Isotopic Signal of Earlier Summer Monsoon Onset in the Bay of Bengal

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Isotopic Signal of Earlier Summer Monsoon Onset in the Bay of Bengal

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ABSTRACT

The onset of the Asian summer monsoon is noticeably controversial, spatially and temporally. The stable oxygen isotope $\delta^{18}O$ in precipitation has long been used to trace water vapor source, particularly to capture the summer monsoon precipitation signal. The abrupt decrease of precipitation $\delta^{18}O$ in the Asian summer monsoon region closely corresponds to the summer monsoon onset. Two stations have therefore been set up at Guangzhou and Lulang in the East Asian summer monsoon domain to clarify the summer monsoon onset dates. Event-based precipitation $\delta^{18}O$ during 2007/08 is much lower at Lulang than at Guangzhou and is attributable mainly to the altitude effect offset by different isotopic compositions in marine moisture sources. The earlier appearance of low $\delta^{18}O_{wt}$ at Lulang than at Guangzhou confirms the earlier summer monsoon onset in the Bay of Bengal. Isotopically identified summer monsoon evolutions from precipitation $\delta^{18}O$ at both stations are verifiable with NCEP–NCAR reanalysis data, indicating that precipitation $\delta^{18}O$ offers an alternative approach to studying the summer monsoon circulation from precipitation $\delta^{18}O$.

1. Introduction

The Asian summer monsoon has long been the research focus of the international monsoon community. However, no consensus has yet been reached regarding the onset and temporal/spatial evolution of monsoon systems. Various criteria have been proposed to evaluate the monsoon onset and evolution (e.g., Fasullo and Webster 2003; Mao and Wu 2007; Wang et al. 2009), forming two major branches of interpretation. One purports that the Asian monsoon starts in the South China Sea (SCS) and then gradually propagates west- and northwestward to the Bay of Bengal (BOB), the Indian Ocean, and East Asia (e.g., Tao and Chen 1987; Lau and Yang 1997; Wang and LinHo 2002). The other proposes the summer monsoon onset over the southeast BOB as earlier than any land monsoon onset (Ananthakrishnan et al. 1981). By observing surface sensible heat and latent heat fluxes, Wu and Zhang (1998) further pointed out that the Asian monsoon onsets first over the eastern coast of the BOB in early May, then over the SCS by 20 May, and finally over India by 10 June. Many other studies (e.g., Qian and Yang 2000; Lau et al. 2000; Mao and Wu 2007; Wu et al. 2012) have drawn similar conclusions. An overview by Ding and Chan (2005), however, still specified an earlier onset of the Asian summer monsoon over the SCS area than the BOB. Yuan et al. (2008) adopted this view in their discussion of the influence of the BOB sea surface temperature on the SCS monsoon onset. Thus, the onset of the Asian monsoon is controversial and requires additional study using diversified approaches.

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The monsoon process is a large-scale interaction among thermal, dynamic, and hydrological processes. The process is usually featured by strong convection and heavy rainfall, thus witnessing frequent phase transitions between vapor and precipitation, which leads to significant variation in the stable isotopic ratios in precipitation in the monsoon domain. The stable isotopic ratio in precipitation is calculated as

$$\delta = \left(\frac{R_{\text{sample}} - R_{\text{reference}}}{R_{\text{reference}}}\right) \times 1000‰,$$

where$R$ is the ratio of the composition of the heavier to lighter isotopes in water ($^{18}O/^{16}O$ for $\delta^{18}O$, or D/H for δD), and the Vienna Standard Mean Ocean Water standard is the reference (Kerstel and Meijer 2002). Studies of $\delta^{18}O$ in precipitation within the Global Network of Isotopes in Precipitation (GNIP) by the International Atomic Energy Agency (IAEA) and World Meteorological Organization (WMO) show significant links of $\delta^{18}O$ in precipitation with surface air temperature, precipitation amount, moisture source(s), and transportation (e.g., Cole et al. 1999; Aggarwal et al. 2004; Vuille et al. 2005). On the Tibetan Plateau, where GNIP stations are sparse, $\delta^{18}O$ in precipitation has recently been continuously studied (e.g., Tian et al. 2001, 2007; Yao et al. 1996), and a close correlation between the $\delta^{18}O$ in precipitation with the evolution of the Asian summer monsoon has been proposed (Tian et al. 2001; Vuille et al. 2005; Yao et al. 1996).

Considering the relatively low temporal resolution of the GNIP data and that the summer monsoon is characterized by active–break cycles at the synoptic scale, we have established two new stations since 2007, the Southeast Tibet Station for Alpine Environment Observation and Research at Lulang (29°46′N, 94°44′E, 3330 m MSL) and the Guangzhou Meteorological Satellite Ground Station (23°06′N, 113°15′E, 10.4 m MSL) (Fig. 1). These stations were established to collect event-based precipitation $\delta^{18}O$ data to detect the onset processes of the Asian summer monsoon and to reveal its intraseasonal variation. Synoptically, the southeast Tibetan Plateau is initially dominated by the Indian monsoon over the BOB [called the BOB monsoon by Wu and Zhang (1998)], while southeast coastal China is dominated by the Asian monsoon over the SCS [called the SCS monsoon by Ding and Liu (2001)].

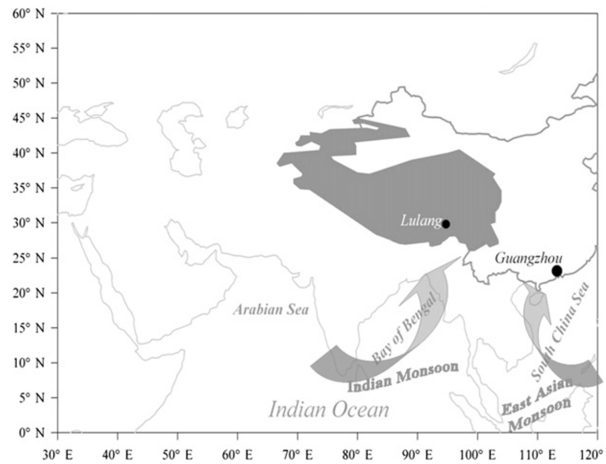

FIG. 1. Location of Lulang Station in the southeast Tibetan Plateau and Guangzhou Station off the coast of SCS. Shaded region represents the Tibetan Plateau. Arrows indicate the major circulation pattern dominative over the region in summers based on numerous atmospheric circulation studies (see section 1).

2. Sampling and laboratory analysis

From January 2007 to January 2009, precipitation samples with event-based amounts greater than 0.1 mm were collected in a deep and open-mouthed container. The samples were poured immediately after the rain- or snowfall collection into 15- or 50-mL polyethylene (PET) bottles and sealed tightly before cool storage. A synchronous meteorological record was kept manually or by an automatic weather station (AWS), including parameters such as precipitation amount, temperature, humidity, air pressure, and wind speed. A total of 348 samples were collected at the Guangzhou Station, and 387 samples were collected at the Lulang Station. The $\delta^{18}O$ of these samples was measured with a measurement and analysis technique (MAT) 253 isotope ratio mass spectrometer at the Chinese Academy of Sciences (CAS)'s Key Laboratory of Tibetan Environment Changes and Land Surface Processes. A number of standard samples, including those close in δ values with the samples (i.e., major standard samples), were interspersed in the measurement to control the precision. The analytical uncertainty for $\delta^{18}O$, $\pm 0.05‰$, and that for δD, $\pm 0.5‰$, is the standard deviation of replicate measurements of those major standard samples.

To further verify our measurements, a local meteoric water line is made by linearly regressing $\delta^{18}O$ against δD in precipitation at Lulang, reaching a slope of 8.24 ($R^2 = 0.98$), similar to the slope of 8.10 ($R^2 = 0.98$) for the GNIP data at Lhasa.

3. Results and discussion

Event-based $\delta^{18}O$ values in precipitation were processed daily as

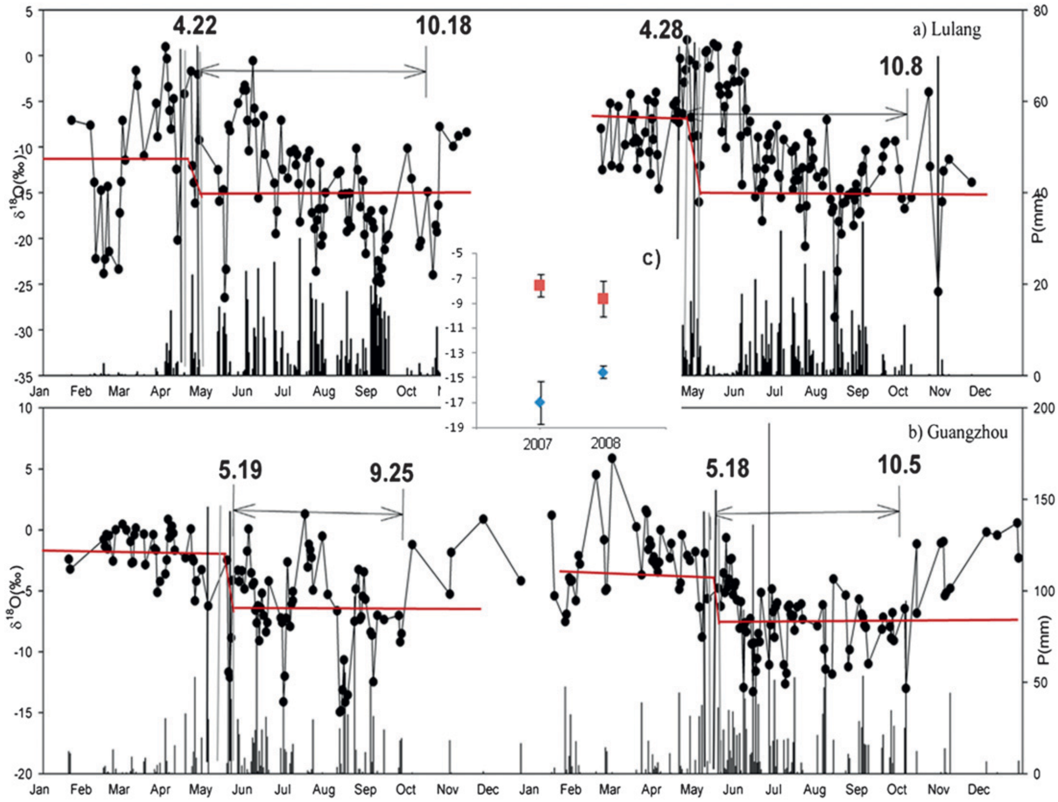

FIG. 2. Variation of precipitation $\delta^{18}O_{wt}$ and amount with days at (a) Lulang and (b) Guangzhou during 2007/08, showing high amount generally corresponding to low $\delta^{18}O_{wt}$. Ramp fit detection [marked with red line in both (a) and (b)] is applied to confirm the abruptness of monsoon onsets during both years identified by precipitation $\delta^{18}O_{wt}$. (c) Overlain on graphs (a) and (b) is the error bar of annual mean summer values of 2007 and 2008 at Guangzhou (red) and Lulang (blue) with those of GNIP data in the same locations/areas.

$$\delta^{18}O_{wt} = \frac{\sum_{1}^{n} \delta_i P_i}{\sum_{1}^{n} P_i},$$

where $\delta^{18}O_{wt}$ indicates the amount-weighted $\delta^{18}O$ averages; δ_i and P_i refer to the $\delta^{18}O$ and the corresponding amount, respectively, of individual precipitation events in one day; and n defines the total events occurring daily.

The $\delta^{18}O_{wt}$ in precipitation during 2007/08 shows a wider variation range (30.33‰ vs 20.93‰) and a larger fluctuation (σ = 6.56 vs 3.85) at Lulang than at Guangzhou. The $\delta^{18}O_{wt}$ average in annual precipitation at Lulang is approximately 5‰–9‰ lower than that at Guangzhou and is ~6‰–9‰ lower in summer, which is attributable to several factors. First, this discrepancy may be due to the altitude effect, that is, the depletion of $\delta^{18}O$ with the progressive condensation of ascending atmospheric vapor along slopes and the rainout of the condensed phase (e.g., Siegenthaler and Oeschger 1980; Gonfiantini et al. 2001). Given the altitudinal difference of 3320 m, an altitude gradient of $\delta^{18}O$ in annual precipitation over China of −0.15‰ (100 m)$^{-1}$ (Liu et al. 2008) and −0.30‰ (100 m)$^{-1}$ (Yao et al. 2009) over the Tibetan Plateau could yield a $\delta^{18}O$ at Lulang ~5‰–10‰ lower than that at Guangzhou. The altitude gradient of $\delta^{18}O$ in the surface water (representative of the long-term average of precipitation) on the plateau during June–September (JJAS) is calculated as −0.27‰ (100 m)$^{-1}$ (Yang et al. 2012), leading to a difference of ~9‰ in summer precipitation, with a greater than 3000 m altitudinal contrast. Second, both stations are mainly supplied by different marine moisture sources, as mentioned above. The Tropospheric Emission Spectrometer data show that the δD annual average is approximately 10‰ lower off the southeast coast of China than over the BOB (e.g., Worden et al. 2007), translating to a moisture source $\delta^{18}O$ approximately 1‰ higher for Lulang than for Guangzhou, thus partly offsetting the depletion because of the altitude effect. Third, both stations posit different distances from their respective moisture sources.

Because both stations are located in the tropics/subtropics, the continental effect is weak (Rozanski et al. 1993) and is thus ruled out as a significant cause of the $\delta^{18}O$ difference.

As shown in Fig. 2, a large amount of precipitation generally accompanies a low $\delta^{18}O_{wt}$, especially during summer (May–October). The biannual data indicate that summer precipitation contributes to ~85.3% of the annual total at Lulang and 80.5% at Guangzhou. The contrast between wet summers and dry winters confirms the dominance of the summer monsoon at the respective stations (Wang and LinHo 2002). The daily $\delta^{18}O_{wt}$ during May–October is linearly regressed against amount, showing an average of 39% of $\delta^{18}O_{wt}$ variance in summers at Lulang, as contributed by amount, in comparison to 50% at Guangzhou. The residual is analyzed against other meteorological parameters. At Guangzhou, apart from the dominative amount effect, the air pressure ($R = 0.29$) and temperature ($R = 0.26$) demonstrate positive correlations with the residual at the 95% confidence level, thus suggesting the reevaporation of raindrops and isotopic exchange with ambient vapor during precipitation. At Lulang, the amount actually yields to wind speed in controlling $\delta^{18}O_{wt}$ variability, with the latter contributing ~56% of $\delta^{18}O_{wt}$ variance in summer, thus highlighting the influence of evapotranspiration and convergence of local recycled water with intruding marine moisture.

The key point of the present study is to evaluate the validity of $\delta^{18}O$ to study monsoon onsets and evolution. Previous studies of the $\delta^{18}O$ in precipitation on the Tibetan Plateau have shown a coincidence of dramatic $\delta^{18}O$ decrease with monsoon onset and a negative correlation between $\delta^{18}O$ and monsoon intensity (Tian et al. 2001; Vuille et al. 2005). We therefore define the monsoon onset isotopically by the following two criteria: 1) the amount-weighted average of daily $\delta^{18}O_{wt}$ in March in the respective year is taken as a threshold and 2) the monsoon initiation is marked from April according to days witnessing a lower-than-threshold $\delta^{18}O_{wt}$ for 4 days within a 7-day period. March is chosen because it better represents the premonsoon condition both meteorologically and isotopically than the winter months (e.g., January or February). A sensitivity test for durations witnessing low $\delta^{18}O_{wt}$ shows no significant shift. The criterion of four out of seven days is chosen because it allows a timely identification of monsoon initiation. Accordingly, 22 and 28 April mark the BOB monsoon onset, while 19 and 18 May mark the SCS monsoon onset in 2007 and 2008, respectively. Those days are all characterized by abrupt and sustained $\delta^{18}O_{wt}$ depletions, with their abruptness verifiable by the ramp fit detection (Fig. 2). Compared with onsets by amount (Table 1), which are synoptically featured by thick clouds (Figs. 3a,b) or lack thereof (Figs. 3c,d), without strong zonal wind in the lower troposphere at the respective station, isotopically identified onsets correspond to strong convection concomitant with developing or intensifying wind (Figs. 3e–h). Without the driving force for large-scale convections, the high amount may have resulted from continental recycling, which can be further proved by the deuterium excess ($d = \delta D - 8\delta^{18}O$) of the Lulang precipitation being much higher in early April (averaging approximately 17.6‰) than in late April (averaging approximately 6.48‰) in 2007. A high d indicates kinetic fractionation and/or partial evaporation of the falling raindrops, thus confirming local water recycling as the major contributor to the earlier high amount. Previous studies also found that local recycling plays an important role in precipitation on the plateau (Liu et al. 2008; Tian et al. 2001). Monsoon onsets by precipitation amount, therefore, need to be treated cautiously. Otherwise, identification by $\delta^{18}O_{wt}$ is close to the modeling results by J. Mao (2011, personal communication) and Wu et al. (2012) for BOB monsoon onset and within the earliest SCS summer monsoon onset period (Wang et al. 2004). The Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model run with the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data also confirms the moisture source as over the SCS for Guangzhou and over the BOB for Lulang during both monsoon onsets (Fig. 4).

In summer 2007, there is a stepwise depletion in $\delta^{18}O_{wt}$ at Lulang at a 20–40-day interval, when the $\delta^{18}O_{wt}$ at Guangzhou demonstrates four obvious depletions in mid-May, the end of June, mid-August, and early September.

TABLE 1. Comparison of monsoon onset dates by different criteria.

BOB monsoon onset	2007	2008
Isotopic criteria_Lulang	22 Apr	28 Apr
Amount_Lulang*	6 Apr	27 Apr
Meridional gradient of upper-tropospheric air temperature (Mao and Wu 2007; Wu et al. 2012)	29 Apr	27 Apr
SCS monsoon onset	**2007**	**2008**
Isotopic criteria_Guangzhou	19 May	18 May
Amount_Guangzhou*	24 Apr	4 May

* The criterion of amount is set according to the Kerala standard for Indian summer monsoon onset. In practice, the daily amount during June–August (JJA) is calculated for the site from the long-term record in GNIP. Thus, the summer monsoon onset at the respective station is marked by an increase of the daily amount to 4 times the JJA daily amount, with the daily average in that pentad larger than or equivalent to the JJA daily amount.

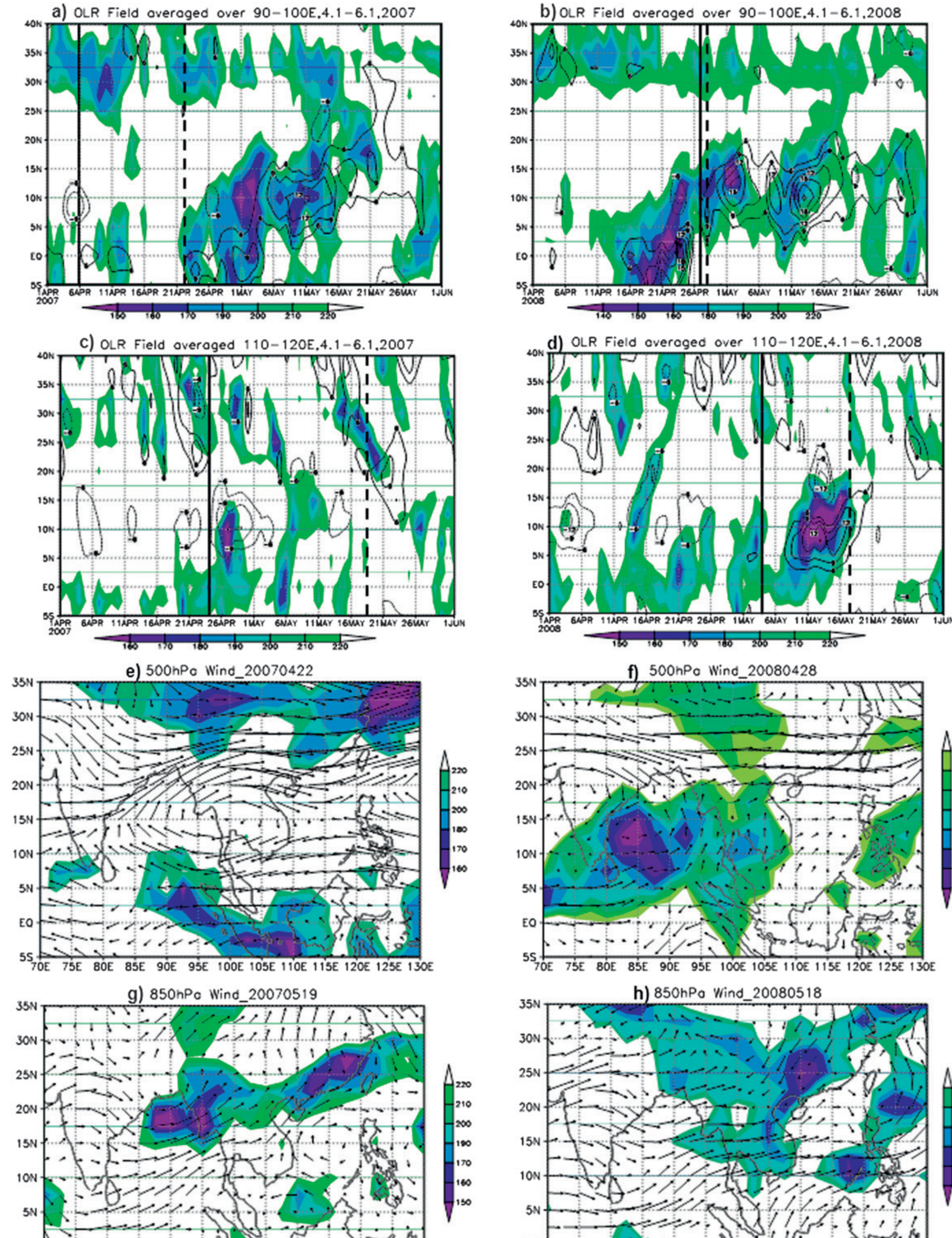

FIG. 3. 850-hPa zonal wind field superimposed on OLR field averaged over 90°–100°E for (a),(b) Lulang and averaged over 110°–120°E for (c),(d) Guangzhou during April–June in 2007 and 2008, respectively. Monsoon onset dates identified by amount are marked by the black lines, while those by $\delta^{18}O$ are marked by black dashed lines. 500-hPa wind for Lulang and 850-hPa wind for Guangzhou superimposed on corresponding OLR during the BOB monsoon onset on (e) 22 Apr 2007 and (f) 28 Apr 2008, and those during the SCS monsoon onset on (g) 19 May 2007 and (h) 18 May 2008. They are plotted based on NCEP–NCAR reanalysis data.

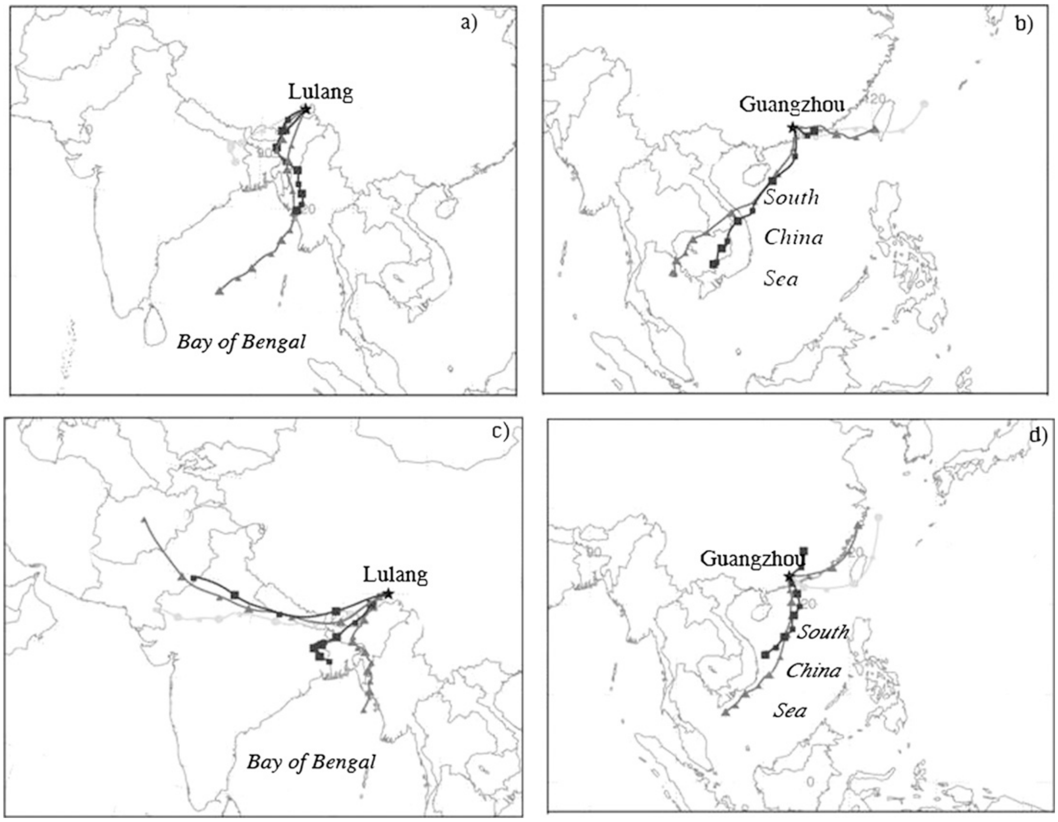

FIG. 4. HYSPLIT moisture back-trajectory run with NCEP reanalysis data for BOB monsoon onset at Lulang on (a) 22 Apr 2007 and (c) 28 Apr 2008, and a similar run for the SCS monsoon onset at Guangzhou on (b) 19 May 2007 and (d) 18 May 2008.

Otherwise, no significant cycles are present for either station in summer 2008. Power spectral density analysis with corresponding daily precipitation data confirms a cycle of 20–40 days in 2007 for $\delta^{18}O_{wt}$ at Lulang and a cycle of ~21 days at Guangzhou (figures not shown), suggestive of intraseasonal oscillation in the summer monsoon evolution. A similar analysis, however, fails to detect any significant cycles with $\delta^{18}O_{wt}$ for either stations in 2008, suggesting interannual differences superimposed on intraseasonal variability. To facilitate a large-scale analysis, the NCEP–NCAR reanalysis dataset was adopted for the 2007/08 summers. Low $\delta^{18}O_{wt}$ values in the 2007 precipitation at Lulang correspond to low outgoing longwave radiation (OLR) simultaneous with intensified surface wind and high local precipitation (Figs. 5a1–a3), suggesting the depletion as attributable to the advection of depleted vapor associated with upwind condensation and fractionation. Likewise, the same trends are seen for Guangzhou in 2007 (Figs. 5c1–c3). Synoptic scenarios significantly vary in 2008, as the OLR around Lulang decreases in both magnitude and averages, concomitant with noticeably intensified wind and local precipitation, while the OLR around Guangzhou decreases, especially in July, corresponding to decreased wind and a dramatic variation of precipitation (Figs. 5b1–b3, d1–d3). Such variation results in intensified advection for Lulang, causing the marine moisture source to undergo less condensation and the precipitation to exchange more frequently with vapor, as reflected by a higher $\delta^{18}O_{wt}$ in summer 2008 than in 2007 (−15.61‰ vs −16.93‰). The result also indicates a strengthening of local convection offset by weakening wind for Guangzhou, reflected by a slightly lower $\delta^{18}O_{wt}$ in summer 2008 than in 2007 (−8.96‰ versus −8.47‰). Such consistencies also confirm the potential value of precipitation $\delta^{18}O$ in capturing atmospheric circulation signals.

4. Conclusions

Daily $\delta^{18}O_{wt}$ in precipitation is acquired for 2007/08 from event-based sampling at Lulang (southeast Tibetan Plateau), principally influenced by moisture from the BOB, and at Guangzhou (southeast China), principally influenced by moisture from the SCS. The $\delta^{18}O_{wt}$ at

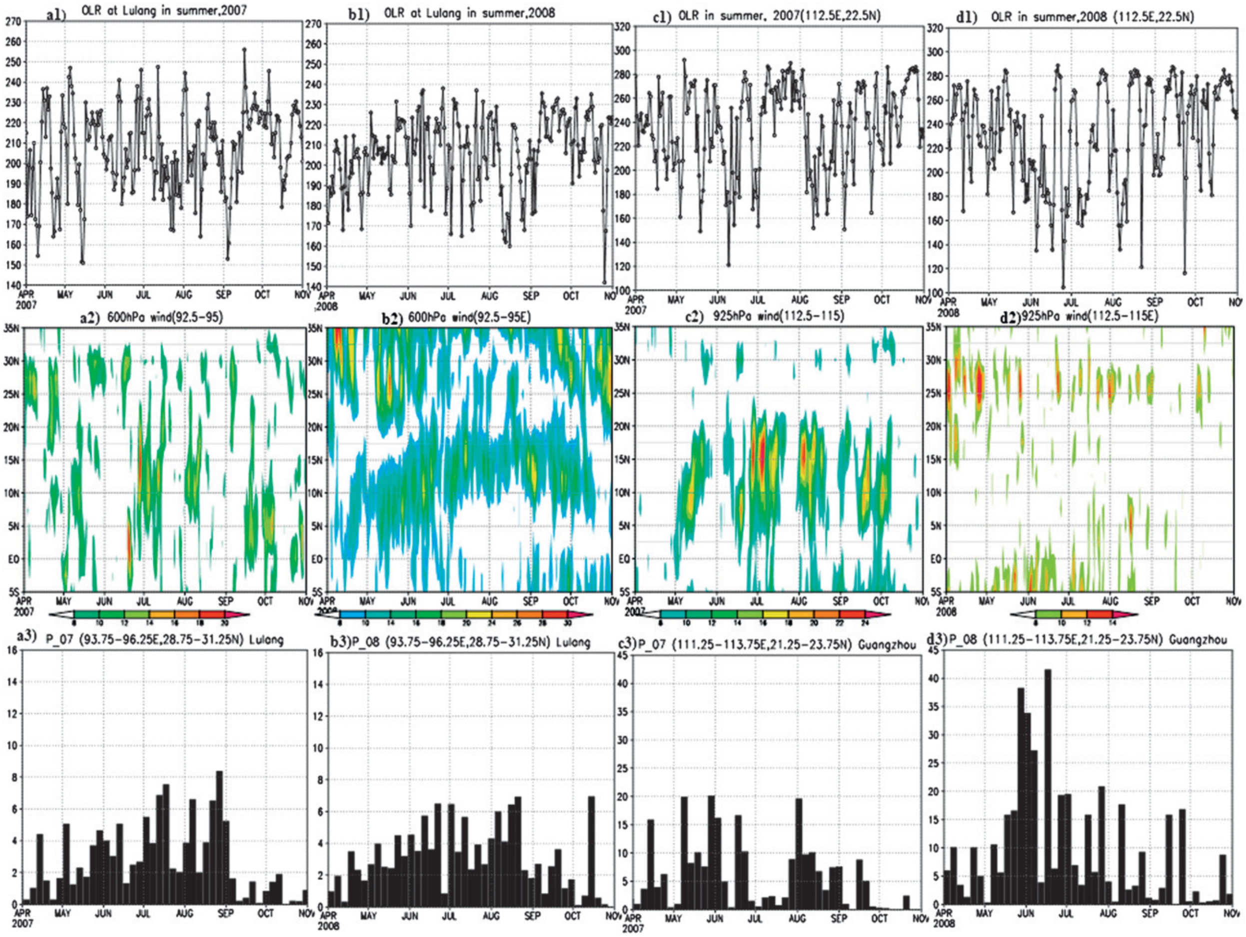

FIG. 5. Variation of OLR and 600-hPa wind magnitude at 30°N, 97°E and pentad precipitation averaged over 28.75°–31.25°N, 93.75°–96.25°E for Lulang during April–November (a1)–(a3) 2007 and (b1)–(b4) 2008, and that of OLR and 925-hPa wind magnitude at 22.5°N, 112.5°E and pentad precipitation averaged over 21.25°–23.75°N, 111.25°–113.75°E for Guangzhou during April–November (c1)–(c3) 2007 and (d1)–(d3) 2008. As NCEP–NCAR reanalysis data are in the resolution of 2.5° × 2.5°, there is no monitoring at the exact locations for either station; the nearest spot and/or closest grid is selected from the dataset for each respective station.

Lulang is lower than at Guangzhou, attributable mainly to the altitude effect offset by a slight difference in moisture sources. The isotopic criteria are set to define the monsoon onset, revealing an earlier onset of the Asian summer monsoon over the BOB than over the SCS, indicated by an earlier depletion of $\delta^{18}O_{wt}$ at Lulang than at Guangzhou during both years. The BOB monsoon onsets earlier than the SCS monsoon by more than 20 days. The dominative factor controlling $\delta^{18}O$ in precipitation is amount at Guangzhou and wind speed at Lulang, though both are important indicators of monsoon intensities. The variation of $\delta^{18}O$ shows a 20–40-day cycle at both stations in 2007 and no cycle in 2008. These intraseasonal and interannual variations in the monsoon process are verified by synoptic scenarios from NCEP–NCAR reanalysis data, thus highlighting the value of high-resolution $\delta^{18}O$ data in monsoon study.

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