ANNUAL AND SEMI-ANNUAL VARIATIONS OF THE GPS-DERIVED PRECIPITABLE WATER VAPOR OVER SUMATERA ISLAND

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ABSTRACT

We have utilized the Global Positioning System (GPS) data at 57 stations distributed over Sumatera Island to investigate spatio-temporal variations of the atmospheric precipitable water vapor (PWV). We focused on the annual and semi-annual cycles of the PWV. Our results showed that Sumatera Island was divided into two distinct areas of annual and semi-annual cycles, where the boundary line between the areas was approximately at 2°S. While the annual cycle dominates the area over the southern side of 2°S, the semi-annual cycle was dominant over the northern side. Our results have further shown that the maximum phase of annual cycle occurs between January-March with considerably large amplitudes (10-15 mm). On the other side, the maximum phase of the semi-annual cycle in general occurred around November and May, whose amplitude was approximately between 1-5 mm. Our results were consistent with other results using rainfall data.

Keywords: Precipitable water vapor, Rainfall, GPS, Ina-CORS

1. Introduction

The Indonesian archipelago is classified as “the Maritime Continent” due to its complex topography resulted from different size of the islands interspersed among the surrounding warm sea waters [1], where the typical value of the sea surface temperature (SST) is constantly above 300 K [2]. These warm waters produce an abundance of water vapor, which in turn will facilitate the development of deep convection. The convection is typically more active than in the other tropical regions and becomes the main heat engine to generate the east-west circulation. This active convection produces a large amount of rainfall which varies highly in space and time [3-5].

There have been numerous investigations on seasonal variations of rainfall over the Indonesian archipelago and their links to the Asian-Australian monsoon system and the El-Nino Southern Oscillation (ENSO), see for examples [3, 6-9]. The variations of rainfall as well as their links to the monsoon and ENSO have motivated some researchers to classify the Indonesian archipelago into several dominant climatic regions.

Sumatera Island is located at the western edge of the Maritime Continent, an area situated between the Indian and Pacific Oceans which also includes the Malay Peninsula and large islands, such as Java, Borneo, Sulawesi, New Guinea, and the Philippines, as well as a galaxy of smaller islands. There are numerous reports describing diurnal, annual and seasonal variations of rainfall and its relationship with other phenomena such as the ENSO and the Madden-Julian Oscillation (MJO) over Sumatera Island and its surrounding area [5, 10-14]. Since the amount of rainfall over the Maritime Continent is mainly triggered by the presence of abundant water vapor, a thorough understanding of the distributions and variations of water vapor is urgently required. For this study, Sumatera Island was chosen due to the intense convective activity in the area [15, 16]. Water vapor is essential for cloud convective activity. Knowledge of the distribution and temporal variation of atmospheric water vapor is, therefore, important in forecasting regional weather and for understanding of the global climate system. However, monitoring the variation of water vapor with high temporal and spatial resolution by conventional techniques, such as radiosondes and water vapor radiometers, is difficult.

The Global Positioning System (GPS) has been widely used to accurately observe atmospheric water vapour with high spatio-temporal resolution, and low operational cost [17-19]. In this research, we utilized the Indonesian Continuously Operating Stations (Ina-CORS), which is established and maintained by the Geospatial Information Agency (Badan Informasi Geospasial, BIG), to investigate long-term variation of atmospheric water vapor over Sumatera Island. Here, we used the precipitable water vapour (PWV) as the main variable to quantify annual and semi-annual variations of the precipitation over Sumatera Island.
2. Methods

GPS Data Processing. We used the GPS data collected by the Ina-CORS during the period of 2011 to 2020. The total number of GPS stations involved is 57 stations. The data were processed using the GAMIT software [20] producing the hourly zenith tropospheric delay (ZTD) for each station. In our case, the ZTD was treated as a stochastic variation with respect to the Saastamoinen model [21] with piecewise linear interpolation in between epochs. The a priori ZHD was calculated using the surface pressure measurements, and if such measurements are not available, the ZHD was generated from the gridded VMF1 [22]. The ZTD variation is constrained to be a Gauss-Markov process with a specified power density of 2 cm²/√hour and, upon applying this constraint, the ZTD values were estimated every 1 hour. To eliminate multipath effects, all observations down to an elevation cutoff angle of 10° were included and the elevation dependency of the ZTD was modeled using the VMF1 mapping function [22]. To remove spurious ZTD values, we applied a modified screening technique originally proposed by [23] and it was applied to the daily ZTD results.

Conversion from ZTD to PWV. All hourly ZTD values were then converted using the following equation [17]:

\[ PWV = \Pi \left( ZTD - \frac{P_s}{g(\lambda, h_{eit})} \right) \]

The terms \( \Pi \) and \( g(\lambda, h_{eit}) \) are defined as:

\[ \Pi = \frac{10^6}{\rho R_w (k_4 + k_5 T_w)} \]  
\[ g(\lambda, h_{eit}) = 1 - 0.00266 \cos(2\lambda) - 0.28 h_{eit} \]

\( P_s \) is the surface pressure, \( \lambda \) and \( h_{eit} \) respectively denote the latitude and the ellipsoidal height (in meters). \( T_w \) is the weighted mean temperature. As for another constant variables, we adopted the following values: \( \rho = 1000 \text{ kg/m}^3 \), \( R_w = 461.51 \text{ J kg}^{-1} \text{ K}^{-1} \), \( k_4 = 375463 \text{ K}^2 \text{ hPa}^{-1} \) and \( k_5 = 229721 \text{ K} \text{ hPa}^{-1} \). In this research, the values for \( P_s \) were derived from the surface meteorological sensor, and those for \( T_w \) were calculated from the European Centre for Medium-range Weather Forecasting (ECMWF) reanalysis data.

Analysis of PWV Time Series. The derived long-term PWV series at each GPS station is analysed to reveal annual and semi-annual cycles of water vapour. In this present work, we followed the procedure described in [3] to estimate the phase and amplitude for each cycle. First, for each year, we constructed the pentad averaged daily PWV data (5-day average), consisting of 73 pentad days. Second, we generated mean climatology pentad data series by averaging the same pentad day for the whole years from 2011 to 2020, resulting in a single PWV series with 73 pentad days. Third, we fitted the mean climatology data series to a theoretical PWV model defined as a sum of the mean (73-pentad) average, and four harmonics with periods of 73 (annual), 26.5 (semi-annual), 18.25 (half-semi-annual) and 9.125 (quarter of semi-annual) pentads by the least square method. The difference between the theoretical model and the original climatology pentad data is sufficiently small, especially for GNSS stations located in the southern hemisphere.

To delineate annual/semi-annual regime areas, we introduced the \( V_{12} \) index, which is defined as:

\[ V_{12} = \frac{A_2}{A_1 + A_2} - \frac{A_1}{A_1 + A_2} \]  

\( A_1 \) and \( A_2 \) denote respectively the annual and semi-annual amplitudes. The \( V_{12} \) index principally represents the percentage different between the annual and semi-annual cycles. While a purely annual regime is indicated by \( V_{12} = +1 \), a pure semi-annual regime is denoted by \( V_{12} = -1 \). Furthermore, a value of \( V_{12} \) near zero indicates that both annual and semi-annual cycles have an equal domination. We then search for a contour zero of \( V_{12} \) to delineate the annual and semi-annual regime areas.

3. Result and Discussion

Annual and Semi-annual Cycles. Figure 1 shows the pentad PWV harmonic analysis for three extreme values of \( V_{12} \) : the smallest (\( V_{12} = -0.90 \)) at CBLG (Balige), equal zero (\( V_{12} = 0.00 \)) at CBJI (Jambi), and the largest (\( V_{12} = +0.68 \)) at CPRI (Pringsewu). Geographical location of those stations can be seen at Figure 3.

CBLG station is located in the area where the semi-annual cycle (\( A_2 = 2.87 \text{ mm} \)) is considerably more dominant than the annual cycle (\( A_1 = 0.15 \text{ mm} \)). It can be seen from both the mean pentad data (grey bars in Figure 1) and the theoretical semi-annual curve (red line in Figure 1), the maximum precipitation occurs twice a year around November and May, respectively. Since CBLG is located in a mountainous area (high altitude), the PWV values at CBLG are smaller than those at the other low altitude stations (CBJI and CPRI). In a mountainous area, the height of the vertical atmospheric column is rather small, and hence such a column contains less PWV.

It is interesting that at CBJI station both annual and semi-annual cycles have a comparable domination
(A₁ ≈ A₂ ≈ 3.90 mm), and hence the value of V₁₂ is equal zero. The mean pentad data reaches maximum values in December and April, while it can also exceed the average in February. On the contrary, the theoretical semi-annual curve shows that the maximum precipitation occurs in October and May. The difference in time occurrence of maximum precipitation between the mean pentad days and the theoretical semi-annual curve indicates that the power of annual cycle shifts the peak of the theoretical semi-annual curve.

Considerably strong annual cycle (A₁ = 9.97 mm) and weak semi-annual cycle (A₂ = 0.15 mm) occur at CPRI station. According to both the mean pentad data and the theoretical annual curve (blue line in Figure 1), the precipitation generally reaches maximum values in February. A little peculiarity can be seen from the pentad data, from which the precipitation can also be large in April.

To evaluate the annual and semi-annual cycles for all GPS stations, we present the phase and amplitude at each station in Figure 2 by an arrow pointing toward a specific direction. While the amplitude is shown by the length of arrow, the phase is shown as a 12-month clock with a northward arrow indicating maximum PWV occurs in January. The arrow rotates clockwise with eastward, southward, and westward arrow indicating April, July, and October.

From Figure 2, it can obviously be seen that the southeastern part of Sumatera Island is dominated by strong annual cycles. The maximum phase of annual cycle comes between January-March with considerably large amplitudes (10-15 mm). In the rest part of Sumatera Island, the semi-annual cycle largely dominates with the amplitude is approximately between 1-5 mm. The maximum phase of the semi-annual cycle in general occurs around November and May. These results are in a good agreement with those reported by [3], [7], and [8]. Results from the Tropical Rainfall Measuring Mission (TRMM) show that the peak maximum in the western and southern Sumatera occurs between September-November and December-February [24].

**Spatial Distribution of the V₁₂ Index.** To evaluate spatial distribution of the annual and semi-annual cycles, we spatially gridded the values of V₁₂ index at all stations into a cell size of 10' x 10' using the spline tension interpolation method [25]. A positive/negative value of V₁₂ represents an area with strong annual/semi-annual cycle. We then used the contour V₁₂ = 0 to demarcate the boundary between areas of annual and semi-annual cycles. The results are depicted in Figure 3. The semi-annual pattern in the west coast in the southern Sumatera cannot be depicted in Figure 3 due to the different interpolation method, as well as different physical characteristics of PWV and rainfall.
Figure 3 reveals that the boundary between areas of annual and semi-annual cycles lies approximately around 2°S. The boundary line as derived from the zero contour of $V_{12}$ is in a good agreement with the one derived by [7] using rainfall data. The discrepancy between these two boundary lines might probably be due to different data set, method of analysis and possible non-linear relation between rainfall and PWV. CJBI station is located near the boundary lines, and the annual and semi-annual cycles have a comparable amplitude (see Figure 1).

Over the southern side of 2°S, the annual cycle is dominant, having a relatively homogeneous amplitude over the whole area. It can also be seen that the semi-annual cycle dominates the region over the northern side of 2°S, having an inhomogeneous amplitude, where the largest amplitude is near 2°N.

4. Conclusion

We have utilized the GPS data from the Ina-CORS to investigate annual and semi-annual variations of the precipitation over Sumatera Island. The island is divided into two distinct areas, based on the dominant cycle, where the boundary line between the areas is approximately around 2°S. While the annual cycle dominates the area over the southern side of 2°S, the semi-annual cycle is dominant over the northern side.

Our results have further shown that the maximum phase of annual cycle occurs between January-March with considerably large amplitudes (10-15 mm). On the other side, the maximum phase of the semi-annual cycle in general occurs around November and May, whose amplitude is approximately between 1-5 mm.

Throughout this present work, we also analysed GPS data all over Indonesian region consisting of 237 stations. The results provide new datasets for accomplishing atmospheric studies using GPS observations in Indonesia. Since GPS are able to provide hourly results, it is also possible to use GPS data for understanding the diurnal atmospheric dynamics.

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