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Aircraft measurement over the Gulf of Tonkin capturing aloft transport of biomass burning

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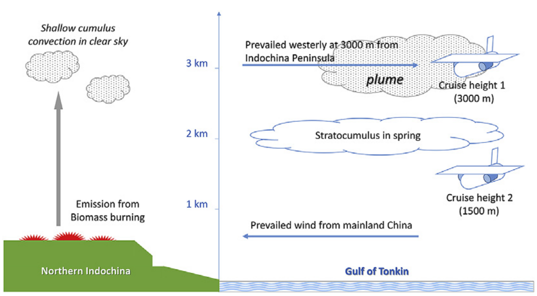
GRAPHICAL ABSTRACT



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ABSTRACT

A suite of aircraft measurements was conducted over the Gulf of Tonkin, located downwind to the east of Mainland Southeast Asia (MSE), between March 23rd and April 6th, 2015. To the best of our knowledge, this campaign of 11 flights (totaling 34.4 h) was the first in-flight measurement over the region. Measurements of sulfur dioxide, nitrogen oxides, ozone, carbon monoxide, black carbon and the particulate scattering coefficient were recorded at approximately 1 500 m (low level) and 3 000 m (high level). Significantly higher measurements of black carbon, carbon monoxide and ozone in the high level on March 23rd and April 5th and 6th were directly related to biomass burning in the MSE and were comparable to severe pollution events at the surface. Similarly, relatively low pollutant concentrations were observed at both altitudes between March 23rd and April 5th. A combined analysis of the measurements with meteorology and satellite data verified that the plumes captured at 3 000 m were attributed to transport in the high altitude originating from biomass burning in northern MSE. Furthermore, each plume captured by the measurements in the high level corresponded to heavy regional air pollution caused by biomass burning in northern MSE. In addition, relatively low levels of the measured pollutants corresponded to relatively light pollution levels in MSE and its adjacent areas. Taken together, these results indicated that aircraft measurements were accurate in characterizing the variation in transport and pollutant levels. During the most active season of biomass burning in MSE, pollutant emissions and their regional impact could vary on an episodic basis. Nonetheless, such concentrated emissions from biomass burning is likely to lead to particularly high atmospheric-loading of pollutants at a regional level and, depending on weather conditions, has the potential of being transported over considerably longer distances. Further investigation of the short-term impacts of such concentrations therefore appears prudent.

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1. Introduction

The springtime emissions from biomass burning in the Mainland Southeast Asia (BBMSE) were linked to significant regional impacts, which led to the area's being considered a global hotspot in terms of poor air quality (Ramanathan et al., 2008; Reid et al., 2012). Emissions from biomass burning not only deteriorate local air quality (Fox et al., 2009) but were shown to have a regional impact due to long-range pollutant transport (Chan et al., 2000; Yen et al., 2012). Moreover, direct and indirect radiative effects could cause changes in the atmospheric general circulation and therefore disturb the East Asian monsoon and regional climate (Ramanathan and Carmichael, 2008; IPCC, 2007). A number of published works based on ground-level measurements or model simulations attributed the observed pollution to the long-range transport of BBMSE (Liu et al., 1999; Chan et al., 2000; Deng et al., 2008; Chuang et al., 2014). However, the transport behavior across the region remains poorly quantified regarding to the height at which transport occurs and the pollutant concentration within the plume.

A number of recent studies explored the regional impacts of BBMSE using satellite data (Xiao et al., 2009; Reid et al., 2012; Jian and Fu, 2014). Other work aggregated long-term cloud–aerosol lidar and orthogonal polarization (CALIOP) datasets to obtain an averaged aerosol vertical distribution over the Mainland Southeast Asia (MSE) and certain downwind areas (Campbell et al., 2013). The transport of pollutants over the Gulf of Tonkin caused by BBMSE mainly occurred at a height of approximately 3 km (Shan et al., 2016). CALIOP is sensitive to extensive optical properties, such as backscatter, which does have a relationship to mass. The dataset may also contain a number of uncertainties, given that it is a retrieval product (Winker et al., 2009). Given these limitations, it is necessary to verify the concentration and transport of pollutants reported by remote sensing data with in situ measurements.

The Gulf of Tonkin lies directly to the east of MSE and is downwind of BBMSE, given the region's prevailing westerly winds in the upper level. Moreover, with no distinct emissions generated from the ocean itself, the Gulf of Tonkin offers an ideal location to investigate the transport of pollutants emitted from northern MSE.

Previous work reported on the thick stratocumulus clouds frequently formed each springtime over the Gulf of Tonkin (Reid et al., 2013), and smoke transport above the stratus deck was investigated through the analysis of remote sensing data (Hsu et al., 2006). The existence of above-cloud aerosols (ACAs) may significantly alter the radiation balance at the top of the atmosphere (Wilcox, 2010) and, as a ubiquitous phenomenon in marine atmospheres, has recently become a focus for research into regional radiative effects and global climate change (Yu and Zhang, 2013). Although an analysis of satellite remote sensing data revealed the existence of ACAs over the Gulf of Tonkin, very little work was published that quantifies the aerosol and gaseous pollutants. Obtaining exact pollutant levels and the optical properties of ACAs are critical to assessing regional radiative effects and related impacts.

Unlike land-based observations, aircraft permit mobile sampling is especially appropriate for large-scale 3-dimensional measurements (Taubman et al., 2006). The aircraft section of the TRansport And Chemical Evolution over the Pacific (TRACE-P) program in spring of 2001 was partly relevant to this study; however, most of the data were gathered to the northeast of MSE (Jacob et al., 2003). Similarly, although aerial research over the relevant area was performed between South China and the Philippines during the Civil Aircraft Based on an Instrument Container (CARIBIC), this research only focused on the upper troposphere (above 7 km) (Lai et al., 2011). To our knowledge, no published work reported aircraft measurements over the Gulf of Tonkin that was aimed at detecting pollution levels in the emissions plume from northern MSE.

Thus, an aircraft measurement campaign was designed to capture data relating to the emissions plume over the Gulf of Tonkin, and it was conducted in the spring of 2015. The measurement of gaseous and aerosol species specific to biomass burning were included in the analysis to characterize the emissions plume. The data were analyzed alongside meteorological and satellite data to clarify the transport of emissions arising from BBMSE.

Table 1
Flight information for the measurement campaign.

Date	Flight	Take-off time	Landing time	Flight duration (h)	Altitude (m)
Mar. 23	1	10:28	13:07	2.7	3080, 1 500
Mar. 25	2	13:16	15:58	2.7	3050, 1 500
Mar. 28	3	8:56	11:32	2.6	3800, 3100, 2100, 1 600
Mar. 29	4	8:49	11:23	2.6	3800, 3000, 2200, 1 500
Mar. 30	5	9:02	11:28	2.4	3750, 3100, 2200, 1 600
Mar. 31	6	14:18	17:00	2.7	3150, 1 550
Apr. 4	7	10:39	14:38	4	3160, 1 550
Apr. 5	8	10:01	14:03	4	3160, 1 550
Apr. 5	9	18:43	21:07	2.4	3780, 3180, 2250, 1 600
Apr. 6	10	10:29	14:33	4.1	3150, 1 600
Apr. 12	11	9:15	13:29	4.2	3000, 1 500
Total (h)	–	–	–	34.4	–

2. Methodology

2.1. Flight design

The aircraft measurement campaign was conducted in the spring of 2015 using a Chinese twin-engine turboprop utility aircraft (Harbin Yun-12; approximate cruising velocity of 200 km h^{-1}). Table 1 shows the details of the 34.4 h of total flight duration recorded during 11 flights from the base at Fucheng Airport (21°35′37″N, 109°18′17″E), Beihai, Guangxi, China. All flights cruised along the same straight line but turned back at different retracing points (depending on limitations imposed by air traffic control during each flight), as shown in Fig. 1: A (20°41′00″N, 108°59′00″E), B (19°35′00″N, 108°33′00″E) and C (18°24′00″N, 108°06′00″E). The figure also presents as red dots the moderate-resolution imaging spectroradiometer (MODIS) fire locations during the period of the aircraft's measurement. The average aerosol optical depth (AOD) was calculated daily during the period of the aircraft measurements (region delimited by the orange box in Fig. 1) to characterize the daily variation of air pollution in northern MSE.

Because of flight restriction, the spiral rising way of flight could not be performed over the area. Measurements were recorded at two heights, 1 500 m and 3 000 m. The aim of the higher altitude measurements was to investigate the transport at high altitude over the Gulf of Tonkin. These two altitudes were chosen for two reasons. First, multiple years of CALIOP data suggested this was where the transport of pollutants at high altitude from northern MSE mainly occurred. Second, the height of the spring cloud deck over the area was reported to extend to 2–3 km (Di Girolamo et al., 2010), so flights at 3 km should be above this and avoid contamination of the results by measurements within the cloud deck. The lower altitude measurements were designed to capture the pollution level in the low level. This altitude is not thought to be heavily involved in the transport of pollutants and could be used to provide a comparison with the higher altitude measurements. As shown in the histogram of heights flown at during each flight (Fig. 2), despite fluctuations (accounted for by prevailing weather conditions), the pilots ensured that the actual flight heights followed the design quite well, with prominent peaks being located at approximately 1 500 m and 3 000 m.