Rainfall-Driven Diurnal Variations of Water Level in the Ciliwung River, West Jawa, Indonesia

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Abstract

A 1-month-long observation of the Ciliwung River, which flows through Jakarta in Indonesia, has revealed evidence of the persistent existence of a diurnal cycle in the water level of a tropical river. This was consistent with the diurnal cycle in rainfall observed by meteorological radar and five rain-gauge stations. The river’s diurnal cycle was distinguishable from the effects of oceanic and atmospheric tides and has a locally time-locked 1-day periodicity and an amplitude of 0.05 m. The day-to-day variation in the amplitude of the river’s diurnal cycle was smaller than the diurnal cycle of the rainfall.


1. Introduction

Tropical rivers return water to the oceans to compensate for the water vapor supplied from oceans to land via atmosphere, and convective clouds that supply rainwater to rivers release latent heat, sustaining the global climate (e.g., Chapter 5, Hartmann 1994). The maximum of convective cloud activity and rainfall is located in the Indonesian maritime continent (IMC) (e.g., Ramage 1968; Hamada et al. 2002). Recently several studies (e.g., Mori et al. 2004; Sakurai et al. 2005; Araki et al. 2006) have shown that the major component of rainfall variation over the large islands of the IMC has a diurnal cycle, which is induced by the development of a cloud system accompanied with local (sea–land breeze) circulation along the long coastlines. Therefore, it has been suggested that the water input from the atmosphere to rivers by rainfall over the IMC has a predominant diurnal cycle.

The world’s fourth largest population (more than 240 million people) is concentrated along the rivers of the IMC. The Ciliwung River originates in the southern highland and runs through greater Jakarta (or JABODETABEK) region (upper-left panel) and greater Jakarta (or JABODETABEK) region (lower-left panel). The C-band Doppler Radar (CDR) (a blue star), automatic observation stations of water level (red stars) and surface weather (triangles) are indicated. The total rainfall distribution observed by CDR during the HARIMAU2010 period (15 January−15 February 2010) is shown for the upper Ciliwung River basin (right panel) to the downstream Ciliwung River (left panel). Severe flood events occurred immediately after extreme rainfall events that were enhanced by a strong persistent trans-equatorial monsoon flow from the Northern Hemisphere in 2007 (Wu et al. 2007; Trilaksono et al. 2012) and in addition by cloud clusters with an intraseasonal variation that were propagated from the Indian Ocean in 2013 (Wu et al. 2013).

There have been few hydrological studies of the Ciliwung River even for the severe flood events mentioned above, because horizontally distributed reliable rainfall data have not been obtained continuously. The purpose of this study is to apply rainfall data from a meteorological radar to the Ciliwung River basin for the first time (Section 2). We revealed evidence of a diurnal cycle in the water level discovered in the downstream of Ciliwung River (Section 3), which was compared with the rainfall observed by the radar and rain gauges (Section 4). The discussion in Section 5 is followed by the conclusion of the study (Section 6), which suggests that the diurnal cycle of the river was caused by rainfall.

2. Observations

We conducted intensive meteorological observations over the greater Jakarta (JABODETABEK: Jakarta, Bogor, Depok, Tangerang, and Bekasi) area during the period from 15 January to 15 February 2010 (Fig. 1), as the final intensive observational period (HARIMAU2010 IOP) of the 5-year Hydrometeorological ARay for Intraseasonal variation-Monsoon AUtomonitoring (HARIMAU) project (Yamanaka et al. 2008). We operated a C-band Doppler radar (CDR; 5.32 GHz) installed at Serpong (6.35°S, 106.67°E; 46 m MSL), raingonsonde and surface meteorological ob-

Fig. 1. Maps of the western part of the Indonesian maritime continent (upper-left panel) and greater Jakarta (or JABODETABEK) region (lower-left panel). The C-band Doppler Radar (CDR) (a blue star), automatic observation stations of water level (red stars) and surface weather (triangles) are indicated. The total rainfall distribution observed by CDR during the HARIMAU2010 period (15 January−15 February 2010) is shown for the upper Ciliwung River basin (right panel) to the downstream station (Manggarai).
observations at surrounding stations. The CDR enabled the observation of rainfall at a time resolution of 6-min and a horizontal range of about 105 km, from which we used 2-km constant altitude plan positioning indicator (CAPP) data over the Ciliwung River basin (6.2°S–6.8°S, 106.8°E–107.0°E) for the present study. The 6-min radar reflectivity (Z) was converted to surface rainfall (R) in the Ciliwung River basin using the Marshall–Palmer formula (Z = 200R^{1.6}) (cf. Doviak and Zrnic 1992). Surface rainfall intensity data from five automatic weather stations (AWS; Citeko, Bogor, Serpong, Serang, and Pramuka) were also used as supplementary data.

For the Ciliwung River, data from an automatic water level recorder with a time resolution of 15 min at Manggarai (6.21°S, 106.85°E), located in the downstream area, were provided by the Ministry of Public Works (PU) during the HARIMAU2010 IOP. Similar data from another station in the upstream area (Katulampa: 6.63°S, 106.84°E) were also obtained, although water levels in the area were disturbed by artificial gate controls.

3. General features of the 1-month observation period

Figure 2 shows the temporal variation of the water level at Manggarai, compared with rainfall intensity and rain cloud migration observed by CDR (see the caption of Fig. 2 for details) during the HARIMAU2010 IOP study period. At Manggarai, the average water level was 3.72 m. We identified the persistent and systematic existence of a diurnal cycle in the water level with an amplitude of ~0.05 m (~30 m^3 s^{-1} discharge). The rainfall intensity (with a peak of ~5 mm h^{-1} over many days) and rain cloud migration (in the meridional direction) also displayed clear diurnal cycles which confirms the findings of previous studies (Mori et al. 2004; Araki et al. 2006; Wu et al. 2007). We also found that rainfall displayed intraseasonal variations (cf. Widiyatmi et al. 1999) and weakened around 23 January and 1 February. An increase in the water level observed during January 15–25 was considered to be mainly due to hydrological processes, because we confirmed that an active phase of intraseasonal variation had passed before the observations began (see, e.g., Fig. 3 of Waliser et al. 2012). Thus, water levels displayed daily variations, but they were not always correlated to and were generally weaker than the variations in rainfall.

For the Ciliwung River, data from Manggarai Station for a 1-month period (15 January–15 February 2010) and their averages (thicker line), and averaged hourly rainfall amounts from (b) the automatic weather station data at Citeko, Bogor, and Serpong, and (c) radar rainfall data over the Ciliwung River basin.

Fig. 2. Temporal variations in (a) the Ciliwung River water level anomaly at Manggarai and (b) the rainfall intensity given by the meridional average of (c) a time–latitude cross section of zonal maximum reflectivity (106.75°E–107.10°E) of C-band Doppler radar data at 2-km altitude during the HARIMAU 2010 IOP observational period (15 January–15 February 2010).

Fig. 3. Diurnal variations in (a) the water level anomaly from each daily average (thinner lines) at Manggarai Station for a 1-month period (15 January–15 February 2010) and their averages (thicker line), and averaged hourly rainfall amounts from (b) the automatic weather station data at Citeko, Bogor, and Serpong, and (c) radar rainfall data over the Ciliwung River basin.

Fig. 4. Spectral analysis of time series of Ciliwung River water levels observed every 15 minutes at Manggarai station for a 1-month period (15 January–15 February 2010).
local rainfall fluctuated widely in space and time. Note that when averaged, the rainfall diurnal variation at the AWS stations (Fig. 3b) coincides with the variation in the water level (Fig. 3a), but there are differences among the AWS stations.

During the observation period, 12 extreme rainfall events (occurred at one or more of the five AWS stations; see Fig. 5) with intensities stronger than 20 mm h\(^{-1}\), as defined by Indonesian Meteorological, Climatological and Geophysical Agency (BMKG) (http://www.bmkg.go.id/BMKG_Pusat/Meteorologi/Prospek_Cuaca_Mingguan.bmkg). We analyzed the migration of rainfall areas for each event based on the CDR data, and categorized two patterns of rainfall migration: zonal (from west to east) and meridional (south to north, or north to south). Note that north and south of the JABODETABEK area are the Jawa Sea and mountains respectively.

Figure 6 shows cases of meridional migration (with migration velocities of 3–15 m s\(^{-1}\) or 15–50 km h\(^{-1}\)) observed during the last 6 days (09–14 February) of the HARIMAU2010 campaign. The local rainfall peaks in the upstream area (including Bogor, Katulampa and Citeko stations) appeared around 17 LT. The amount of daily rainfall calculated from CDR data averaged for these 6 days with meridional migrations was 54.5 mm day\(^{-1}\), which was larger than the amounts averaged for the whole observational period (33.4 mm day\(^{-1}\)) and for days with zonal migrations (27.6 mm day\(^{-1}\)). This was considered reasonable because the river basin is elongated in the meridional direction. In the case of 09–11 February, the largest rainfall intensity area of about 48.5 dBZ (corresponding to intensity of ~40 mm h\(^{-1}\)) migrated meridionally within a period of 2–3 hours on each day, and the local daily rainfall was 169.8 mm.

However, the daytime rise (maximum – minimum) of the river water level for such an extreme rainfall case was still 10–15 cm. These extreme rainfall events with a clear diurnal cycle and meridional migration caused flooding of the Ciliwung River, but the floods were localized and were not as serious as those in 2007 or 2013. As mentioned in the previous section, the amplitude of the diurnal cycle of river water was not significantly changed by the total amount of diurnal rainfall at least in the observations reported here.

On 13 February (as shown in Fig. 6), the diurnal cycle of river water was unclear partly because of the opening a gate by the operator of PU in response to river water rising beyond their warning level, which was the only one case during the 1-month period of the HARIMAU2010 IOP. The southward migration from the sea to the mountains in the morning was also very striking on this particular day. On the other five days shown in Fig. 6 we observed only northward migrations or much weaker southward migrations.

5. Discussions

Some previous studies have reported diurnal cycles within mid-latitude rivers (Burt 1979; Lundquist and Cayan 2002), due mainly to daytime increases in evapotranspiration, infiltration, or snow melt under low rainfall conditions. These cycles were much weaker than those reported here. Artificial water controls may generate a diurnal cycle (White 2005), but no such operations were undertaken during the observation period. Therefore, the persistent existence of the diurnal cycle of the Ciliwung River reported here cannot be explained by the causes reported in previous studies.

The diurnal cycle of the water level reported here also cannot be explained by the ocean tide actually observed near the river mouth. The diurnal component dominates the semidiurnal component (Fig. 4). The phase of the diurnal cycle is fixed to local time, with no modification by the lunar cycle (Fig. 3). The global atmospheric tide predominates in Jakarta near the equator (see Hagan et al. 2002), but the surface pressure amplitude of its diurnal component (weaker than the semidiurnal component) is about 0.6 hPa, corresponding to a 0.6 cm rise/fall in the water level at 02:00/14:00 LT, which is clearly smaller than and different from the observed diurnal cycle.

Therefore, the cause of the diurnal cycle observed at Ciliwung River can be almost uniquely explained by the diurnal cycle of rainfall. However, the local instant rainfall of ~3 mm h\(^{-1}\) for 3–4 h (~10 mm daily) cannot fully explain the water level increase of 0.1 m or 100 mm, meteorological (rainfall area) and hydrological processes in the upstream catchment area must be considered. The rainfall area (corresponding to a meridional scale of ~20 km seen in Fig. 6) was about 400 km\(^2\) almost every day (suggesting a total
amount of rainwater of $4 \times 10^6 \text{m}^3$ and it migrated in the meridional direction. This migration was associated with the circulation of sea–land breezes (Mori et al. 2004; Araki et al. 2006; Wu et al. 2009), which are generated by the contrast in sea/land heating and predominate along the long coastlines of the large islands of the IMC, and free from synoptic-scale cyclones. Rainfall and clouds activated over the convergence of the sea and land breezes migrated in the meridional direction from land to sea in the evening and from sea to land in the morning, as observed here. For the cases shown in Fig. 6, migrations in the direction of the land breeze ($10$ and $14$ February) were faster than those in the sea breeze direction ($9$ and $11$–$13$ February). The migrations in the direction of the land breeze were in the same direction as the river flow, and may include a case where rainfall provided a massive amount of water that reached the downstream area earlier than the river flow.

In the case of the severe flood event in 2007, rainfall with clouds migrating northward (from mountains to the sea) mainly after sunset was amplified by a strong persistent trans-equatorial monsoon flow from the Northern Hemisphere (Wu et al. 2007; Trilaksono et al. 2012). Water level data of the Ciliwung River during this flood and another event in 2002 indicated a rise of about $2$ m after the peaks of rainfall in the diurnal cycle. A flood event in 2013 ($2.5$ m at its maximum amplitude) occurred in a different phase of the diurnal-cycle of cloud migration (from sea to land in the morning), which interacted with the intraseasonal variation (Wu et al. 2013).

6. Conclusions

In this study, we have shown that a systematic water-level diurnal cycle with an amplitude of $0.05$ m is persistently generated in the Ciliwung River basin by the diurnal cycle of rainfall, which amounts to about $100$ mm in the catchment area. When the rainfall area (cloud) migrates with a sea-land breeze circulation roughly parallel to the river flow, the total amount of diurnal rainfall over the river basin is increased, but the diurnal cycle of river water is not significantly changed.

In the case of the serious floods of 2007 and 2013, the rise in the water level was about $20$ times ($2$ m) more than the persistent diurnal cycle reported here. Relationships between such flood events and the amplified diurnal cycle will be studied by numerical simulations in a subsequent study.

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References


