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Key Points:

- The hot summer in East Asia in 2022 is due to the extremely strong and westward expanded western Pacific subtropical high
- The hot summer is caused by the long-term trend and amplified by positive feedback among the surface air temperature (SAT), cloud, and downward shortwave radiation
- North American Multi-model Ensemble does not capture the observed spatial distribution pattern and amplitudes of SAT anomalies

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Causes and Predictions of 2022 Extremely Hot Summer in East Asia

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Abstract In the background of long-term global warming, the northern hemisphere experienced an extremely hot summer in 2022 with the hottest on record for Europe and China, and the second-hottest for North America and Asia. The hot summer concurred with a triple-dip La Niña in the tropical Pacific. Given the extremity of the hot summer in East Asia in 2022, in this work, we examine the associated atmospheric circulation and assess the real-time predictions from the North American Multimodel Ensemble (NMME). Also, we identify the contributions of long-term warming trends, sea surface temperature (SST) forcing, and an atmospheric feedback to the hot summer. The hot summer in East Asia in 2022 is due to the extremely strong and westward expanded western Pacific subtropical high. That leads to cloud cover reduction and increases in net downward shortwave radiation at the surface, and further strengthens the positive surface air temperature (SAT) anomalies. In contrast, the seasonal-interannual variation of SST has a minor impact. Thus, the hot summer is mainly associated with the long-term trend and amplified by the positive feedback among the SAT, cloud cover, and net downward shortwave radiation. NMME with the initial conditions in May 2022 predicts positive SAT anomalies in most regions of East Asia, but does not capture the observed spatial distribution pattern and amplitudes. The failure implies the challenge of state-of-the-art climate models in predicting such extreme events.

Plain Language Summary In the context of global warming, the northern hemisphere experienced an extremely hot summer in 2022 with the hottest on record for Europe and China. The hot summer concurred with a triple-dip La Niña in the tropical Pacific during 2020–2023. In this work, we examine the causes and assess the real-time predictions and predictability of the hot summer in East Asia. The hot summer in 2022 is due to the extremely strong and westward expanded western Pacific subtropical high. For the averages in the main hot summer region in East Asia in 2022, the largest contribution is from the long-term trend (~50%), and for the rest 50%, half of them is from the feedback among atmospheric circulation-surface air temperature-cloud cover-net downward shortwave radiation. In contrast, the seasonal-interannual components of the global sea surface temperatures play a secondary role. Multi-model ensemble with the initial conditions in May 2022 predicts positive surface air temperature anomalies in most regions of East Asia, especially in August. However, compared with the observations, both the spatial distribution pattern of surface air temperature anomalies and their amplitudes have distinguished biases in the North American Multimodel Ensemble predictions. The failure implies the challenge of state-of-the-art climate models in predicting such extreme events.

1. Introduction

More and more observations support the evidence that human activities produced increases in greenhouse gas concentrations have resulted in warming in the atmosphere, ocean, and land on regional and global scales (IPCC, 2021). For example, according to U. S. National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NCEI)'s report (https://www.ncei.noaa.gov/access/monitoring/monthly-report/global/202113), the global temperature in 2021 was 0.84°C above the 20th-century average, and the years 2013–2021 all rank among the 10 warmest years on record. Under the background of the warming trend, it is expected that extremely warm winters and hot summers will occur more often in some regions in the future (e.g., Domeisen et al., 2022; Hu et al., 2000; IPCC, 2021; Van Oldenborgh et al., 2022). East Asia is one of the regions with significant warming trends observed (e.g., Hu et al., 2003; IPCC, 2021; Van Oldenborgh et al., 2022). Thus, the impact of greenhouse gas concentrations on East Asian climate is expected to be remarkable (e.g., Hu et al., 2000; Jiang et al., 2012; J. P. Li et al., 2018; Liu et al., 2019).

In such background, East Asia experienced an extremely hot summer in 2022 (Figure 1). According to NOAA NCEI's report (https://www.ncdc.noaa.gov/sotc/global), the summer of 2022 was the hottest on record for Europe and China, the second-hottest for North America and Asia, and the fifth-hottest June-to-August period for planet Earth since record-keeping began in 1880. With the intensity of heatwave events, impact scale, and duration taken into account, the combined intensity of heatwave events in the 2022 summer was the strongest since 1961 according to Beijing Climate Center (https://www.cma.gov.cn/en2014/news/News/202208/t20220821_5045788.html). There were 1680 (1426) meteorological observatories in China with daily maximum surface air temperature (SAT) exceeding 35°C (37°C). 265 stations in China with a long-term period of observations set an all-time heat record in August 2022 and additional 41 stations did so in July 2022, and 16 in June 2022. These extreme temperatures led to the declaration of the first-ever national-level red alert on 12 August 2022, by China Meteorological Administration. Such an extremely hot summer is a threat to human health and ecosystems (Domeisen et al., 2022). Thus, it is necessary to understand its causes and predictability to enhance preparedness and to minimize adverse impacts.

Interestingly, the hot summer in 2022 concurred with a triple-dip La Niña in the tropical Pacific during 2020–2023 (Fang et al., 2023; X. Li, Hu, Tseng, et al., 2022). Considering that El Niño-Southern Oscillation (ENSO) plays a crucial role in seasonal-interannual climate variability and predictability (Hu et al., 2022; X. Li, Hu, Gong, & Jha, 2022; National Research Council, 2010; Yulaeva & Wallace, 1994), we couldn't exclude the role of the La Niña in 2022 in affecting the hot summer in East Asia in 2022. Moreover, atmospheric feedback may also be involved in the extremely hot summer in East Asia in 2022, like that in the 2021 North American heatwave (e.g., Bartusek et al., 2022; Philip et al., 2022).

Given the extremity of the hot summer in East Asia in 2022, it is of great interest to understand the cause and predictability. In this work, we examine the associated atmospheric circulation and assess the real-time predictions from multiple climate models. Also, we identify the contributions of long-term warming trends, sea surface temperature (SST) forcing, and atmospheric feedback to the hot summer. The rest of the paper is organized as follows. The observational and model forecast and simulation data, and methods are introduced in Section 2. Section 3 shows the atmospheric circulation and feedback and Section 4 accesses the prediction and predictability. A summary and discussion are given in Section 5.

2. Observational and Model Data, and Methods

Monthly mean SST is from the latest version of the optimum interpolation SST on a 1° × 1° grid (OIv2.1, Huang et al., 2021). OIv2.1 SST incorporates observations from different platforms (satellites, ships, buoys, and Argo floats) and covers the period since September 1981. With the SST data, the Niño4 index is defined as the averaged SST anomalies in the region (5°S–5°N, 160°E–150°W) to represent ENSO. The leading modes of the SST anomalies in the Indian Ocean are represented by the Indian Ocean Dipole (IOD, Saji et al., 1999) and the Indian Ocean Basin mode (IOBM) indices. IOD is the difference of averaged SST anomalies between the western (10°S–10°N, 50°–70°E) and eastern (10°S–0°, 90°–110°E) Indian Ocean, and IOBM index is the SST anomalies averaged in (20°S–20°N, 40°–110°E).

Monthly mean land SAT is from a station observation-based global analysis at 0.5° × 0.5° resolution for the period from 1948 to the present (Fan & van Dool, 2008). The station data are from the Global Historical Climatology Network version 2 and the Climate Anomaly Monitoring System (GHCN + CAMS). Geopotential height at 500 hPa (H500), vertical velocity at 500 hPa (w500), middle and low-level cloud cover, and net downward shortwave radiation at the surface are from Climate Forecast System Reanalysis (CFSR, Saha et al., 2010). CFSR is a global coupled atmosphere-ocean-land surface-sea ice system, including the coupling of atmosphere and ocean during the generation of the 6-hr guess field, an interactive sea-ice model, and assimilation of satellite radiances. The atmospheric model of CFSR contains observed variations in carbon dioxide, together with changes in aerosols and other trace gases and solar variations to reflect the impact of human activities and natural factors.

The real-time predictions for the summer of 2022 are accessed with the North American Multimodel Ensemble (NMME, Kirtman et al., 2014). Current NMME includes six models: NCEP CFSv2, the National Aeronautics

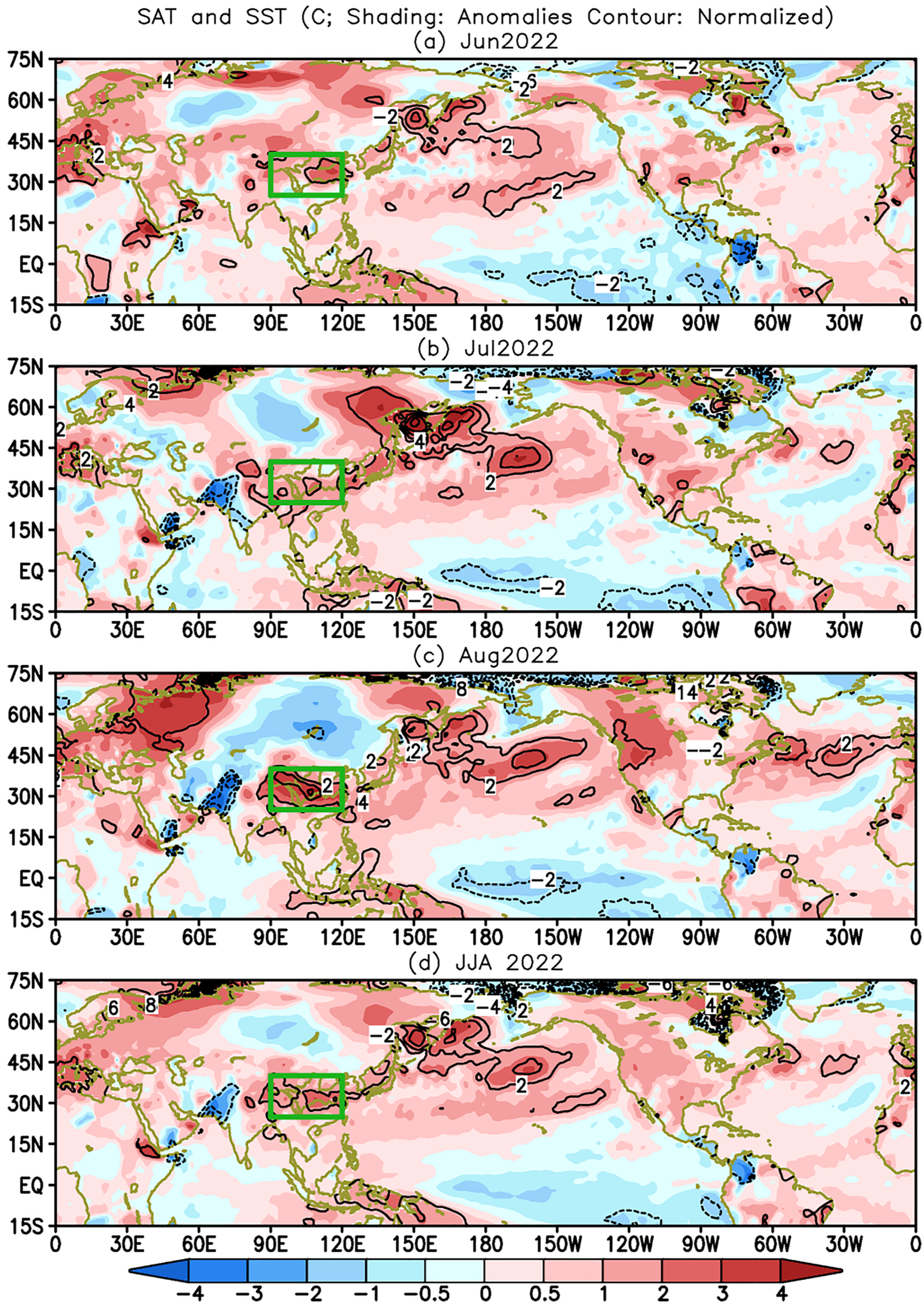

Figure 1. Sea surface temperature and surface air temperature anomalies (shading) and their normalized anomalies (contours) in (a) June, (b) July, (c) August, and (d) June-July-August (JJA) 2022. The unit for shading is °C, and the contour interval is 2. The green line rectangles are the region to be used to calculate the regional means in Figure 11.

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and Space Administration NASA_GEOS5v2, the National Center for Atmospheric Research NCAR_CCSM4, the Geophysical Fluid Dynamics Laboratory GFDL_SPEAR, and the Environment and Climate Change Canada CanCM4i and GEM_NEMO. The NMME 9-month prediction (hindcasts and real-time forecasts) archives start from January 1982 to the present. The ensemble member ranges from 4 to 24 and the spatial resolution of the NMME data is $1° \times 1°$ (Kirtman et al., 2014; https://www.cpc.ncep.noaa.gov/products/NMME/).

To isolate the influence of global SST on the predictability and variability of the 2022 East Asian hot summer, Atmospheric Model Intercomparison Project (AMIP) experiments are examined. In the AMIP simulation, the atmospheric component (Global Forecast System) of version 2 of the Climate Forecast System (Saha et al., 2014) is forced by the observed time-varying global monthly SSTs and sea ice. The model has a horizontal resolution of T126 (~105 km) and 64 vertical levels. The 18 integrations/members are from January 1981 to the present with different atmospheric initial conditions (Hu et al., 2020; X. Li, Hu, Gong, & Jha, 2022). In the following analyses, we examine both the raw and detrended responses.

The common period of these data (January 1982–December 2022) is used in this analysis. The anomalies are defined as the departures from monthly mean climatologies during January 1991–December 2020.

To estimate the linear contribution of a factor "X" (e.g., the Niño4, IOD, IOBM indices, or cloud cover anomaly) to SAT anomaly in June-July-August (JJA; or June, July, August) 2022, linear regression-based reconstruction is computed. First, the statistical linear regression of SAT anomalies onto "X" during JJA (or June, July, August) 1982–2022 are calculated. Then the reconstructed SAT anomalies in JJA (or June, July, August) 2022 are the multiplication of the corresponding linear regression coefficient and the observed value of "X" in JJA (or June, July, August) 2022. All linear regressions and reconstructions are calculated with detrended data. In the linear regression calculations, the results are almost identical with and without JJA 2022, and in the flowing, we only show the results with JJA 2022.

3. Atmospheric Circulation and Feedback

In the 2022 summer (Figure 1d), above-normal temperatures (SATs) over land prevail in the middle and high latitudes of the Northern Hemisphere with some minor cooling in the central Eurasian continent. The positive SAT anomalies exceed two standard deviations in eastern Siberia and northwestern Northern America in July. Over the oceans, extremely high SSTs (marine heatwaves) are observed in the middle and high latitudes of the northwestern Pacific Ocean in June-August and in the middle latitudes of the North Atlantic Ocean in July and August with the amplitudes reaching 2–6 standard deviations. Meanwhile, negative SST anomalies are present in the central and eastern tropical Pacific which are associated with the triple-dip La Niña event in 2020–2023 (Fang et al., 2023; X. Li, Hu, Tseng, et al., 2022).

In East Asia, positive SAT anomalies are dominant and the hot summer is extremely severe. In June 2022 (Figure 1a), the positive SAT anomalies reach two standard deviations in the regions from the Yangtze River to the Yellow River. The positive SAT anomalies persist in East Asia and shift southward in July 2022 (Figure 1b). The high SAT strengthens and expands along the Yangtze River, as well as in southern Japan and Northwest China in August 2022 (Figure 1c). For JJA 2022 (Figure 1d), the large positive SAT anomalies expand from Northwest China to southern and central Japan via central-eastern China with the anomalies exceeding two standard deviations along the Yangtze River.

Summer climate anomalies in East Asia are affected by the variations of the WPSH and circulation anomalies in the middle and high latitudes (Liu et al., 2019). In June 2022 (Figure 2a), the strength and area of WPSH are comparable with the climatology. It seems that the above-normal temperatures in June 2022 are more significantly affected by the circulation anomalies in the high latitudes than WPSH. For instance, the persistently anomalous blockings in the high latitudes may play an anchor role for the long-lasted hot weather in central-eastern China. In contrast, in July and August, as well as JJA 2022, WPSH is extremely strong and expands westward compared with the climatology (see 5,860 gpm contours in Figure 2; thick black contour for 2022 and green contour for climatology in 1991–2020), and East Asia is mostly controlled by anomalous high pressures (shading in Figures 2b–2d). Specifically, the H500 anomalies over the region between the Yangtze and Yellow Rivers are larger than one standard deviation in July and JJA 2022, and three standard deviations in August 2022. As a result of the strong and westward expansion of WPSH, cold air from the high latitudes is unfavorable to invade central-eastern China, leading to persistent high temperatures in eastern China. Correspondingly, the South Asian

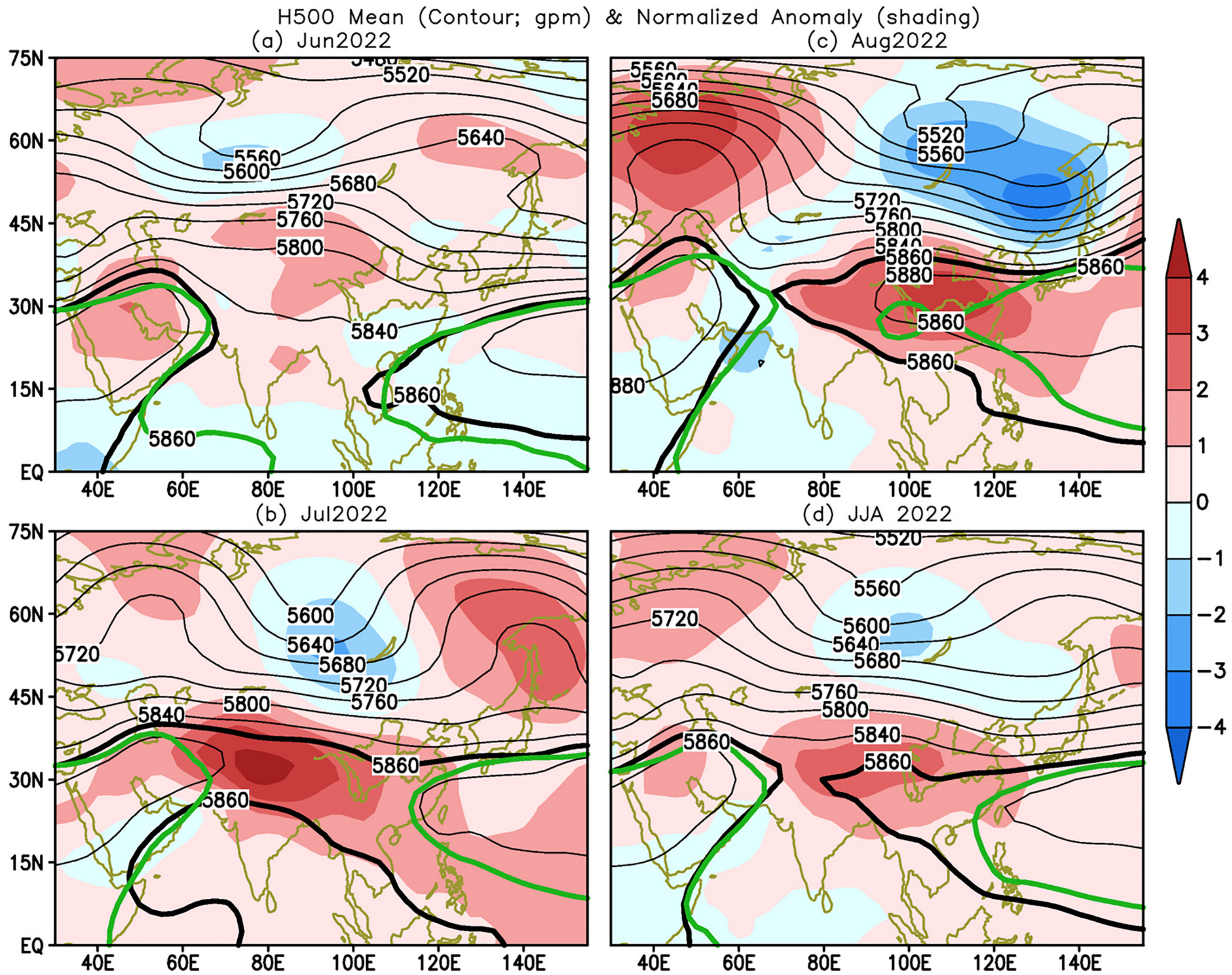

Figure 2. H500 (contour) and normalized anomalies (shading) in (a) June, (b) July, (c) August, and (d) JJA 2022. The thick black and green contours are 5,860 gpm, which represent the subtropical high in 2022 and in the 1991–2020 mean, respectively. The unit is gpm for the contours.

high at the upper troposphere and the local Hadley cell over East Asia are also anomalously strong (not shown; D. Zhang et al., 2023; X. Zhang et al., 2023).

Physically, H500 anomalies are linked to vertical velocity anomalies. For example, in JJA 2022, positive H500 anomalies along the middle and lower reaches of the Yangtze River (Figure 2d) are associated with subsidence in the region (Figure 3a). The anomalous subsidences (Figure 3a) associated with strong WPSH (Figure 2d) lead to reductions of middle and low-level cloud cover (Figure 3b) and increases in net downward shortwave radiation at the surface (Figure 3c), which further strengthens the positive SAT anomalies (Figure 3d). Thus, the positive feedback among the atmospheric circulation, SAT, cloud cover, and net downward shortwave radiation anomalies may be a crucial factor resulting in the severe and persistent hot summer in East Asia in 2022. Here, the "feedback" refers to a mutual enhancement among the atmospheric circulation, SAT, cloud cover, and net downward shortwave radiation anomalies, which may be triggered by atmospheric circulation anomalies, such as westward extension and strengthening of WPSH.

Quantitatively, in the region with maximum SAT anomalies in East Asia (see the green rectangles in Figures 1 and 4), the SAT anomalies linked to the reduction of middle and low-level cloud cover can reach about 0.5°C with the regional maxima along the lower reach of the Yangtze River (Figure 4). Here, the contributions of the feedback among SAT, cloud cover via net downward shortwave radiation at surface in summer 2022 are estimated

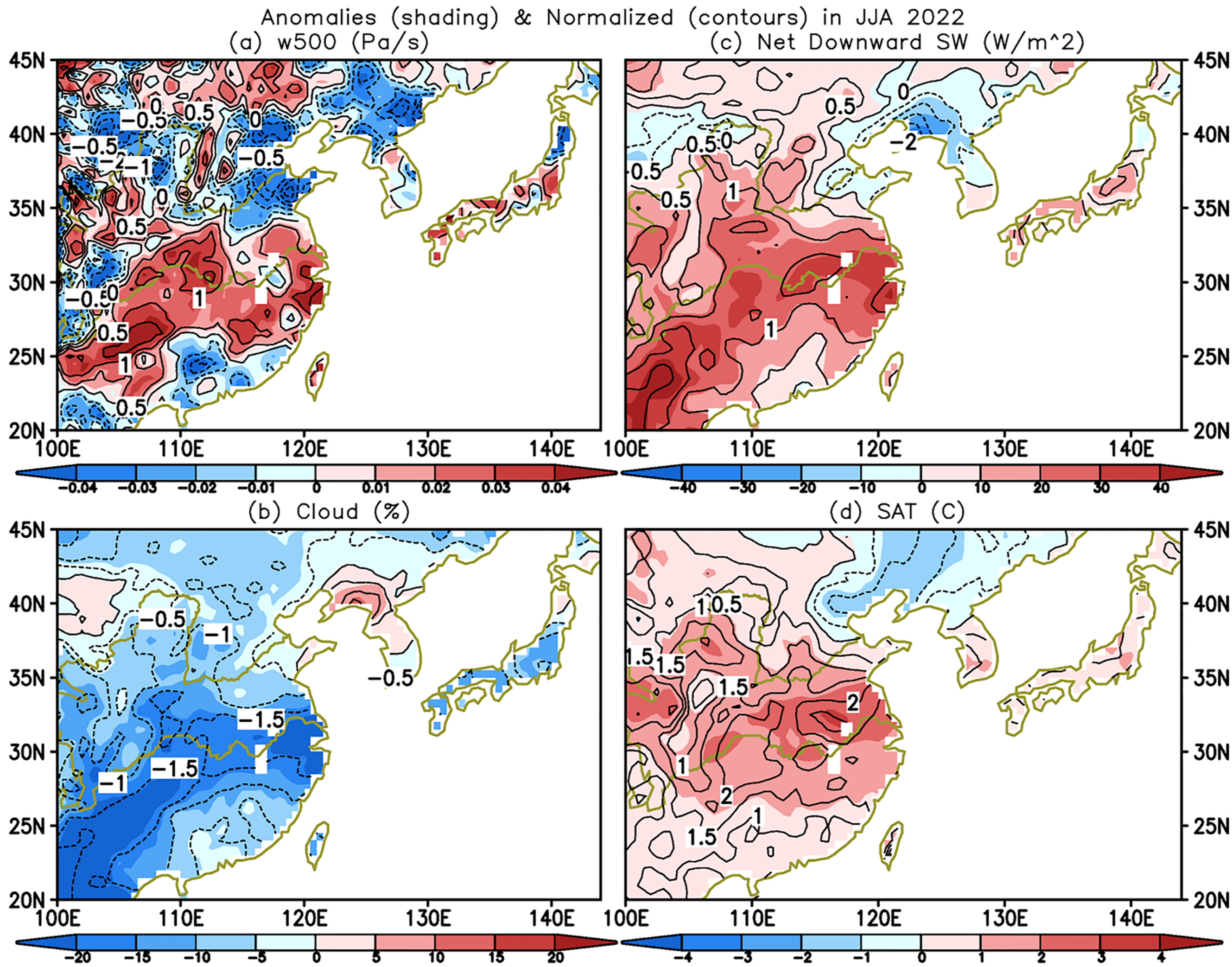

Figure 3. The anomalies (shading) and normalized anomalies (contours) of (a) vertical velocity anomalies at 500 hPa (w500), (b) middle and low-level cloud cover, (c) net downward shortwave radiation at the surface, and (d) surface air temperature (SAT) over land in JJA 2022. The units of the anomalies are Pa/s for w500, % for cloud cover, W/m^2 for radiation, and °C for SAT. Positive (negative) anomalies in panel (a) represent downward (upward) movement, and positive (negative) anomalies in panel (c) are downward (upward) shortwave radiation.

through the reconstruction based on linear regressions of SAT onto the cloud cover anomalies and the values of the cloud cover anomalies in summer 2022 (see Section 2 for the details of the reconstruction approach).

To further examine the importance of the feedback among SAT, cloud cover via net downward shortwave radiation in summer 2022, we calculate the local correlation of SAT anomalies with middle and low-level cloud cover anomalies during 1982–2022 (Figure 5) in (a) June, (b) July, (c) August, and (d) JJA. The significance of correlation varies with region. The significant and steady negative correlations are present over eastern China in June-August, including the regions between the Yangtze and Yellow Rivers, and also in South Korea and Japan in July, August, and JJA. The significant negative correlations mean that more/less middle and low-level cloud cover is associated with less/more shortwave radiation reaching the surface and lower/higher SAT. That is consistent with Nitta and Hu (1996, see their Figure 6). They indicated that the co-variations of summer rainfall and temperature anomalies in China are mostly in eastern China. The correlations are weaker in northern China and mostly not significant in western China. That is probably due to that rainfall associated with thunderstorms is a big contributor to total rainfall in these regions in summer. Compared with the impact of long-last rainfall in the Meiyu season in central-eastern China, the impact of short-spell thunderstorms on overall net shortwave radiation at the surface and SAT in northern and western China is smaller, resulting in smaller and less significant correlations.

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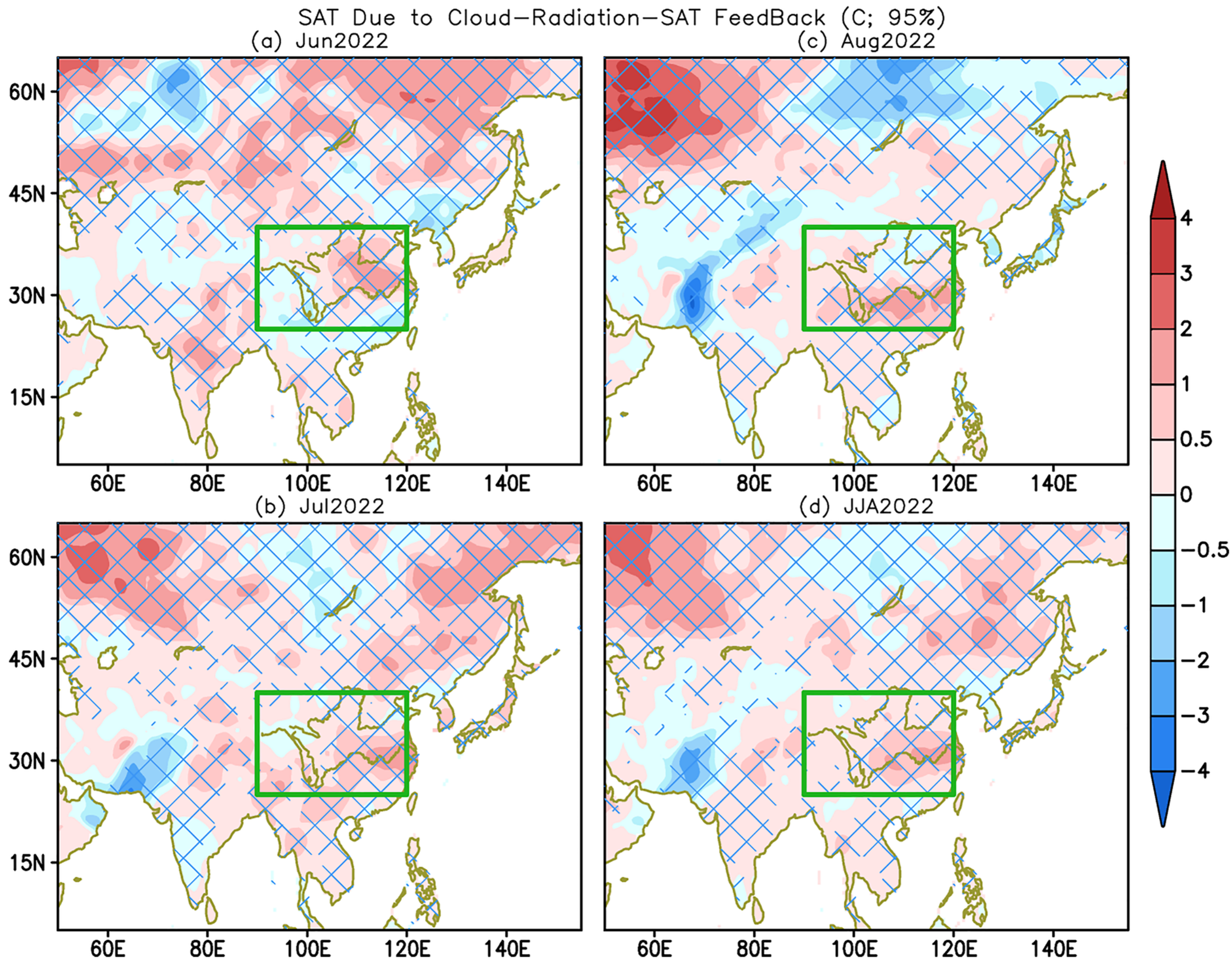

Figure 4. Surface air temperature (SAT) anomalies linked to the feedback among SAT, middle and low-level cloud cover, and net downward shortwave radiation at the surface in (a) June, (b) July, (c) August, and (d) JJA 2022. The feedback is estimated through local linear regressions of SAT onto the cloud cover with timing the values of the cloud cover anomalies in summer 2022. The unit for shading is °C. The green line rectangles are the region to be used to calculate the regional means in Figure 11. The linear trends are eliminated before the calculations. The hatched regions represent the significance of the regression at the level of 95% using an *F*-test.

For the JJA anomalies averaged in (25°–40°N, 90°–120 E) (the green rectangles in Figure 4), we can see that the hottest summer in 2022 since 1982 (Figure 6a) is associated with the smallest middle and low-level cloud cover (Figure 6b) and the strongest net downward shortwave radiation at the surface (Figure 6c). Nevertheless, in reality, there may be multiple and complicated feedback processes involved in the heat summer in 2022. For example, the atmospheric circulation pattern can enhance SAT anomalies through both adiabatic heating from the descent, diabatic heating from radiation and land-surface feedback, as well as horizontal advection. To examine the contribution from the atmospheric circulation anomalies, we repeat the calculation in Figure 4 with H500 anomalies (not shown). It is noted that the atmospheric circulation (H500) feedback has a minor contribution to SAT anomalies in June 2022 and an appreciable contribution in August 2022. For the JJA 2022, the atmospheric circulation feedback has an overall smaller contribution to SAT anomalies than the cloud cover-net shortwave radiation feedback (Figure 4d). That may imply a crucial role of the cloud cover, shortwave radiation, and temperature feedback in the extremely hot summer in 2022.

4. Prediction and Predictability

The real-time predictions of the summer temperature anomalies in 2022 are assessed with NMME. As an example, here, we show the predictions with the initial conditions in May 2022. In the predictions, SAT anomalies are

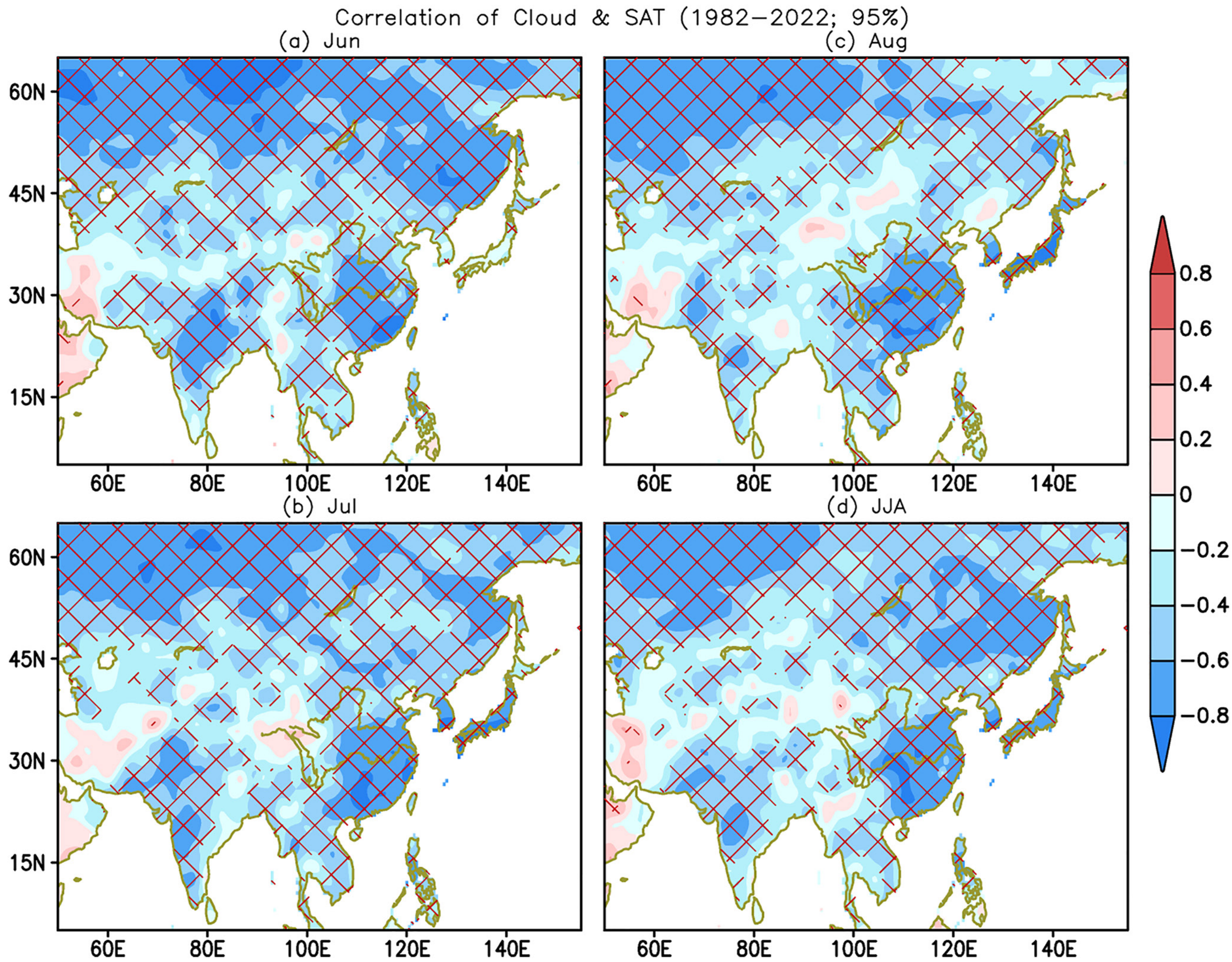

Figure 5. Linear correlations of surface air temperature anomalies with middle and low-level cloud cover anomalies during 1982–2022 in (a) June, (b) July, (c) August, and (d) JJA. The hatched regions represent the significance of the correlations at the level of 95% using a *T*-test.

mostly positive in East Asia, especially in August (Figure 7c). In June 2022, some minor coolings are predicted in Northeast and South China, and central and northern Japan (Figure 7a). The cooling is in the Indian subcontinent as well as a small region of the coast region of North China for the July prediction (Figure 7b). For the JJA 2022 (Figure 7d), NMME predicted positive SAT anomalies are concentrated in Mongolian and Siberian regions with minor positive or negative anomalies in the lower latitudes and the eastern portion of mainland of China.

Compared with the observations (Figure 1), we note that both the spatial distribution pattern of SAT anomalies and their amplitudes have distinguished biases in the NMME predictions (Figure 7). For example, NMME failed to capture the positive anomalies of SAT in the regions between the Yangtze and Yellow Rivers. The failure might be due to the inherent feature of the low predictability of summer climate variability in East Asia (e.g., Hu et al., 2020; Liang et al., 2019). That is consistent with the low signal-to-noise ratios (SNR; contours in Figure 7). The low predictability is also a common feature of extra-tropical land climate variability (Kumar & Hoerling, 1995; X. Li, Hu, Gong, & Jha, 2022). Moreover, model biases may be an additional reason for the low prediction skill (e.g., Liang et al., 2019).

The observed SAT anomalies in 2022 consist of the long-term trend (maybe due to global warming), SST (and land moisture and temperature) forcing response, and internal variability which is mainly driven by atmospheric dynamics. For the long-term trend, warm tendencies are dominated in East Asia with maximum warming trends in the regions from western China to Mongolia (Figure 8). Such long-term trends may be due to the increases in greenhouse gas concentrations (e.g., Hu et al., 2003; Liu et al., 2019). Nevertheless, the spatial distribution pattern of the trends bears little similarity to the observed anomalies in summer 2022. Thus, human activity-induced

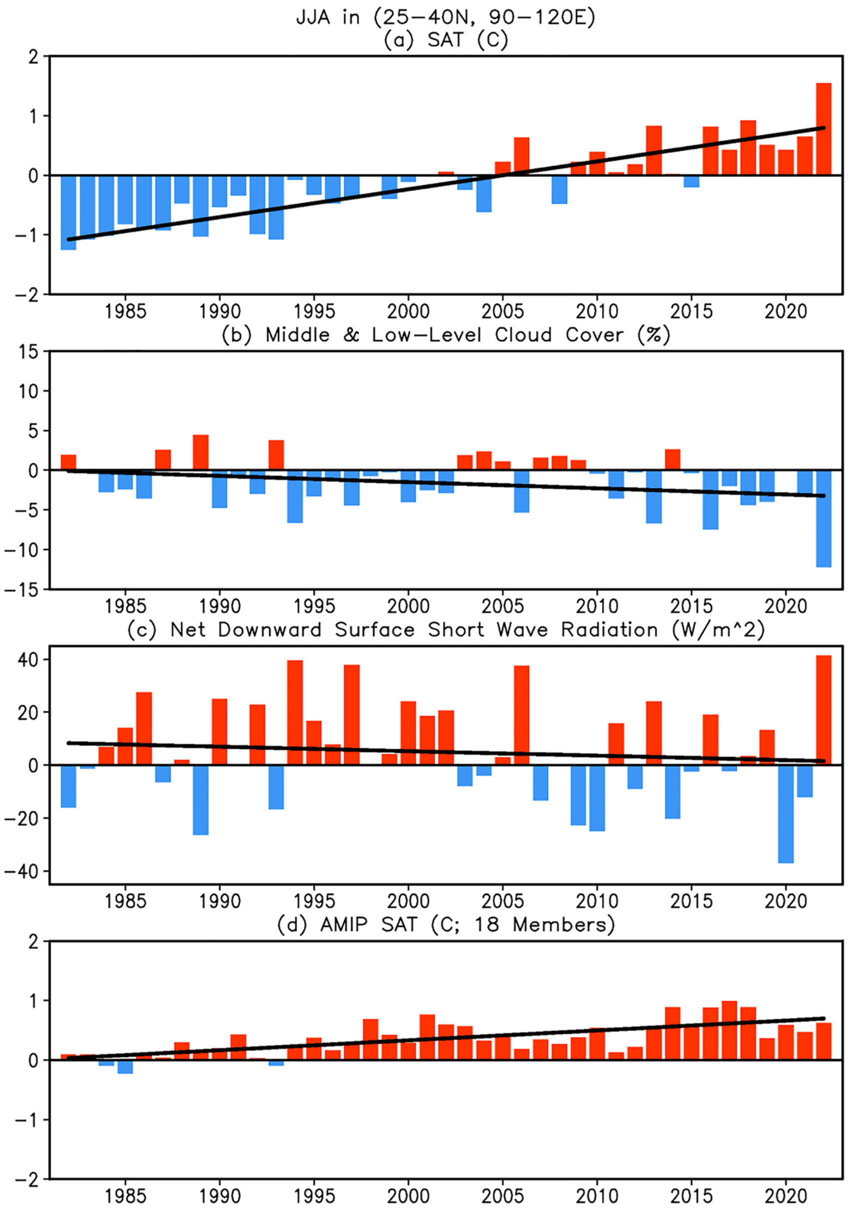

Figure 6. JJA anomalies (bars) and linear trend (lines) averaged in (25°–40°N, 90°–120°E) for (a) observed surface air temperature (SAT), (b) middle and low-level cloud cover, (c) net downward shortwave radiation at the surface, and (d) Atmospheric Model Intercomparison Project simulated (not detrended) SAT. The units are °C for SAT, % for cloud cover, and W/m^2 for radiation.

warm trends contribute to the hot summer in East Asia in 2022 mainly by providing a warm background. The spatially heterogeneous distribution of the positive SAT anomalies is driven by other factors, including SST forcing and the atmospheric internal dynamics-driven variability.

The impact of SST forcing on the hot summer is estimated by assessing the SAT anomalies in the 18-member ensemble mean of the AMIP experiments. Through the ensemble average, the internal variability is largely eliminated and the SST forced response is isolated (Hu et al., 2020; X. Li, Hu, Gong, & Jha, 2022). To eliminate the response to the long-term trend in SST and to isolate the response to the seasonal-interannual variations of SST, all 18 members are detrended. Figure 9 displays the ensemble mean detrended SAT anomaly of 18 members in summer 2022. It is noted that the AMIP simulated anomalies are smaller than the observations, and both negative and positive anomalies are present. Meanwhile, the SNR is mostly smaller than 0.5 (contours in Figure 9), meaning low consensus of the SST response. For the not detrended response (not shown), the positive

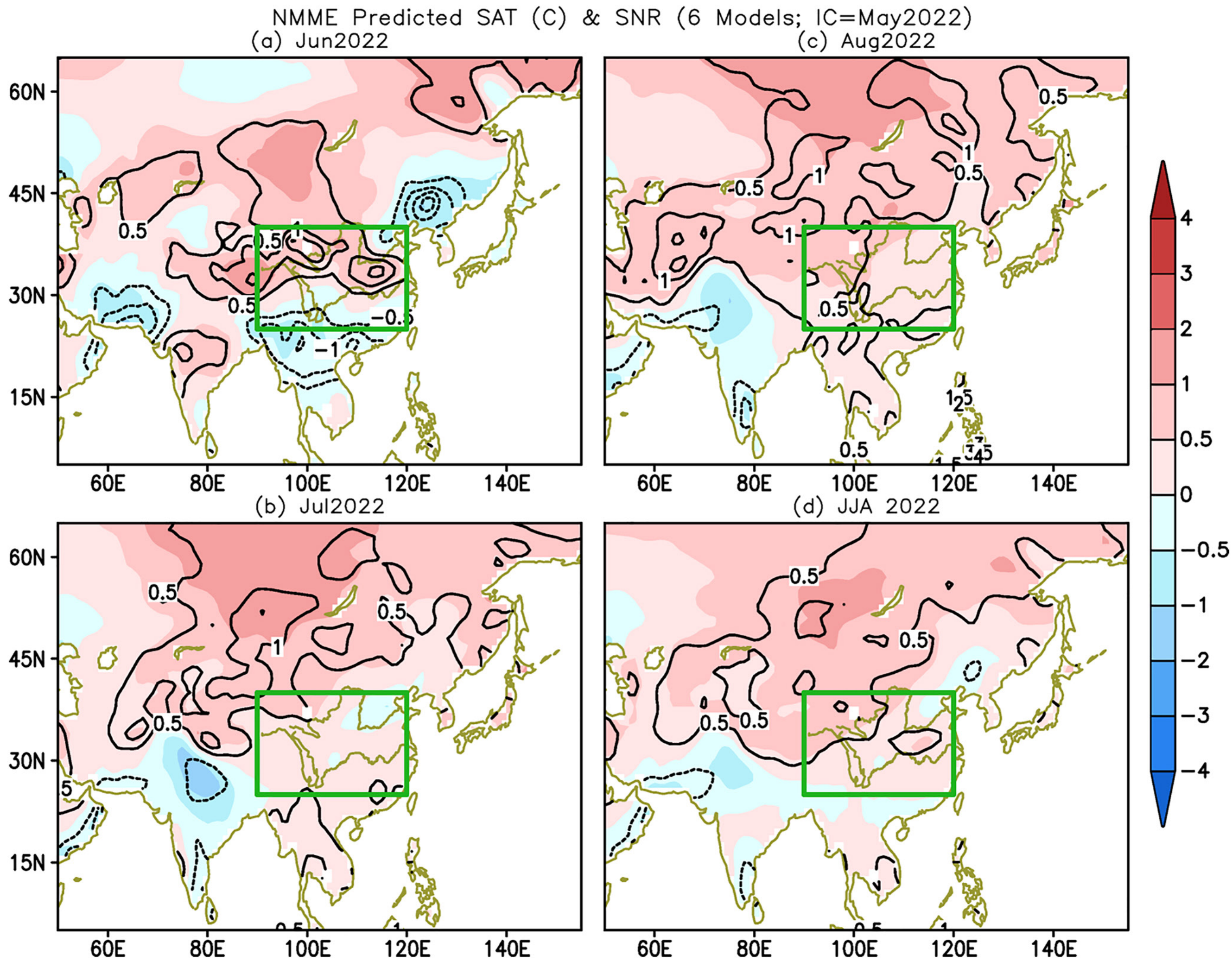

Figure 7. North American Multimodel Ensemble predicted surface air temperature anomalies (shading) and signal-to-noise ratio (SNR; contours) over land in (a) June, (b) July, (c) August, and (d) JJA 2022 with initial conditions in May 2022. The unit is °C for the anomalies and the contour interval is 0.5 with zero contours not shown. The SNR is defined as the ratio of the anomalies to the standard deviation of the departure of one member of each of the 6 models from the 6-model ensemble mean. The green line rectangles are the region to be used to calculate the regional means in Figure 11.

SAT anomalies are seen in June, July, and JJA 2022 in the regions from Southwest China to central-eastern China, and the SAT anomalies are small in East Asia in August 2022. The overall SAT anomaly amplitudes in the AMIP simulations are smaller than the observations in East Asia in the summer of 2022 (Figure 1). Thus, the SST forcing associated with the triple-dip La Niña event in 2020–2023 may not be a major contributor to the hot summer in East Asia in 2022 and is not the main factors leading to the spatially heterogeneous distribution of SAT anomalies in East Asia in 2022. That is consistent with some previous studies. For example, R. Chen et al. (2019) argued that the extremely hot middle summer in Central and South China during 2017 was unrelated to ENSO.

The model used in the AMIP run might miss the influence of SST in the hot summer in East Asia in 2022 due to its infidelity (biases). To further estimate the contributions of SST anomalies in the tropical Indian and Pacific Oceans in JJA 2022 to the hot summer in East Asia, we calculate the linear regression-based reconstructions for SST variability in the tropical Pacific and Indian Oceans. First, the statistical linear regressions of SAT anomalies onto each of the Niño4, IOD, and IOBM indices in JJA during 1982–2022 are calculated, respectively. Then the reconstructed SAT anomalies from each index in JJA 2022 are the multiplication of the corresponding linear regression coefficients and the observed value of the index (Niño4, IOD, or IOBM indices) in JJA 2022, respectively (Figures 10b–10d). To eliminate the impact of long-term trends, the data are detrended. Compared with the observations (Figure 10a), the reconstructed SAT anomalies are much smaller and the corresponding correlations

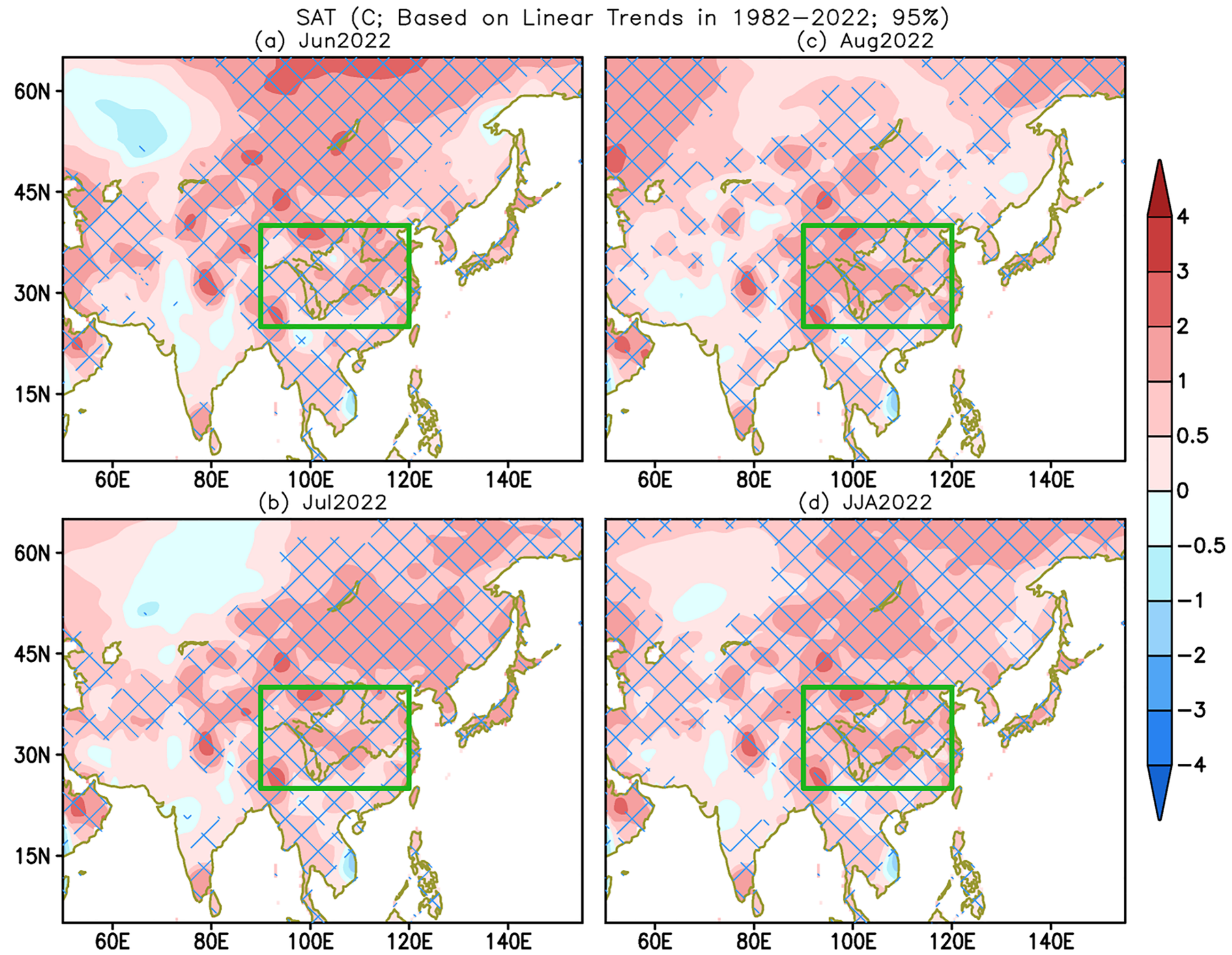

Figure 8. Surface air temperature anomalies in (a) June, (b) July, (c) August, and (d) JJA 2022 calculated based on the linear trends during 1982–2022. The unit is °C. The green line rectangles are the region to be used to calculate the regional means in Figure 11. The hatched regions represent the significance of the linear trends at the level of 95% using an *F*-test.

are mostly not significant in eastern China (see hatched lines in Figures 10b–10d). The amplitudes of the reconstructed SAT anomalies are mostly smaller than 0.2°C in central-eastern China, which is the region with the largest SAT anomalies in the observations (Figure 10a). Moreover, some negative SAT anomalies are seen in the region in the constructions based on the Niño4 and IOD indices (Figures 10b and 10d). The results are similar if Niño3.4 instead of Niño4 is used. The weak influence of ENSO on hot summer in eastern China in 2022 is consistent with previous work such as Wu et al. (2003, see their Figure 3). That is also the case for the North Atlantic tri-pole mode (Zuo et al., 2013; not shown). For the averages in (25°–40°N, 90°–120°E) in JJA 2022, the values are 0.06, 0.06, and 0.12°C for the reconstructions based on the Niño4, IOD, and IOBM indices, respectively. Thus, based on the AMIP simulations and the statistical reconstruction, we conclude that the seasonal-interannual components of SST in the global oceans may just have a minor contribution to the hot summer in East Asia in 2022.

These results suggest that the long-term warming trends contribute to the hot summer in East Asia in 2022. Meanwhile, their appreciable differences in the amplitudes and spatial pattern compared with the observations imply that other factors, such as the positive feedback among SAT, cloud cover, and net downward shortwave radiation, may also play an indispensable role in generating the hot summer. To quantitatively estimate the contributions from different factors, Figure 11 shows the observed SAT anomalies and contribution estimations averaged in the main region of the hot summer in East Asia in 2022 (25°–40°N, 90°–120°E; see the green line rectangles in Figures 1, 4, and 7–9). For the individual months and JJA 2022, the largest contribution is from the long-term trend and the second-largest contribution is from the atmospheric circulation-SAT-cloud cover-net shortwave

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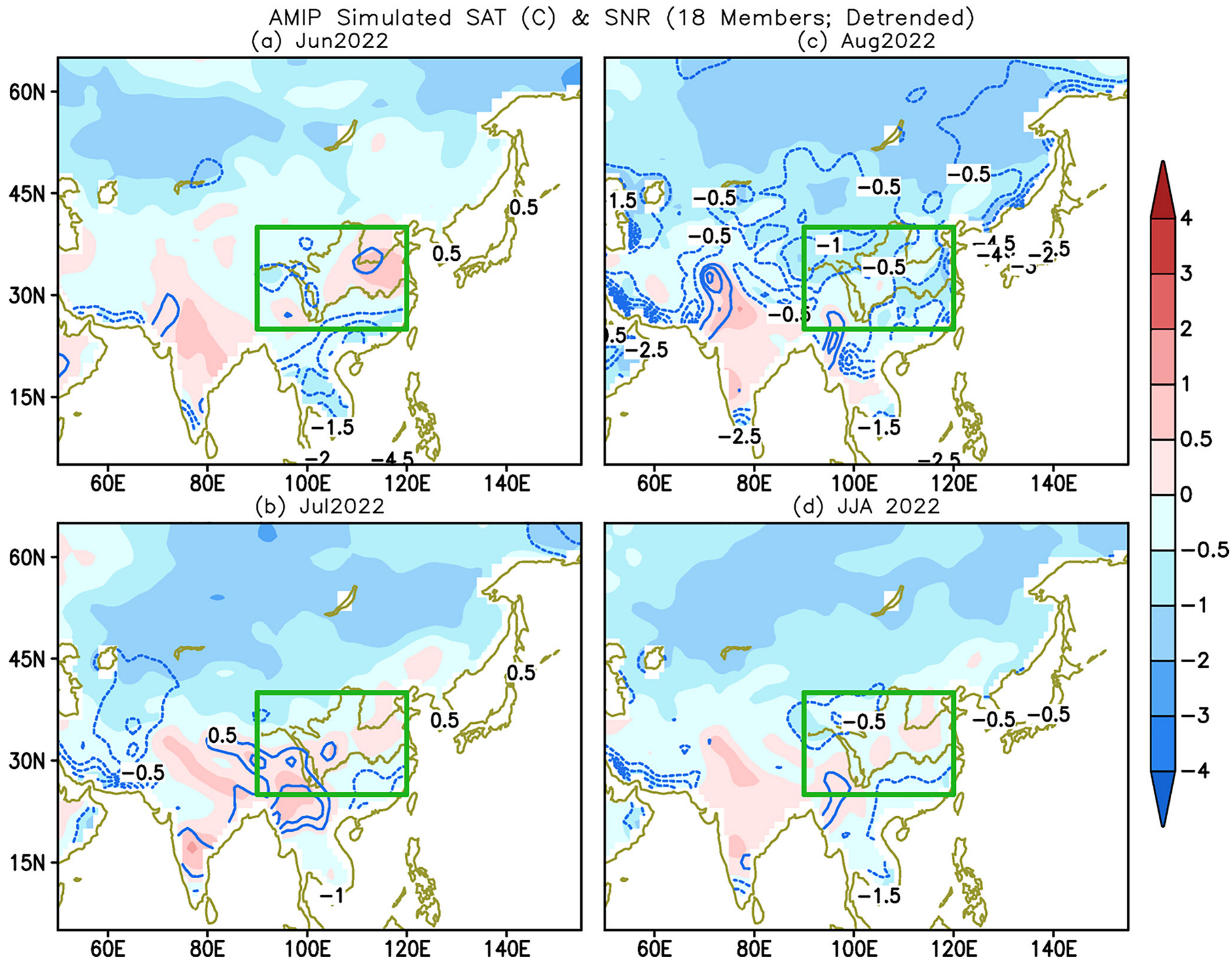

Figure 9. Atmospheric Model Intercomparison Project ensemble mean of detrended surface air temperature anomalies (shading) and signal-to-noise ratio (SNR; contours) of 18 members in (a) June, (b) July, (c) August, and (d) JJA 2022. The unit is °C for the anomalies and the contour interval is 0.5 with zero contours not shown. The SNR is defined as the ratio of the anomalies to the standard deviation of the departure of each of the 18 members from their ensemble mean. The green line rectangles are the region to be used to calculate the regional means in Figure 11.

radiation feedback. For the averages in JJA 2022, the contribution from the long-term trend is about 50%, and for the rest 50%, half of them is from the feedback. In other words, the feedback contributes about 25% to the total heating (Figure 11). However, for the SST forcing at seasonal-interannual time scales (associated with the triple-dip La Niña event in 2020–2023), its contribution is ignorable in June and July 2022, and negative in August and JJA 2022. That is consistent with Luo and Lau (2019). They suggested that El Niño (La Niña) may strengthen (weaken) the heatwave activities in most areas of China, especially in southern China. Moreover, for the SAT anomaly in August 2022, the trend plus the feedback contributions are still smaller than the observation (Figure 11c), implying that some other processes, such as subseasonal variations and land processes, may also play a role. Thus, for the main hot summer region of East Asia in 2022, the positive SAT is largely associated with the long-term trend and atmospheric internal dynamics and amplified by the positive feedback among the SAT, cloud cover, and net downward shortwave radiation. In contrast, the SST variation has a minor impact.

5. Summary and Discussion

In the context of global warming, the northern hemisphere experienced an extremely hot summer in 2022 with the hottest on record for Europe and China, and the second-hottest for North America and Asia. The hot summer concurred with a triple-dip La Niña in the tropical Pacific during 2020–2023. Given the extremity of

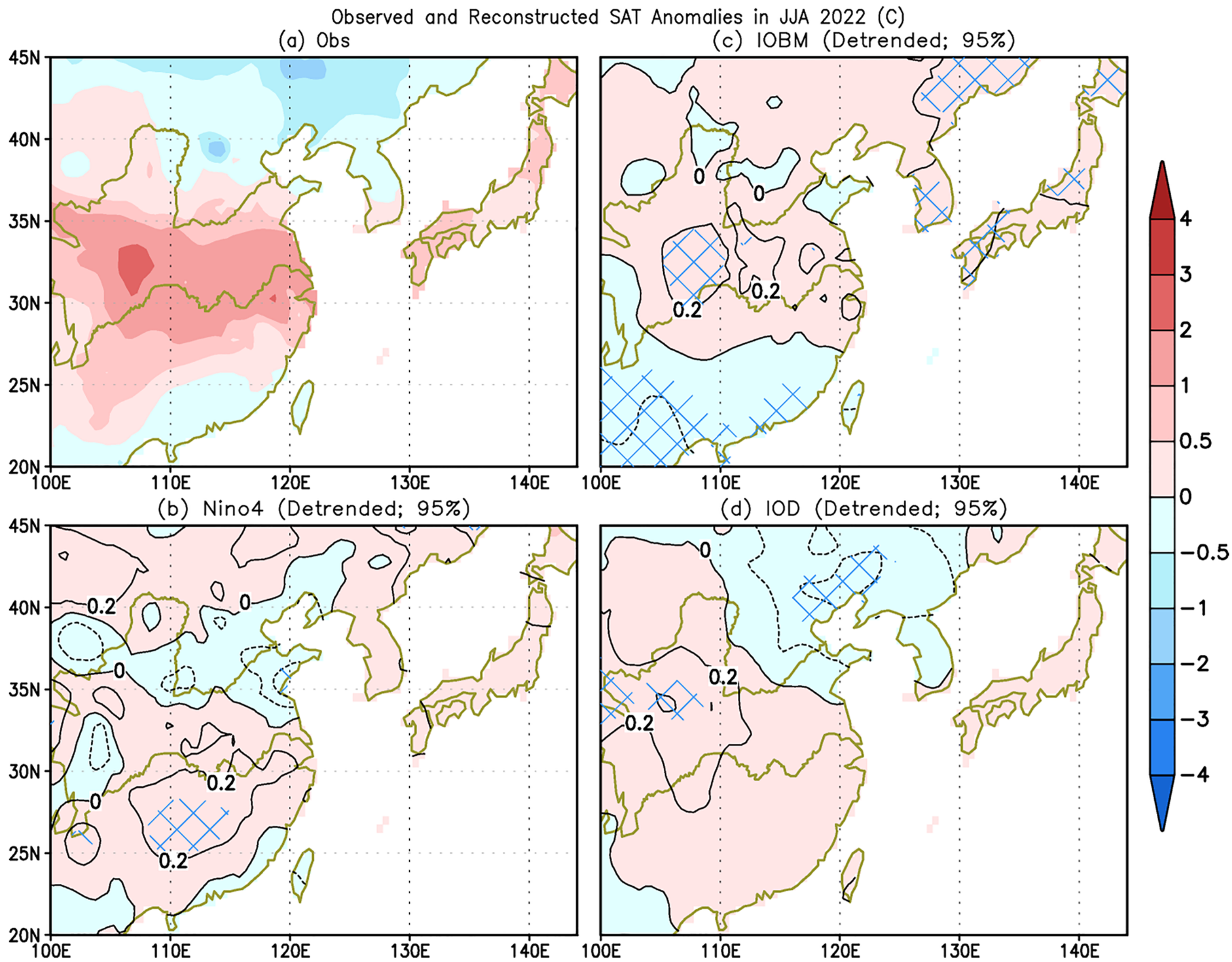

Figure 10. (a) Observed and reconstructed surface air temperature (SAT) anomalies in JJA 2022 based on the linear regression of the SAT anomalies in JJA 1982–2022 with the observed (b) Niño4, (c) Indian Ocean Basin mode, and (d) Indian Ocean Dipole indices in JJA 2022. The data are detrended. The unit is °C and the contour interval in panels (b–d) is 0.2°C. The hatched regions represent the significance of the linear correlations between the indices and SAT at the level of 95% using a *T*-test.

the hot summer in East Asia in 2022, to understand the cause and predictability, in this work, we examine the associated atmospheric circulation and assess the real-time predictions from multiple climate models. Also, we identify the contributions of long-term warming trends, SST forcing, and an atmospheric feedback to the hot summer.

The positive temperature anomalies reach two standard deviations in the regions between the Yangtze and Yellow Rivers in June 2022. The positive temperature anomalies persist in East Asia and shift southward in July 2022, and strengthen and expand along the Yangtze River, as well as in southern Japan and Northwest China in August 2022. The hot summer in 2022 is due to the extremely strong and westward expanded WPSH. The strengthened and westward expanded WPSH is consistent with the projection of some climates in global warming scenarios (X. Chen et al., 2020; Liu et al., 2014). The subsidence associated with strong WPSH leads to cloud cover reduction and increases in net downward shortwave radiation at the surface, which further strengthens the positive SAT anomalies. The positive feedback among the SAT, cloud cover, and net downward shortwave radiation may be associated with a vertical heat dome-like circulation (D. Zhang et al., 2023; X. Zhang et al., 2023). Moreover, in addition to the positive feedback among atmospheric circulation-SAT-cloud cover-net downward shortwave radiation, the long-term trends with maximum warming in the regions from western China to Mongolia are also important contributors. In contrast, the seasonal-interannual components of the global SSTs are not the major cause of the hot summer in East Asia in 2022.

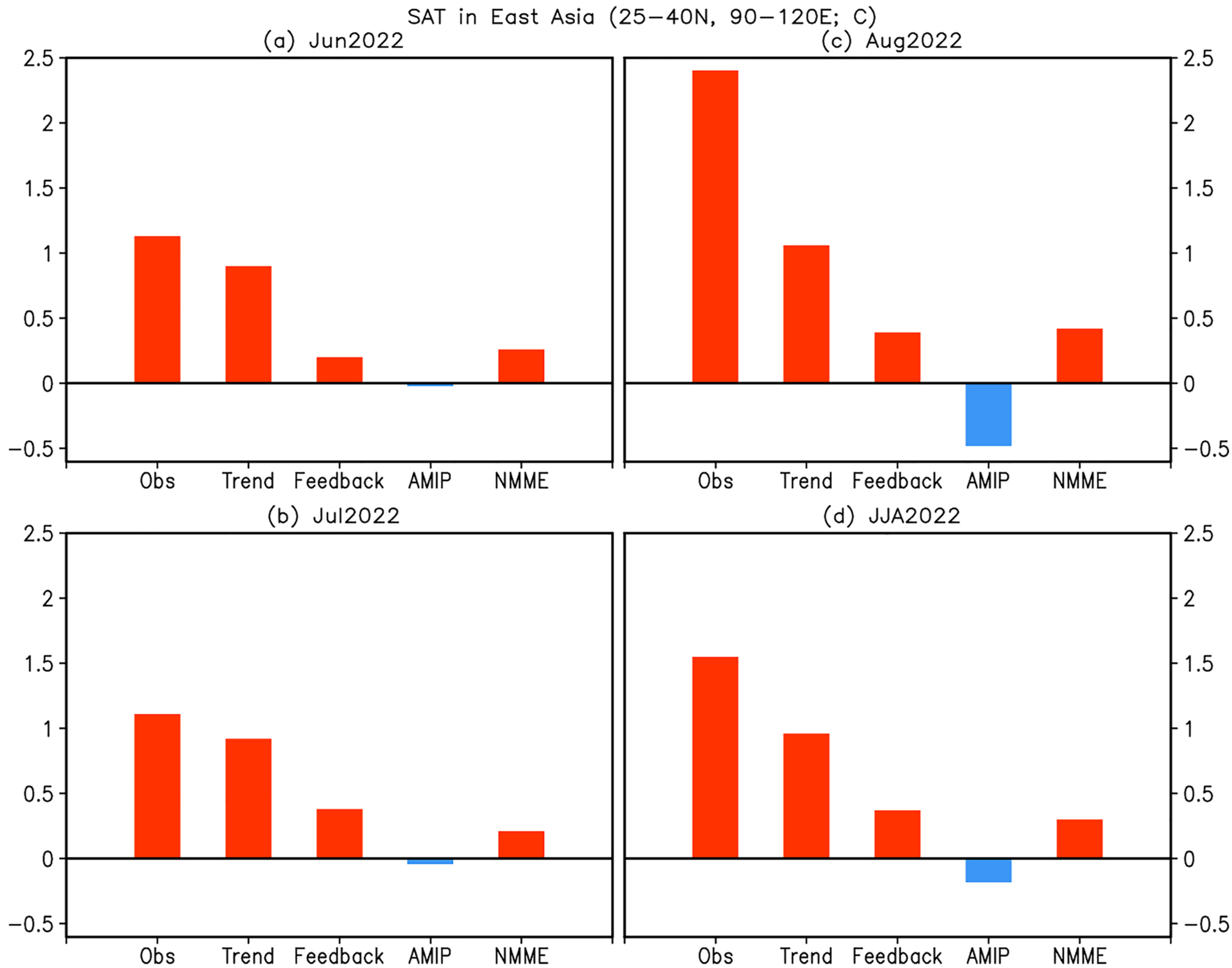

Figure 11. Surface air temperature (SAT) anomalies averaged in (25°–40°N, 90°–120°E; see the green line rectangles in Figures 1, 4, and 7–9) in (a) June, (b) July, (c) August, and (d) JJA 2022. At the *x*-axis, "Obs," "Trend," "Feedback," "AMIP," and "NMME" represent the values from the observations (Figure 1), observed linear trend (Figure 8), estimates based on linear regression of SAT anomalies onto middle and low-level cloud cover anomalies with detrended data (Figure 4), Atmospheric Model Intercomparison Project detrended response (Figure 9), and North American Multimodel Ensemble predictions (Figure 7), respectively. The regressions or reconstructions are computed locally, then averaged over the domain.

For the averages in the main hot summer region in 2022, the largest contribution is from the long-term trend, and the second largest is from the feedback among atmospheric circulation-SAT-cloud cover-net downward shortwave radiation. Thus, the high temperatures in the main hot summer region of East Asia in 2022 are associated with the long-term trend and amplified by the positive feedback among the SAT, cloud cover, and net downward shortwave radiation. Here, the contribution of the SAT-cloud cover-net downward shortwave radiation to the hot summer in 2022 is estimated based on linear regression, and nonlinear processes might have an impact on the estimate.

The NMME with the initial conditions in May 2022 predicts positive SAT anomalies in most regions of East Asia, especially in August. However, compared with the observations, both the spatial distribution pattern of SAT anomalies and their amplitudes have distinguished differences in the NMME predictions. Especially, NMME failed to capture the maximum positive anomalies of SAT in central-eastern China. The failure implies the challenge of state-of-the-art climate models in predicting such extreme events.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

OIv2.1 monthly mean SST, land surface air temperature, CFSR, NMME predictions, and AMIP simulations are available at Huang et al. (2021), Fan and van Dool (2008), Saha et al. (2010), Kirtman et al. (2014), and Hu et al. (2020), respectively.

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