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EDITORIAL

Consecutive extreme flooding and heat wave in Japan: Are they becoming a norm?

In July 2018, Japan experienced two contrasting, yet consecutive, extreme events: a devastating flood in early July followed by unprecedented heat waves a week later. Death tolls from these two extreme events combined exceeded 300, accompanying tremendous economic losses (BBC: July 24, 2018; AP: July 30, 2018). Meteorological analysis on these 2018 events quickly emerged (JMA-TCC, 2018; Kotsuki *et al.*, 2019; Tsuguti *et al.*, 2019), highlighting several compound factors: a strengthened subtropical anticyclone, a deepened synoptic trough, and Typhoon Prapiroon that collectively enhanced the Baiu rainband (the Japanese summer monsoon), fostering heavy precipitation. The comprehensive study of these events, conducted within a month and released by the Japan Meteorological Agency (JMA) (JMA-TCC, 2018), reflected decades of knowledge of the Baiu rainband and new understanding of recent heat waves in southern Japan and Korea (Xu *et al.*, 2019). Regardless, an extended forecast of this record-breaking precipitation remains challenging, with a skillful prediction of no more than 3 days (Kotsuki *et al.*, 2019). Given the impending Baiu season of 2019, it is prudent to reflect upon these successive 2018 events by parsing out the critical components while discussing the potential of future compound extremes.

1 | STATE OF THE SCIENCE

The timing of the July 2018 heavy rainfall and heat wave events coincided with the distinct lifecycle of the East Asian summer monsoon (EASM) featuring the active, break, and revival phases (Chen *et al.*, 2004; Ding, 2007). Figure 1a outlines these EASM phases by showing the climatological 10-day rainfall evolution averaged in southern Japan (using Climate Prediction Center Global Unified Gauge-Based Analysis from 1981 to 2010; see caption for details). Each year, southern Japan experiences the passages of the Baiu rainband in late June and the Northwestern Pacific Subtropical High (NPSH) in late July, causing an abrupt rainfall increase (active phase) followed by a quick drying and associated warming (break phase). By early September, the expanding western Pacific monsoon trough reaches southern Japan, while the frequency of tropical cyclones increases (Chen *et al.*, 2004). Putting these together, one could argue that the 2018 sequential events in southern Japan indicate a much-amplified EASM lifecycle (Figure 1a), featuring the strong Baiu rainfall, an intense monsoon break, and the landfall of Super Typhoon Jebi in early September.

The atmospheric features that enhance the ascent and instability of the Baiu rainband have been extensively studied (Sampe and Xie, 2010); these include the upper-level westerly jet and traveling synoptic waves, mid-level advection of warm and moist air influenced by the South Asian thermal low, and low-level southerly moisture transport associated with an enhanced NPSH. These features are outlined in Figure 1b as (A) the NPSH, and particularly its western extension; (B) the western Pacific monsoon trough; (C) the South Asian monsoon; (D) the mid-latitude westerly jet and quasistationary short waves, as well as the Baiu rainband itself; these are based on previous studies (Sampe and Xie, 2010; JMA-TCC, 2018; Tsuguti *et al.*, 2019). All of these circulation features were observed in the July 2018 heavy precipitation event with an additional presence of Typhoon Prapiroon and a stationary short-wave trough over Korea (Tsuguti *et al.*, 2019). These notable circulation features were present during the heat wave as well (Figure 1c), while the upper-level trough was replaced by a short-wave ridge known to accompany heat waves in Korea and southern Japan (Xu *et al.*, 2019).

Interannual variations of these circulation features have been linked to sea surface temperature (SST) variability nearby and afar (Sampe and Xie, 2010; Imada *et al.*, 2013). Under a warmer climate, a wealth of literature has indicated that an enhanced EASM and its circulation components (Figure 1b) are the likely outcome. The Baiu rainband has been observed and projected to intensify (Kusunoki *et al.*, 2006). In southwestern Japan, intense Baiu precipitation (>100 mm/day) has increased by 9% and may rise another 15% in the future (Kanada *et al.*, 2012). Observed and projected intensification in the NPSH (Kusunoki *et al.*, 2006; Imada *et al.*, 2013), southwesterly low-level winds, and moist static energy (Kanada *et al.*, 2012; Seo *et al.*, 2013) altogether can increase the chance of heavy Baiu precipitation. However, long-term changes of the Baiu onset-termination process are manifold and involve complex tropical–mid-latitude

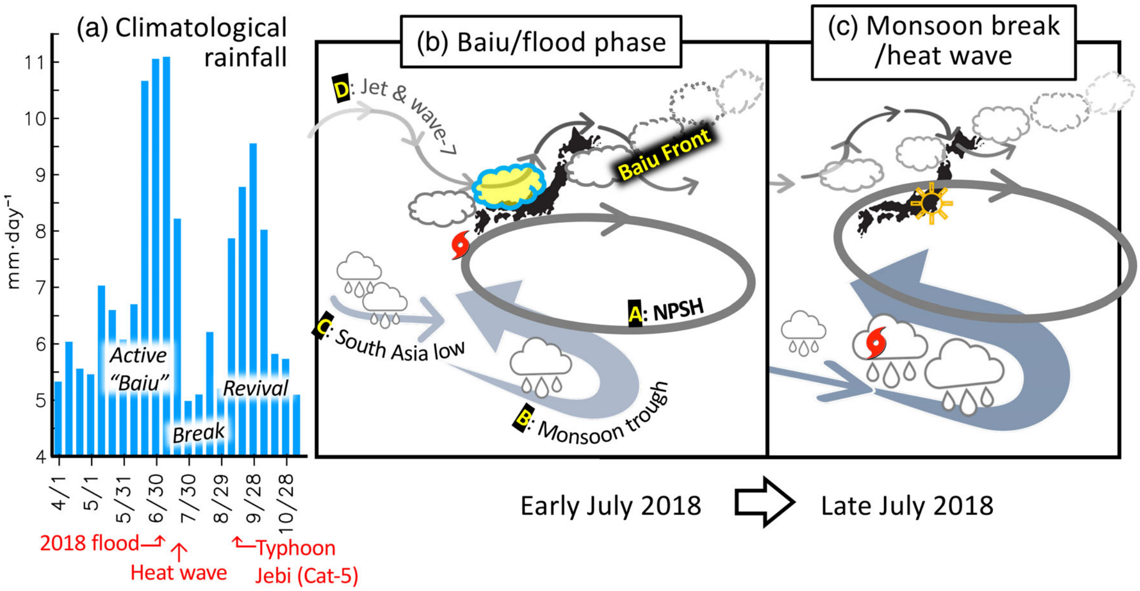

FIGURE 1 (a) Climatological 10-day mean precipitation averaged over southern Japan within the domain outlined in Figure S1 (inset), following Figure 3 of *Chen et al*. (2004) using data of 1981–2010. Three phases of the East Asian summer monsoon (EASM) lifecycle overlap the rainfall histogram, along with the 2018 events indicated at the bottom of the *x*-axis. Precipitation is derived from the NOAA/CPC Global Unified Gauge-Based Analysis https://www.esrl.noaa.gov/psd/data/gridded/data.cpc.globalprecip.html. (b) Schematic diagram showing the circulation features known to enhance the Baiu rainband (train of clouds), referred to as A, B, C and D as explained in the main text. The red typhoon symbol indicates Typhoon Prapiroon, and the blue-yellow cloud indicates the flood. (c) Same as (b) but for the break phase of EASM in which the heat wave took place (orange sun symbol), depicting the intensification and northward migration of NPSH and the expanded monsoon trough, as well as an upper-level ridge west of Japan. The typhoon symbol in the monsoon trough indicates Typhoon Maria. The transition from the active/Baiu phase to the break phase typically takes place within 1 week, consistent with the sequential events of 2018 flooding and heat wave

interactions. Intensification of the NPSH (A in Figure 1b) has been linked to the warming climate (Kusunoki *et al.,* 2006; He and Zhou, 2015); this is likely caused by the enhanced monsoon trough (B in Figure 1b) through local Hadley circulation and Rossby wave dispersion (Kusunoki *et al.,* 2006; He and Zhou, 2015). An intensified NPSH can enhance the moist low-level southerly flows toward southwestern Japan while increasing the thermal gradient along the Baiu, further destabilizing the frontal zone. An intensified NPSH also produces stronger subsidence and low-level warming when it reaches southern Japan, contributing to the increased occurrence of heat waves during the break phase. Correspondingly, Kim *et al*. (2019) found that the intensity of compound events like the succession of heavy rainfall and heat wave in Japan is projected to increase in the warmer climate.

The less palpable factors in this EASM paradigm of increased compound extremes concern the effects of the changing South Asia low (C in Figure 1b) and mid-latitude westerly jet (D in Figure 1b) on the Baiu rainband. The evolutions of the South Asian monsoon and thermal high pressure over the Tibetan Plateau influence the upper-level jet position and associated thermal advection from the eastern plateau, which can trigger convection along the Baiu rainband. Subseasonal variation of the Indian summer monsoon can affect EASM through atmospheric short-wave teleconnection (Ding and Wang, 2007). A recent study (He *et al.,* 2019) notes the effect of increased latent heating over the Tibetan Plateau on the intensification of the EASM circulations, which could influence the Baiu rainband. In the mid-latitudes, the jet stream and associated synoptic activity have weakened over recent decades, attributed to the rapid warming in the Arctic (Coumou *et al.,* 2018). Prior to the 2018 early-July flood, a circumglobal short-wave pattern was observed in association with heat waves in North America, Western Europe, and the Caspian Sea region, as well as rainfall extremes in South-East Europe and Japan (Kornhuber *et al.,* 2019). However, what this implies for the quasistationary waves, as was observed in summer 2018 (D in Figure 1b), is less clear.

2 | PUTTING THE 2018 EVENTS INTO PERSPECTIVE

Two features of the intensified Baiu rainband in 2018 are worth noting. The first concerns the stationary short-wave train leading up to the record rainfall. As shown in Figure S1a and described in Kornhuber *et al*. (2019), the upper-level meridional (v) wind averaged from June 27 to July 3, 2018 demonstrates a distinct wave-7 structure embedded in the jet stream from West Europe to Japan. Longitude time evolution of the daily v-wind

(Figure S1b using the National Center for Environmental Prediction Reanalysis-2 data) indicates that the short-wave train formed in mid-June and persisted for a month (arrows in Figure S1b). This short-wave train underwent a marked amplification around June 23, triggering an eastward Rossby wave energy propagation (not shown) that deepened the short-wave trough over the Korean Peninsula a week later (~June 28); the resulting amplified trough led to a persistent increase in precipitable water over Japan during the onset of heavy precipitation (Figure S1c). While traveling synoptic waves are known to intensify Baiu rainfall (Sampe and Xie, 2010), the aforementioned wave-7 structure is stationary (Figure S1b) and not transient. The polarity and position of this stationary wave train coincide with the observation that the persistence of circumglobal teleconnection with wave numbers 5–7 has increased (Wang *et al.,* 2013; Lee *et al.,* 2017; Coumou *et al.,* 2018). By July 10, 2018, the short-wave train had dissipated and, as a result, did not contribute to the heat wave (Figure S1b).

The second feature of note is the energized tropical intraseasonal oscillation (TISO). The TISO not only modulates tropical convection but also strengthens the NPSH and associated southerly low-level winds that feed moisture into the Baiu rainband. In the western Pacific, TISO triggers the northward migrations of both the monsoon trough and the NPSH (Chen *et al.,* 2004; Jiang *et al.,* 2004). Based on Figure S2, two active TISO episodes occurred over the Philippines Sea during 2018, the first one in early June and the second in mid-July. Recall in Figure S1c that the NPSH was located between 20° and 25°N in mid-June, while the Baiu rainband covered southwestern Japan (30°–35°N), coinciding with the second TISO episode. During the later heat wave of late July, the expanded monsoon trough (15–20°N) also intensified the NPSH while pushing it further north to cover southwestern Japan. This observation, together with the absence of propagating Rossby short waves during the heat wave (Figure S2), defies the argument associating the recent increase in heat waves over Japan and Korea with amplified mid-latitude short waves of Eurasian origin (Kornhuber *et al.,* 2019; Xu *et al.,* 2019). Thus, the second TISO event in 2018 plays a dominant role in strengthening the NPSH and subsequent heat wave in Japan (JMA-TCC, 2018).

Typhoons Prapiroon and Maria played a role in the 2018 heavy precipitation and subsequent heat wave. Typhoon Prapiroon made landfall in southwestern Japan and further increased the elevated precipitable water prior to the heavy Baiu rainfall (Figure S1c). We note that typhoons do affect southwestern Japan during the Baiu season (Chen *et al.,* 2004). Typhoon Maria formed within the deepened monsoon trough, where it further enhanced the NPSH during 8–12 July through the northward fluxes of Rossby wave activity (not shown). Subsequently, the enhanced NPSH and subsidence set the stage for the heat wave.

3 | WAYS FORWARD

The atmospheric circulations and SST variation enhancing the Baiu rainfall in southwestern Japan have been extensively studied, while climate projections consistently indicate an intensified Baiu rainband and increased heat waves. The 2018 extreme Baiu rainfall and subsequent heat wave fits that of past climate diagnostics and future climate projections. Here, the authors call for an integrated view of the amplified EASM "lifecycle" that influences the extreme Baiu rainfall and subsequent heat wave in the same season, as well as the roles mid-latitude short-wave amplification and active TISO played in 2018.

Recent research has shed light on the potential drivers of quasistationary short waves during boreal summer, such as wave resonance within the jet stream waveguide that can trap and maintain the waves' energy (increasing persistence) and the shifting of the jet itself. The conditions under which wave resonance is likely to occur can, in principle, be detected and anticipated at an early stage, before the wave grows in amplitude (c.f., Figure S1b). The tropical influence of active TISO episodes on persistent mid-latitude short waves could also serve as a precursor for detecting amplified subseasonal teleconnection. The extent to which these circulation features collectively modulate the EASM lifecycle, which could strengthen the Baiu rainfall, heat wave, and typhoons combined, challenges the research in subseasonal predictability of compound extreme events.

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SUPPORTING INFORMATION

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