Interannual variation of springtime biomass burning in Indochina: Regional differences, associated atmospheric dynamical changes, and downwind impacts

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1. Introduction

During March and April, widespread burning occurs across farmlands in Indochina in preparation for planting at the monsoon onset. This burning occurs in conjunction with local hot-dry-stagnant air and generates smoke and haze aerosol pollution, particularly over the valley terrain of the northern peninsula [Kim Oanh and Leelasakultum, 2011]. Because the resultant aerosols affect not only the local region but also the air quality downwind, many studies have examined the climate and weather characteristics in association with biomass burning [Duncan et al., 2003; Yen et al., 2013; Wang et al., 2015]. In general, biomass burning occurs over Indochina during the time period from February to April, with a maximum occurrence in March (Figure 1b). After the monsoon rainfall onset in late April, the occurrence of fire events becomes minimal. The annual variation of aerosol concentrations over Indochina depends on the prevailing times of biomass burning [Gautam et al., 2013; Huang et al., 2013]. Some reports revealed that aerosols generated by biomass burning could be reduced by the increase of precipitation and monsoon circulation due to rainout and washout processes [Sanap and Pandithurai, 2015; Sonkaew and Macatangay, 2015].

Based on the NOAA’s Hybrid Single-Particle Lagrangian-Integrated Trajectory model simulations, earlier studies [Yu et al., 2008; Yen et al., 2013] demonstrated that the long-range transport of Indochina’s biomass burning pollutants has a significant impact on the surface air quality of downstream areas, particularly in Taiwan. The biomass burning emissions are uplifted above the planetary boundary layer through regional convergence at the lower level and strong thermal buoyancy [e.g., Yen et al., 2013; Wang et al., 2015]. After being lifted, the aerosols are transported to Taiwan by the low-level westerly jet (Figures 1c and 1d) within 2–3 days [e.g., Cheng et al., 2013; Yen et al., 2013; Dong and Fu, 2015]. These aerosol transports can result in significant increase of air pollutant concentrations in Taiwan, as reported by many studies [e.g., Lee et al., 2011; Yen et al.,...
For example, Chuang et al. [2015] noted that the concentrations of particulate matter (PM) at Mt. Lulin of Taiwan was increased from approximately 15–20 μg m\(^{-3}\) to 53–64 μg m\(^{-3}\) on 12 March 2010 after the arrival of the biomass burning plume from Indochina. Even though the aforementioned relationship between biomass burning in Indochina and its downwind influences on concentration of air pollutants (e.g., PM\(_{10}\) and PM\(_{2.5}\)) in Taiwan has been reported [e.g., Yen et al., 2013; Chuang et al., 2015], the contribution of the low-level trough over the Bay of Bengal (so-called India-Burma Trough; Figure 1d) on the aerosol transport pattern has not been emphasized. Several studies have suggested that the India-Burma Trough is a key system affecting the weather and climate over Southeast Asia, especially in winter [e.g., Suo et al., 2008; Suo and Ding, 2009; Zhou et al., 2009; Zong et al., 2012; Wang et al., 2011; Li and Zhou, 2016]. Suo and Ding [2009] noted that the India-Burma Trough is generally established in October, is maintained from November to the following February, and peaks from March to May. Li and Zhou [2016] further suggested that the interannual variation of winter precipitation over southwest China is modulated by the change of the India-Burma Trough. As inferred from this documented literature, it is likely that the changes in the India-Burma Trough might play an important role in modulating the interannual variation of biomass burning in Indochina and its downwind impacts on the air quality in Taiwan.

In 2007, the Seven SouthEast Asian Studies (7-SEAS) project (http://7-seas.gsfc.nasa.gov/) was established to perform research in the field of aerosol-meteorology and climate interactions from Java through the Malay Peninsula and Southeast Asia to Taiwan [Reid et al., 2013; Lin et al., 2013]. The Lulin Atmospheric Background Station (LABS), located at Mt. Lulin (altitude: 2862 m; 23°28′07″N, 120°52′25″N; http://lulin.tw) in central Taiwan, started operations on April 2006 to provide continuous observations of a variety of aerosol concentrations.
chemistry parameters, trace gases, etc. The long-term observational data collected by the 7-SEAS project and LABS in Taiwan now provide a great opportunity for studying the relationship between the variations of biomass burning in Indochina and the variations of air quality in Taiwan on an internal interannual time scale.

This study aims to examine the interannual variation of biomass burning in Indochina and its associated atmospheric dynamical changes, with a focus on understanding the role of the India-Burma Trough in modulating the aerosol transport from Indochina to LABS in Taiwan. Considering a large domain from the tropics to 25°N of Indochina (Figure 1a), the atmospheric circulation features important for the modulation of the interannual variation of biomass burning in different subregions of Indochina might be different. This inference, together with the regional differences in the interannual variation of biomass burning and its downwind impacts, will be clarified in the subsequent analysis.

The remainder of this paper is organized as follows. In section 2, the data used for the analyses are described. Section 3 reports the spatial-temporal characteristics of the interannual variation of biomass burning in Indochina, their relations to air quality in Taiwan, and the associated atmospheric circulation features. Discussion is provided in section 4. A summary is given in section 5.

2. Data and Methodology

In this study, the biomass burning activity from 2005 to 2015 is identified by fire data from Moderate Resolution Imaging Spectroradiometer (MODIS; http://modis.gsfc.nasa.gov/) on board NASA’s Terra and Aqua satellites. The MOD14 (Terra) and MYD14 (Aqua) active fire product detects fires in 1 km pixels that are burning at the time of overpass under relatively cloud-free conditions [Giglio et al., 2003]. The overpass time for Terra and Aqua are approximately 10:30 and 13:30 local time, respectively. The daily fire counts are calculated from the sum of the MOD14 and MYD14 data sets. Because the MODIS fire count data exhibit some quality problem in the early 2000s [Giglio, 2013; Giglio et al., 2013], only data from 2005 onward were used. For a detailed review of the MODIS fire count data, please refer to Giglio [2013].

To further validate the representativeness of MODIS fire count for biomass burning activities over Indochina, we also examined the biomass burning dry matter emissions (hereafter, biomass burning emissions) provided by the Global Fire Emissions Database, version 4 (GFED4s; http://globalfiredata.org/data.html) [Giglio et al., 2013]. The GFED4s provides various types of biomass burning emissions, and this study only used the changes of total amount of biomass burning emissions (i.e., the summation of all types). It should be noted that MODIS exhibits a limit in capturing peat burning [Giglio et al., 2010]; however, we considered this limitation neglectable because the proportion of peat burning to total biomass burning emissions over Indochina is small [e.g., Shi and Yamaguchi, 2014]. As will be shown in Figure 3 (discussed later), the interannual variation of the GFED4s’ total biomass burning emissions matches well with that of the MODIS fire count over Indochina. This result indicates that MODIS fire count can represent biomass burning activities over Indochina, consistent with Yu et al. [2008] and Wang et al. [2015].

To examine the impact of biomass burning on downwind air quality, we selected LABS as the representative location because the transportation of the biomass burning plume from Indochina to Taiwan has been well documented by the measurement data collected from this station [e.g., Ou Yang et al., 2014, and references therein]. The instrument for the PM$_{10}$ and PM$_{2.5}$ mass concentration is the tapered element oscillating microbalance (RP 1400a, USA). In this study, we used only PM$_{10}$ data (~10 years) because of its longer record compared to PM$_{2.5}$ data (~3 years).

For the observational precipitation, we used 3 hourly Tropical Rainfall Measuring Mission (TRMM) 3B42 satellite precipitation [Huffman et al., 2007]. TRMM 3B42 data have been widely used for the depiction of rainfall variation over South and East Asia [Hong et al., 2005; Zhou et al., 2008; Huang and Chan, 2012; Huang and Wang, 2014]. For the meteorological data (including wind fields and humidity), we used the National Centers for Environmental Prediction–Department of Energy (NCEP-DOE) Reanalysis 2 [Kanamitsu et al., 2002]. The calculation of the moisture flux from NCEP-DOE Reanalysis 2 is based on equation (1):

$$Q = \frac{1}{g} \left[ \rho_i \int_0^R V_q dp \right]$$  

where $V$ denotes the horizontal wind vectors, $q$ is the specific humidity, $g$ is the gravity, and $p$ is the pressure level [Chen et al., 1988]. Following Chen et al. [1988], the moisture flux can be separated into rotational ($Q_R$)
and divergent \( Q_D \) components, which can be further expressed in terms of the stream function \( \psi_Q \) and potential function \( \chi_Q \) of the moisture flux:

\[
Q = Q_R + Q_D = \dot{k} \times \nabla \psi_Q + \nabla \chi_Q, \tag{2}
\]

\[
\nabla^2 \psi_Q = \dot{k} \cdot \nabla \times Q, \tag{3}
\]

\[
\nabla^2 \chi_Q = \nabla \cdot Q. \tag{4}
\]

The fields of \( \psi_Q \) and \( \chi_Q \) are obtained by solving the Poisson equation for equations (3) and (4).

Hereafter, unless noted otherwise, the variables used for examination are the monthly means of March and April (MA mean) during the time period of 2005–2015. The anomaly of a variable designates the removal of climatological monthly mean from each month. The index of northern Indochina biomass burning activities was defined as the amount of MODIS fire count over the domain of 17–22°N, 97–102°E (red box in Figure 2a), while the index of southern Indochina biomass burning activities was defined as the amount of MODIS fire count over the domain of 10–15°N, 102–107°E (red box in Figure 2b). The selection of these two specific domains was based on the analysis in Figure 2, as explained later.

### 3. Results

#### 3.1. Characteristics of Biomass Burning in Indochina and Its Downwind Impact

Figure 1d shows the climatological mean distribution of biomass burning activities (i.e., the MODIS fire count) in Indochina averaged over the focused time period. Visually, the amount of biomass burning activities is
larger over northern Indochina, covering most of Burma and northern Thailand, than over southern Indochina. To clarify how these biomass burning activities varied on the interannual time scale, we applied empirical orthogonal function (EOF) analysis on the anomalies of biomass burning activities for the time period of 2005–2015 (Figure 2). The EOF analysis was based on singular-value decomposition (SVD) approach. The SVD approach, which avoids having to compute the covariance matrix directly, provides an optimal way for data sets with a large spatial dimension [Hannachi et al., 2007]. Any missing space/time data were removed before applying the SVD approach. For the detailed review of the EOF analysis (including historical background, formulation and computation, and application), please refer to Hannachi et al. [2007].

In Figure 2, only the results of the first two EOF modes, together explaining approximately 90% of the total interannual variability of biomass burning activities, are presented. Spatially, the first EOF mode shows that the variation is mainly over northern Indochina, with a largest variation center over northern Thailand (Figure 2a). Corresponding to this spatial distribution, the temporal variation of Figure 2a shows that more (less) biomass burning likely occurred over northern Indochina in the years of 2007 and 2010 (2005, 2008, 2011, and 2015). In contrast, it can be inferred from the spatial-temporal patterns of the second EOF mode (Figure 2b) that over southern Indochina more (less) biomass burning occurred in the years of 2005, 2010, and 2013–2015 (2006, 2007, 2009, and 2012). Additionally, Figure 3 shows the time series of biomass burning activities over the major variation domain of northern Indochina (17–22°N, 97–102°E; marked in Figure 2a) and southern Indochina (10–15°N, 102–107°E; marked in Figure 2b). Consistent with that implied from Figure 2, the results of Figure 3 confirm that the interannual variation of biomass burning activities over northern Indochina is different to that over southern Indochina.

To understand which subregion of biomass burning has a larger impact on the aerosol concentration in Taiwan, we further compared the time series of PM$_{10}$ at LABS in Taiwan (blue lines) with the time series of biomass burning activities/emissions over the major variation domain of northern Indochina (Figure 3a) and southern Indochina (Figure 3b). Notably, the fluctuation of PM$_{10}$ at LABS in Taiwan seems to match better with the fluctuation of biomass burning activities/emissions over northern Indochina than over southern Indochina. More specifically, the maximum (minimum) of PM$_{10}$ at LABS in Taiwan occurred in the years of 2007 and 2010 (2008, 2011, and 2015), when the maximum (minimum) of biomass burning activities/emissions occurred over northern Indochina. Statistically, the temporal correlation coefficient between the interannual variation (i.e., linear trend removed) of PM$_{10}$ at LABS in Taiwan and the biomass burning activities/emissions over northern Indochina is approximately 0.86/0.81 (significant at the 95% confidence interval). Such a temporal variation of PM$_{10}$ is found to be less related to the temporal variation of biomass burning activities/emissions over southern Indochina (the correlation between the two time series in Figure 3b is only $-0.15/-0.14$). These findings (Figures 2 and 3) highlight the importance of

Figure 3. Time series of MA mean of biomass burning activities (bar) and total biomass burning dry matter emissions (green dashed line) over the two selected domains: (a) northern Indochina (17–22°N, 97–102°E; marked in Figure 2a) and (b) southern Indochina (10–15°N, 102–107°E; marked in Figure 2b). In Figures 3a and 3b, the blue line represents the time series of MA mean of PM$_{10}$ at LABS in Taiwan.
considering regional differences in the discussions of the remote impact of Indochina’s biomass burning on the air quality in Taiwan.

3.2. The Associated Atmospheric Circulation Features

Next, we examined the atmospheric circulation changes that are associated with the change of biomass burning over northern Indochina. Here the index of northern Indochina biomass burning activities (i.e., the amount of MODIS fire count over the domain of 17–22°N, 97–102°E; red boxed area) and six selected variables: (a) GFDE4s total biomass burning dry matter emissions, (b) 850 hPa wind circulation $V_{850}$, (c) 700 hPa wind circulation $V_{700}$, (d) stream function of the moisture flux $\psi_Q$, (e) potential function of the moisture flux $\chi_Q$, and (f) precipitation $P$ extracted from TRMM observations. The time period of correlation is from 2005 to 2015. Only the areas with significant changes (at the 90% confidence interval) are shaded/shown. The color scale of Figures 4a–4f is given in the bottom plot.

**Figure 4.** Temporal correlation coefficient between the MA mean index of northern Indochina biomass burning activities (i.e., the amount of MODIS fire count over the domain of 17–22°N, 97–102°E; red boxed area) and six selected variables: (a) GFDE4s total biomass burning dry matter emissions, (b) 850 hPa wind circulation $V_{850}$, (c) 700 hPa wind circulation $V_{700}$, (d) stream function of the moisture flux $\psi_Q$, (e) potential function of the moisture flux $\chi_Q$, and (f) precipitation $P$. The time period of correlation is from 2005 to 2015. Only the areas with significant changes (at the 90% confidence interval) are shaded/shown. The color scale of Figures 4a–4f is given in the bottom plot.
climatological mean in the lower and middle troposphere (Figures 4b and 4c). A further examination on the associated change of $\psi_Q$ (Figure 4d) has indicated that the increase in northwesterly wind behind the India-Burma Trough could advect dryer air from the higher latitude to northern Indochina. This would facilitate a moisture divergence center to be formed over the west coast of Indochina, as revealed by the associated change of $\chi_Q$ (Figure 4e). Furthermore, such a suppression of the moisture supply from the Bay of Bengal would result in less precipitation to be formed over northern Indochina (Figure 4f), and this dryer condition can help promote the local biomass burning activities (Figure 4a). The argument that less precipitation favors more biomass burning is also suggested by Dong and Fu [2015] but for the change of biomass burning accumulated over "entire" Indochina.

Figure 5 presents the correlation maps between the index of southern Indochina biomass burning activities (i.e., the amount of MODIS fire count over the domain of 10–15°N, 102–107°E: boxed area) and six selected variables: (a) GFDE4s total biomass burning dry matter emissions, (b) $V_{850\text{ hPa}}$, (c) $V_{700\text{ hPa}}$, (d) $\psi_Q$, (e) $\chi_Q$, and (f) precipitation $P$ extracted from TRMM observations. The time period of correlation is from 2005 to 2015. Only the areas with significant changes (at the 90% confidence interval) are shaded/shown. The color scale of Figures 5a–5f is given in the bottom plot.
Bengal in the lower and middle troposphere (Figures 5b and 5c). In conjunction with the Bay of Bengal anticyclone system, the northerly wind is intensified over southern Indochina. Such a circulation change could advect the dryer air from higher latitude to southern Indochina, as noted from the associated change of $\psi Q$ (Figure 5d). As a result, the moisture flux is divergent over south of the South China Sea (Figure 5e), and less precipitation has occurred over southern Indochina (Figure 5f). Obviously, these circulation changes that are important for the modulation of biomass burning over southern Indochina (Figure 5) are very different to those important for the modulation of biomass burning over northern Indochina (Figure 4). This finding explains why the interannual variation of biomass burning over Indochina is locally dependent.

It should be mentioned that to be transported to Taiwan, the air pollution created by Indochina’s biomass burning has to be uplifted to the level with a stronger westerly jet [e.g., Yen et al., 2013; Dong and Fu, 2015]. Thus, to clarify why the biomass burning over northern Indochina (as compared to that over southern Indochina) has a larger impact on the PM$_{10}$ in Taiwan, we further examined the relationship between the change in vertical motion ($-\omega$; positive values denote the upward motions) and the change in index of northern Indochina biomass burning activities (defined in section 2) The result (Figure 6a) shows that the change in northern Indochina’s biomass burning activities is positively correlated to the change in upward motion over the area between Indochina and Taiwan at levels up to 700 hPa. This finding, together with Figures 4e and 4f, implies that more active but dryer upward motion occurred over northern Indochina in the years with greater biomass burning. After the air pollution is uplifted to upper levels, the increase in the westerly wind ahead of the intensified India-Burma Trough (e.g., Figures 4b and 4c), which appeared in the levels up to 500 hPa...
(Figure 6b), can then help transport the PM$_{10}$ from northern Indochina to Taiwan. In comparing Figures 6a and 6b, there is no clear positive relationship between the change in southern Indochina’s biomass burning activities and the change in local upward motion (Figure 6c) or the change in the westerly jet over the area between Indochina and Taiwan (Figure 6d). As a result of the differences between Figures 6a and 6b and Figures 6c and 6d, the change in southern Indochina’s biomass burning is not as important as the change in northern Indochina’s biomass burning in terms of the change of PM$_{10}$ at LABS in Taiwan.

Notably, in addition to the interannual variation, the PM$_{10}$ at LABS in Taiwan seems to be modulated by a decreasing trend (see Figure 3). However, the time period of 2007–2015 is too short to reasonably identify the existence of such a trend. A further examination on this issue is suggested in the future when a longer period of data is available.

4. Discussion

From section 3, it can be concluded that the change of the India-Burma Trough plays an important role in modulating the interannual variation of biomass burning activities over northern Indochina and its impact on PM$_{10}$ at LABS in Taiwan. Thus, it is important to understand what might cause the change in the India-Burma Trough on the interannual time scale. The recent study of Li and Zhou [2016] suggested that the interannual variation of the wintertime (December to the following February) India-Burma Trough is part of the South Asian jet wave train and is modulated by El Niño–Southern Oscillation (ENSO) via the Philippine Sea anticyclone. Here we will clarify if the change of the springtime (March and April) India-Burma Trough is also connected to the change of the South Asian jet wave train and ENSO.

Figure 7 shows the correlation map of the 700 hPa vorticity [i.e., $\zeta$ (700 hPa)] and the wind vectors associated with the index of northern Indochina's biomass burning activities (defined in section 2). It is interesting to note that $\zeta$ (700 hPa) over the area of the India-Burma Trough is positively correlated with $\zeta$ (700 hPa) over the western Mediterranean Sea and Saudi Arabia and negatively correlated with $\zeta$ (700 hPa) over the eastern Mediterranean Sea and the Arabian Sea. A better illustration of such a wave train can be revealed in the correlation map of the 700 hPa stream function [i.e., $\psi$ (700 hPa)] with the northern Indochina’s biomass burning index, as shown in Figure 8a. By comparing this springtime wave train pattern (Figure 8a) with the wintertime wave train pattern identified in Li and Zhou [2016], it is noted that the former also appeared along the South Asian jet but with different variation centers. Such a difference might be attributed to the seasonal variation of the South Asian jet.

Previous studies suggested that the propagation of the Rossby wave from the Mediterranean Sea to the Bay of Bengal is one of the key mechanisms for the enhancement of the India-Burma Trough in wintertime [Suo...
et al., 2008; Li and Zhou, 2016). To clarify if this is also true for the enhancement of the India-Burma Trough in the springtime, we used the area-averaged $\zeta$ (700 hPa) over the western Mediterranean Sea (37.5°N–42.5°N, 2.5°W–2.5°E) as an index to correlate with $\psi$ (700 hPa) for March and April of 2005–2015. As revealed in Figure 8b, the wave train pattern with an upstream source over the western Mediterranean Sea propagates downstream across the Mediterranean Sea, Saudi Arabia, and Arabian Sea to the area covering the northern Bay of Bengal, northern Indochina, and south China. This pattern is consistent with that shown in Figure 8a, suggesting that the propagation of such a wave from the western Mediterranean Sea can modulate the change of the India-Burma Trough in the springtime.

We also examined the possible modulation from the downstream ENSO signal to the India-Burma Trough by using the wintertime sea surface temperature (SST) averaged over the Niño3.4 region as an index to correlate the following springtime $\psi$ (700 hPa); the result is given in Figure 8c. It is found that the change of wintertime SST over the Niño3.4 region is positively related to the change of the following springtime anticyclone over the area covering most of the South China Sea (hereafter, South China Sea anticyclone (SCSA)). Consistent with this finding, the bubble chart given in Figure 9 shows that during an El Niño (La Niña) event, a stronger (weaker) SCSA in the following springtime can be expected [e.g., Wang and Zhang, 2002]. As noted from
Figures 1d and 7, the existence of SCSA can help strengthen the westerly jet ahead of the India-Burma Trough [e.g., Wang et al., 2011]. In other words, the change in the springtime India-Burma Trough can be modulated by the previous winter’s ENSO signal from the tropical East Pacific via the SCSA. To better illustrate the relationship between the SCSA and ENSO, a longer time period (1979–2015) of NCEP-DOE Reanalysis 2 data is used for constructing Figure 9. Details of how the SCSA is established during El Niño development can be found in Wang and Zhang [2002].

Finally, we compared the changes of the India-Burma Trough, SCSA, and biomass burning activities over northern Indochina by the bubble chart given in Figure 9. It is noted that in the years with strengthening in both the India-Burma Trough and SCSA (i.e., 2007 and 2010), the amount of biomass burning over northern Indochina is greater than other years with an increase in the India-Burma Trough (i.e., 2012). Consistent with this finding, in the years with weakening in both the India-Burma Trough and SCSA (i.e., 2008 and 2011), the amount of biomass burning over northern Indochina is lower than in other years with a decrease in the India-Burma Trough (i.e., 2005 and 2015). Based on these results, it is suggested that even though the changes of the India-Burma Trough do not always follow the SCSA changes (or the ENSO signal changes), monitoring the SCSA changes (or the ENSO signal changes) does aid in the prediction of the interannual variation of biomass burning over northern Indochina and its impact on PM$_{10}$ in Taiwan. For instance, weakened SCSA and abnormally low biomass burning in 2011 (Figures 2a and 3a) are found consistently with the unusually high 2011 premonsoon rainfall, particularly in March, over northern Thailand [Promchote et al., 2015]. This likely suggests that high precipitation can reduce the burning activities over northern Indochina.

It should be noted that although our study reveals the correlations among biomass burning, the India-Burma Trough, and SCSA, there are some additional factors, such as land use change [Reid et al., 2013], that might be involved in the changes of biomass burning. For instance, maize-cultivated lands were largely expanded in 2007 over the mountainous terrain in northern Thailand, Myanmar, and Lao, promoted by the high grain price [Food and Agriculture Organization of the United Nations, 2016] and private companies; crop residue burning was probably largely increased in this year.

Figure 9. Bubble plot of the springtime (March and April mean) India-Burma Trough index (defined as the area-averaged 700 hPa vorticity, $\zeta$, over 20–30°N, 85–110°E) and the corresponding South China Sea anticyclone index (defined as the “negative” 700 hPa vorticity, $-\zeta$, area averaged over 5–15°N, 95–120°E) during 1979–2015. The explanation for examining the changes over the longer time period (1979–2015) is given in the manuscript. The orange (blue) bubbles are the positive (negative) sea surface temperature anomalies (SSTAs) over the Niño3.4 region in the previous winter, with the size of the bubbles indicating the magnitude of the SSTA. The red (blue) open circles are the years with maximum (minimum) PC1 values of Figure 2.
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**5. Summary**

In this study, the spatial-temporal characteristics of the interannual variation of biomass burning in Indochina and its downwind impact on PM$_{10}$ at LABS (a high-mountain station) in Taiwan are examined. Diagnoses show that biomass burning activities in Indochina vary with two geographical regions: a primary region in northern Indochina and a secondary region in southern Indochina. PM$_{10}$ at LABS in Taiwan is mainly associated with the interannual variation of biomass burning over northern Indochina but not over southern Indochina.

Changes in biomass burning over northern Indochina and southern Indochina are found to be modulated by different types of atmospheric circulation changes. It is noted that the role of the India-Burma Trough is important to the changes of northern Indochina’s biomass burning activities and its associated aerosol transport pattern. As summarized in Figure 10, our results show that in the years with an intensified India-Burma Trough, an increase in northwesterly wind over the southwest side of the Tibetan Plateau (i.e., behind the India-Burma Trough) can advect dryer air from higher latitude to northern Indochina. The associated dryer condition promotes local biomass burning activities. Furthermore, ahead of the intensified India-Burma Trough, the associated increase in upward motion helps uplift the polluted air to the free troposphere, in which the associated increase in the westerly jet transports the PM$_{10}$ from northern Indochina to Taiwan.

![Figure 10. Schematic diagram for illustrating how an intensified India-Burma Trough modulates the occurrence of biomass burning in northern Indochina and its downwind impact on Taiwan. The numbers of 1–3 represent the order of the process. Step 1: an increase in northwesterly wind, behind (to the west) the intensified India-Burma Trough, advects the dryer air from higher latitude to northern Indochina. Step 2: the dryer condition (i.e., less precipitation and moisture divergence) promotes local biomass burning activities. Step 3: the increase in upward motion, ahead (to the east) of the intensified India-Burma Trough, helps uplift the polluted air to the free troposphere, in which the associated increase in the westerly jet transports the PM$_{10}$ from northern Indochina to Taiwan.](image-url)
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