–W (E–ESE and NNE–NE) winds during the 09–17 LT (17–23 LT and 04–08 LT) period(s). This diurnal cycle of WD was most evident in February, the driest month. In contrast, the diurnal cycle of the appearance ratio of WD became unclear from May (when the rainy season began) to September. The appearance ratio of SSW–WSW winds remained high for most of the day, especially in August when the rainy season peaked. The seasonal changes in the diurnal cycle of WD were suggested to be closely related to the full development of the SW monsoon around the west coast of Luzon Island in the Philippines. In October when the NE monsoon started and the rainy season withdrew, the diurnal cycle of WD was again recognized.

Although the WS was higher during the daytime than during the night-time in each month, the strength and peak time of the WS changed from month to month: the daytime WS peaked from 15 to 16 LT in August and at 13 LT in December, whereas the night-time WS from 01 to 07 LT

reduced from February to April (i.e., during the dry season).

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