The Record-Breaking Hot Summer in 2015 over Hawaii and Its Physical Causes

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ABSTRACT

Hawaiian surface air temperature (HST) during the summer of 2015 (from July to October) was about 1.5°C higher than the climatological mean, which was the hottest since records began in 1948. In the context of record-breaking seasonal-mean high temperature, 98 exceptional local heatwave days occurred during the summer of 2015. Based on diagnoses and simulations, this paper demonstrates that the record-high HST during the summer of 2015 arose mainly from the combined effects of the interannual and interdecadal variability of sea surface temperature anomalies (SSTAs). The interannual variability of SSTAs, with an El Niño–like pattern in the tropics and cold (warm) anomalies over the western (eastern) North Pacific, was the primary contributor to the abnormally high HST in the summer of 2015. This interannual tropical–extratropical SSTA pattern was accompanied by low-level southwesterly anomalies over the central North Pacific, which weakened the climatological northeasterly trade winds and reduced the ventilation effect, warming Hawaii. Numerical experiments further revealed that the SST warming in the subtropical eastern North Pacific was mostly responsible for the weakened trade winds and warming over Hawaii. Interdecadal SST warming in the tropics was a secondary factor. By superimposing the positive SSTAs over the Indo-Pacific warm pool and tropical North Atlantic Ocean upon the climatological-mean maximum SST regions, it was found that these anomalies led to enhanced convection over the Maritime Continent and the oceans around Mexico, causing anomalous subsidence and reduced cloud cover over the tropical central North Pacific. The reduced cloudiness increased the amount of downward solar radiation, thus warming Hawaii.

1. Introduction

Located in the tropical central North Pacific, Hawaii is famous for its pleasant climate and weather, with constant favorable temperature, mild humidity, and breezy conditions. The nature of the climate is directly attributable to the year-round North Pacific northeast/east trade winds, which represent one of the largest and most consistent circulation systems in the world (Wyrski and Meyers 1976). The trade winds prevail over the islands throughout the year, for 85%–95% of the time in summer, and 50%–80% of the time in winter. Interruption of the trade winds often brings about unusually adverse weather in Hawaii (Sanderson 1993). However, the trade winds, precipitation, and temperatures of Hawaii nonetheless show considerable year-to-year variation and long-term changes (Garza et al. 2012). Many studies have examined the relationship between the Hawaiian trade winds and local rainfall and streamflow. For instance, based on EOF analyses in different seasons, Lyons (1982) argued that the trade winds are always the primary factor of the leading rainfall mode over Hawaii, as compared to southwesterly wind, convection, and tropical disturbance. Timm and Diaz (2009) suggested Hawaii’s regional rainfall is largely controlled by the strength and direction of the trade winds. Bassiouni and Oki (2013) suggested that the long-term (1913–2008) decreasing trend of local streamflow is closely related to changes in the trade winds over Hawaii. Because Hawaii is surrounded by ocean, the sea surface temperature (SST) is

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considered an important boundary forcing for local rainfall (Taylor 1984; Ropelewski and Halpert 1987; Chu and Chen 2005). On the interannual time scale, Chu (1995) reported that El Niño can shift the upper-tropospheric jet stream to the east, leading to a divergence in the lower-level troposphere over Hawaii. Meanwhile, the convection caused by El Niño in the equatorial region can also result in a compensating descending motion over Hawaii via a local meridional circulation. The anomalous descending motion and divergence inhibits the development and maintenance of subtropical cyclones over Hawaii and the southeastward propagation of strong frontal systems into the island chain, resulting in suppressed rainfall. Chu (1989) also suggested a positive relationship between precipitation indices for Hawaii and the Southern Oscillation index. Specifically, more (fewer) precipitation extremes occur during La Niña (El Niño) years. However, although Hawaii tends to be dry during most El Niño events, reduced rainfall also occurs in the absence of El Niño. Meanwhile, Jayawardena et al. (2012) suggested that La Niña is not the only requirement for prolonged stormy weather over the Hawaiian Islands. More recently, O’Connor et al. (2015) indicated that Hawaii experiences lower-than-normal rainfall in La Niña years. Indeed, a shift toward drier conditions (i.e., reduced precipitation) for Hawaii in La Niña years occurred in 1983. On the interdecadal time scale, Hawaiian rainfall is negatively correlated with the Pacific decadal oscillation (PDO) (Diaz and Giambelluca 2012). A phase change in the PDO is considered as the main cause for change in the trade winds. Chu and Chen (2005) clarified that there is a joint impact of the PDO and El Niño on Hawaii’s rainfall.

Other studies have explored the variability of Hawaiian surface air temperature. For instance, Nullet and Ekern (1988) found that significant warming took place at Honolulu and Hilo between the 1950s and 1980s, and they suggested changes in cloudiness may play a role in Hawaiian local temperature change. Giambelluca et al. (2008) indicated Hawaii has experienced rapid warming, especially since the mid-1980s. They found that Hawaii used to be tightly coupled to the PDO, but this relationship has broken down in recent decades. Safeeq et al. (2013) reported that the diurnal temperature range over Oahu declined during the 39 years of their study (1969–2007) as a result of a rapid warming of minimum temperature. Maximum temperature generally followed the PDO, but not for the period when there was increased local rainfall.

As demonstrated above, compared to the numerous studies on the variation of precipitation over Hawaii, the variability of surface air temperature in this region has attracted less attention. In fact, temperature variation in Hawaii is an influential factor for its terrestrial and marine ecosystems, water resources, agricultural production, and tourism industry. As will be reported in this paper, Hawaiian surface air temperature (HST) in the summer of 2015 was about 1.5°C warmer than the climatological mean, which was the hottest since records began nearly 70 years ago. This inspired us to revisit the variability of summer HST. Moreover, as previous diagnostic studies have indicated, the surrounding SST (e.g., El Niño and PDO) variation is not always related to the trade winds, rainfall, and temperature over Hawaii; thus, a clear physical mechanism through which the SST drives the variability of the summer trade winds and HST needs to be clarified by numerical simulations. In this context, the objectives of the present study were to explain the record-breaking hot summer of 2015 over Hawaii and to unravel the mechanism through which the SST drives the variability of summer HST on both interannual and interdecadal time scales.

Following this introduction, section 2 describes the data, method, and dynamical model utilized in the study. Section 3 shows the evidence for the record-breaking HST in 2015, and the characteristics of observed variation in HST during 1948–2015. Section 4 demonstrates the role of the interannual variability of SST in driving HST. Section 5 explores the impact of interdecadal changes of SST on HST. Section 6 provides conclusions and further discussion.

2. Data, method, and model

The daily mean 2-m air temperature, with a T62 Gaussian grid (192 × 94 points) horizontal resolution, from the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalyses (R-1; Kalnay et al. 1996), was applied to calculate the surface air temperature over Hawaii. The atmospheric circulation variables were also obtained from R-1, with a 2.5° × 2.5° horizontal resolution. The monthly mean SST data, with a 2.0° × 2.0° horizontal resolution, were derived from the improved (version 3) Extended Reconstructed SST dataset (Smith et al. 2008). The precipitation rate, the downward solar radiation flux, and the total cloud cover (entire atmosphere considered as a single layer), with a T62 Gaussian grid (192 × 94 points) horizontal resolution, were obtained from the Twentieth Century Reanalysis, version 2 (Compo et al. 2011). The period of analysis for all data spanned from 1948 to 2015. The average of 1961–90 was used as the climatological mean.
To examine the variability of HST, we defined an HST index as the area-mean surface air temperature over the entire Hawaiian island chain between 18°-23°N and 161°-154°W. The selection of the domain follows the previous work of Diaz and Giambelluca (2012). The 11-yr running mean of the HST index was used to represent the interdecadal component of the HST index, whereas the interannual component was obtained by removing the interdecadal anomaly from the original HST index. Note that, because there is a tapering problem when calculating the running mean, the interdecadal component of the first five years and the last five years of HST could be estimated by the mean value of the available data with a shorter window. For example, the interdecadal component of 2014 and 2015 could be estimated by the mean of 2009–15 and 2010–15, respectively. To provide more evidence for the record-breaking hot summer, aside from the HST index, we also calculated a local heatwave day index in the same region. Following the definition reported by Fischer and Schär (2010), a heatwave day was defined as a spell of at least six consecutive days with the maximum temperature exceeding the local 90th percentile of the control period (1961–90). The 90th percentile was calculated for each calendar day at each grid point, using a 15-day time window.

To reveal the relationship between HST and the large-scale atmospheric circulation and SST field, composite and regression analyses were used. Their statistical significance was assessed using a Student’s t test. To uncover the relative roles of regional SSTAs in driving the record-breaking high HST in the summer of 2015, an atmospheric general circulation model (AGCM) was employed. The AGCM used was ECHAM4.6, developed by the Max Planck Institute for Meteorology (Roeckner et al. 1996). ECHAM4.6 has a horizontal resolution of around 2.8° × 2.8° (T42) and 19 vertical levels extending from the surface to 10 hPa. The control and sensitivity experiments were integrated for 20 years, with slightly different initial conditions for each year, and the last 15 years of model outputs were used for diagnosis. The difference between the ensemble of the sensitivity and control experiments was used to represent the atmospheric response to the specified SSTA forcing.

3. Observed hot summer over Hawaii in 2015

Figure 1a shows the climatological annual cycle of Hawaiian monthly surface air temperature. The data indicate that July, August, September, and October (JASO) are the four warmest months over the Hawaiian Islands (18°–23°N, 161°–154°W). Thus, in the present study, we chose JASO as the Hawaiian summer season. Figure 1b shows a linear trend of increasing surface air temperature over the Hawaiian Islands at a rate of approximately 0.3°–0.45°C (30 yr)-1 (Giambelluca et al. 2008), which is comparable to the global warming rate of the last three decades (IPCC 2013). Notable from Fig. 1c is that the summer air temperature in 2015 around the Hawaiian Islands was uniformly 1.2°–1.5°C warmer than the climatological mean, and this level of warming is around 3 times the standard deviation of temperature over the Hawaiian Islands (0.4°–0.5°C; Fig. 1d).

The above observational evidence suggests HST was abnormally high in 2015, but to what extent? Figure 2 shows the time series of HST and the number of heatwave days, from 1948 to 2015. We can see from the data that the summer of 2015 was the hottest for Hawaii for the 68 years. Furthermore, a record-high 98 exceptional heatwave days occurred during the summer of 2015. Note, however, that the HST index presents pronounced interannual variability and interdecadal variability. On the interdecadal time scale, there is a pronounced interdecadal changepoint during the early 1980s. Before the 1980s, HST was generally below the climatological mean but became higher than the climatological mean after the early part of that decade. The 2015 HST occurred in the positive phase of this interdecadal oscillation. On the interannual time scale, the 2015 HST happened to be a positive interannual peak. Thus, it is apparent that a positive phase of interdecadal HST and a positive peak of interannual HST jointly contributed to the record-high HST in 2015.

In summary, the extremely hot summer of 2015 over Hawaii arose directly from a combination of interannual and interdecadal HST variability. From Fig. 2, it is apparent that the interannual component was the fundamental contributing factor, accounting for a large part of the 2015 HST, whereas the interdecadal component contributed to a relatively smaller portion. Two questions therefore arise: 1) What are the characteristics of the circulation and SST field associated with the interannual and interdecadal component of HST? 2) How does the SST drive the variability of HST on these two time scales? In the following section, we report on our investigation of the underlying physical mechanisms of HST variability on the interannual and interdecadal time scales, respectively.

4. Mechanism for record-breaking HST

To search for some hints regarding the main driver behind the record-breaking HST, we first reviewed the climatological background during the Hawaiian local summer. Figure 3 shows the climatological-mean surface air temperature, 850-hPa wind, and outgoing
longwave radiation (OLR) field, along with the maximum SST region (>28°C) during JASO. Because of the cold temperature advection by the pronounced east/northeast trade winds, the Hawaiian Islands are relatively cooler than other regions at the same latitude. For instance, the JASO surface air temperature at Honolulu (21°19'N, 157°50'W), the capital city of Hawaii, is about 2°C lower than Hong Kong (22°15'N, 114°15'E), where temperature is around 27°C. The surface temperature zonal profile at 20°N (Fig. 3, bottom) clearly indicates that the temperatures from 120° to 160°W (including the Hawaiian Islands) are much lower than elsewhere, except for some mountainous regions. Thanks to Hawaii’s unique geographical position, a weakening/strengthening of the trade winds plays an influential role in changing HST. Thus, the determinant of the variation in the trade winds was our priority when attempting to understand the variation of HST in this study. Meanwhile, because the Hawaiian Islands are located in the tropics and dominated by the North Pacific subtropical high (NPSH) and downward vertical motion (suppressed convection) (Fig. 3), HST is also affected by the amount of downward solar radiation reaching the surface layer. The variation of downward solar radiation is directly related to cloudiness. As Nullet and Ekern (1988) indicated, changes in cloudiness may in turn produce a change in HST. Thus, the level of local solar radiation (cloudiness) change was another concern as we examined the variation of HST. Keeping these two concerns in mind, in the following subsections we highlight how the interannual and interdecadal variation of SST influence the local trade winds and solar radiation (cloudiness) and ultimately drive HST.

a. Physical mechanism for interannual HST variability

Because the interannual component contributed to the majority of the abnormal HST in 2015, we began by examining the physical mechanism underpinning the variability of HST at this time scale. The circulation and SST fields associated with the interannual variability of HST are plotted in Fig. 4. In Fig. 4a, positive surface air temperature anomalies appear in the tropical eastern/central Pacific and subtropical North Pacific along the west coast of North America, whereas negative temperature anomalies can be found around 40°N in Eurasia, the western North Pacific, and North America. The SST regression field (Fig. 4b) is quite similar to that of...
From Figs. 4c and 4d, we can see that enhanced precipitation and more clouds appear in the central equatorial Pacific, which is a response to the tropical eastern/central Pacific SST warming. However, over the tropical central North Pacific, where the Hawaiian Islands are located, the precipitation and cloud fields show no significant anomalous signal.

Associated with the anomalous interannual temperature pattern are the low-level westerly/southwesterly anomalies over the tropical central Pacific and central North Pacific (20°–40°N). As discussed above, this low-level wind anomaly is in the opposite direction of the climatological easterly/northeasterly trade winds over the Hawaiian Islands and leads to a warm advection. As shown in Table 1, on the interannual time scale, the temporal correlation coefficient (TCC) between the HST index and simultaneous central North Pacific trade wind index is 0.69, exceeding the 99% confidence level. The climatological trade winds advect cooler air to the Hawaiian Islands (Fig. 3), while a reduced trade winds situation suppresses the cold advection/ventilation effect, causing HST to be much warmer (Fig. 4a).

Thus, on the interannual time scale, the question of how the Hawaiian Islands become relatively warmer should be transferred into questioning why the east/northeast trade winds are weakened. As discussed above, a weakened trade winds situation is closely associated with the SST pattern over the Pacific. But which part of the SSTs is responsible for the weakened trade winds? Table 1 shows that the SSTs over the Niño-3.4 region are highly correlated with the trade wind index (with a TCC of 0.62) and HST index (with a TCC of 0.54), suggesting El Niño may influence HST. However, note that the SSTs over the eastern North Pacific are also closely related to the trade winds and HST, attaining a TCC of 0.67 and 0.92, respectively. Thus, we cannot simply conclude that El Niño is the major determinant for the variation of the trade winds in summer over Hawaii.

To examine which part of the Pacific SSTs plays an essential role in affecting the central North Pacific trade winds, four sensitivity experiments with specified SST forcing over different regions were conducted (see Table 2 for a description of the experiments). The first sensitivity experiment (sen_IA) was forced by the climatological SST plus the SSTAs in both the tropical and central North Pacific (Fig. 5a). The second sensitivity experiment (sen_IA1) was forced by the climatological SST plus negative SSTAs over the midlatitude western North Pacific (Fig. 5b). The third sensitivity experiment (sen_IA2) was forced by the climatological SST plus anomalous SST warming over the tropical central and eastern

![Fig. 2. Time series of the summer (JASO) HST index (°C; black line with open circles) and its interdecadal component (11-yr running mean HST index; magenta line) and interannual component (HST index with its 11-yr running mean anomalies removed; long dashed blue line), along with the number of summer (JASO) heatwave days (days; right-hand y axis; red bars) for the period 1948–2015. The blue dot indicates the year 2015.](http://journals.ametsoc.org/doi/pdf/10.1175/JCLI-D-16-0438.1)
Pacific (Fig. 5c). In the fourth sensitivity experiment (sen_IA3), the model was forced by the climatological SST plus a warming pattern over the subtropical and midlatitude eastern North Pacific (Fig. 5d). The specified SSTA patterns above were derived from the regressed SSTA field shown in Fig. 4b. The control run (ctrl_run) was forced by the climatological SST only.

Figure 5 shows the simulated 850-hPa wind response from the four sensitivity experiments. When the SSTAs in the tropical and North Pacific are specified (Fig. 5a), an anomalous low-level wind pattern similar to that observed (Fig. 4a) appears over the Pacific. A large-scale cyclonic circulation anomaly dominates over the North Pacific, which weakens the climatological NPSH. To the south flank of the anomalous cyclonic circulation, there are pronounced westerly winds over the central North Pacific, favoring an increase in HST. When only cooling SSTAs in the midlatitude western North Pacific are imposed, the circulation response is insignificant (Fig. 5b), suggesting such cooling SSTAs may be a passive result driven by the atmosphere. Note that in response to warming SSTAs in the tropical central equatorial Pacific (Fig. 5c), there are low-level westerlies (easterlies) to the west (east) of the positive SSTA center. The tropical SSTAs excite a so-called Pacific–East Asian teleconnection (Wang et al. 2000), with cyclonic and anticyclonic anomalies propagating from the central/eastern tropical Pacific to the western North Pacific. However, the Hawaiian Islands in this case are dominated by weak easterly anomalies (Fig. 5c), which are not favorable for a warming of HST.

Figure 5d illustrates the 850-hPa wind response to the positive SSTAs in the subtropical and midlatitude eastern North Pacific. To the west of the positive SSTAs over the subtropical eastern North Pacific, a low-level cyclonic anomaly is induced, leading to southwesterly anomalies over Hawaii. Two possible mechanisms may explain this circulation anomaly response to the positive SSTAs. First, the low-level circulation anomaly is a Gill–Matsuno-type response (Matsuno 1966; Gill 1980) to the positive SSTAs. However, this interpretation may be speculative because the observed convection (Figs. 4c,d) induced by the positive SSTAs over the northeastern Pacific is not significant or in large scale. The second mechanism highlights the anomalous SST gradient (Lindzen and
in the boundary layer. Because of the warming over the northeastern Pacific, the SST gradient becomes weakened. Therefore, the trade wind becomes weakened and a southwesterly anomaly appears. Both of these suggested physical mechanisms still need to be further verified through more diagnosis of model outputs. Because of the cyclonic circulation response to the positive eastern North Pacific SSTAs, the Hawaiian Islands are dominated by westerly/southwesterly wind anomalies (weakened trade winds), leading to a positive temperature anomaly over Hawaii. This sensitivity experiment suggests an importance of the warming SSTAs in the subtropical and midlatitude eastern North Pacific in reproducing observed westerly/southwesterly anomalies over the Hawaiian Islands.

Thus, for the interannual time scale, the simulation results reported above indicate that the summer trade winds over the Hawaiian Islands are greatly influenced by the subtropical and midlatitude eastern North Pacific SSTAs, rather than the tropical SSTAs in the Niño-3.4 region. The weakened trade winds act to warm the surface air temperatures around the Hawaiian Islands through a reduction of the cold advection/ventilation effect.

But is the above finding applicable in every observed hot and cold Hawaiian summer? Fig. 6 shows the anomalous Pacific SSTA pattern in five extremely high HST years (Fig. 6, left) and five extremely low HST years (Fig. 6, right), based on the interannual component of HST (Fig. 2). From Fig. 6 (left), we can see that, when HST is extremely high, the subtropical and midlatitude eastern North Pacific SSTAs are always positive.
with a cyclonic circulation anomaly appearing over the North Pacific where the climatological NPSH is located. Over the south of the anomalous cyclonic circulation, the Hawaiian Islands are always dominated by the anomalous westerly/southwesterly (weakened trade winds). In stark contrast, when HST is extremely low (Fig. 6, right), the midlatitude eastern North Pacific SSTAs are always negative, driving an anticyclonic circulation anomaly over the North Pacific. Hawaii is controlled by the easterly/northeasterly (enhanced trade winds). Note that the SSTAs over the tropical central/eastern Pacific and midlatitude eastern North Pacific are not necessarily in phase, although their correlation coefficient is 0.55 (Table 1). In high HST years, while the midlatitude eastern North Pacific is positive, the SSTAs over the central/eastern tropical Pacific can be negative, such as

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<th>Expt name</th>
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<td>ctrl_run</td>
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<td>sen_IA</td>
<td>Climatological SST plus SSTAs over both the tropical and North Pacific (10°S–60°N, 120°E–80°W) in JASO in Fig. 4b</td>
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<td>sen_IA1</td>
<td>Climatological SST plus anomalous cooling over the midlatitude western North Pacific (30°–60°N, 120°E–140°W) in JASO in Fig. 4b</td>
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<td>sen_IA2</td>
<td>Climatological SST plus anomalous warming over the tropical central and eastern Pacific (10°S–10°N, 160°E–80°W) in JASO in Fig. 4b</td>
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<td>sen_IA3</td>
<td>Climatological SST plus anomalous warming over the subtropical and midlatitude eastern North Pacific (10°–60°N, 160°E–100°W) in JASO in Fig. 4b</td>
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<td>sen_ID</td>
<td>Climatological SST plus SSTAs over the IPW (20°S–30°N, 40°–160°E) and TNA (20°S–30°N, 90°W–20°E) in JASO in Fig. 7b</td>
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Fig. 5. The simulated summer (JASO) 850-hPa wind response to regional SSTA forcing (°C; shading) with (a) both cooling and warming in the tropical and North Pacific, (b) a cooling in the midlatitude western North Pacific, (c) a warming in the tropical central and eastern Pacific, and (d) a warming in the subtropical and midlatitude eastern Pacific. Only winds significant at the 95% confidence level are shown, and the dashed blue rectangle indicates the Hawaiian Islands, as shown in Fig. 1.
in 1996, whereas, in low HST years, when the midlatitude eastern North Pacific is negative, the SSTAs over the central/eastern tropical Pacific can be positive, such as in 2012.

Therefore, based on observation and simulation, on the interannual time scale we conclude that the trade winds and HST are mainly determined by the subtropical and midlatitude eastern North Pacific SSTAs,
rather than the central/eastern tropical SSTAs. One may ask whether sensible heating also contributed to the record-high HST in 2015, given the abnormal warming SSTAs around Hawaii. To answer this question, and to quantitatively examine the relative importance of horizontal temperature advection and sensible heat flux to the record-high HST in 2015, we calculated a thermal budget over the Hawaiian region (figure not shown). The results indicated that the anomalous upward long-wave radiation cooling (which is proportional to the fourth power of surface air temperature, according to the Stefan–Boltzmann law) in 2015 was mainly balanced by the warm anomalous temperature advection, and the contribution of sensible heat flux was so small that it could be omitted. According to the empirical formula of Smith (1988), sensible heating is mainly determined by surface wind speed and the air–sea temperature difference. Note that, because of the small air–sea temperature difference over Hawaii, the climatological-mean sensible heating flux is quite small. For the summer of 2015, the wind speed was weakened because of the weakened trade winds, so it is understandable that the sensible heating flux was even less than that of the climatological mean. Therefore, we conclude that the sensible heating flux was not important for the record-high HST in the summer of 2015 over Hawaii.

b. Physical mechanism for interdecadal HST variability

The interdecadal component was the secondary contributor to the abnormal HST in 2015. Figure 7 shows the circulation and SST composite differences between the periods before and after the early 1980s (the 1985–2015 mean minus the 1948–78 mean). In Fig. 7a, there is a nearly uniform positive anomalous surface air temperature throughout the whole of the tropics (from 20°S to 20°N). The most significant and largest warming appears in the Indo-Pacific warm pool (IPW) and tropical North Atlantic Ocean (TNA). Cooling signals appear in the subtropical Asian continent and central North America. The cooling over subtropical Asia and the warming over the Indian Ocean leads to a reduced land–sea thermal contrast during boreal summer. This results in a weakened East Asian summer monsoon, which is characterized by low-level northeasterly anomalies along the East Asian coast and an anomalous

Fig. 7. The composite difference (1985–2015 mean minus 1948–78 mean) for (a) surface air temperature and 850-hPa wind, (b) SST, (c) precipitation, and (d) total cloud, during summer (JASO). Red dots indicate the area passing the 95% confidence level, and only winds significant at the 95% confidence level are shown. The dashed blue rectangle indicates the Hawaiian Islands, as shown in Fig. 1.
Anticyclone over the Asian continent (Fig. 7a). The SST composite differences show a pattern that is reasonably consistent with that of the surface air temperature (Fig. 7b). Uniform positive anomalies are confined to the tropical oceans, with significant warming over the IPW and TNA. From the interdecadal rainfall and total cloud anomaly fields (Figs. 7c,d), we can see clearly that there are two large-scale anomalous convective regions—one over the IPW region and the other over the oceans around Mexico/the TNA. Comparing the cloudiness pattern (Fig. 7d) with the SSTA pattern (Fig. 7b), it is possible that the significantly warm IPW and TNA SSTAs may play active roles in triggering the rainfall/cloud anomalies over the two regions. In contrast, in the central North Pacific, negative rainfall anomalies and negative cloudiness are collocated with the warm SSTAs. This implies that the SSTAs on the central Pacific are a result of atmospheric forcing (due to increased downward shortwave radiation), not a cause of reduced rainfall and cloud. The Hawaiian Islands are situated directly under the reduced cloud-cover region in the central North Pacific (Fig. 7d).

The observational analyses suggest that suppressed convection over the central North Pacific is likely a result of warm-SSTA remote forcing over both the IPW and TNA, through driving an anomalous zonal circulation. But why do the SSTAs in the IPW and TNA play an active role while the tropical central Pacific SSTAs play a passive role? Such a region-dependent SSTA forcing feature may largely depend on the SST seasonal-mean state. As shown in Fig. 3, a high JASO-mean SST (>28°C) appears over the IPW and TNA, whereas the equatorial central/eastern Pacific is the cold-tongue region. Even given the same warm-SSTA forcing, convection is likely to be enhanced over the Maritime Continent and oceans around Mexico/the TNA, where the maximum SSTs are located. In addition, the interdecadal SSTAs, observationally, are also most pronounced in the IPW and TNA (Fig. 7b). This is why the SSTAs in these two regions play active roles in driving atmospheric circulation (rainfall and cloud) anomalies. As such, because of the SSTA forcing over the IPW and TNA, the greatly suppressed precipitation and reduced clouds are confined to the central North Pacific (Figs. 7c,d) via anomalous zonal overturning circulation. To further examine this assertion, the normalized 11-yr running area-mean SSTs over the tropical IPW and TNA and the corresponding atmospheric variables averaged over the central North Pacific are plotted in Fig. 8a. The data show that the SSTs of both basins feature an interdecadal change around the early 1980s. In turn, all the variables over the central North Pacific show a pronounced interdecadal turning around the same time. From the pre-1980s to the post-1980s, the IPW and TNA SSTs persistently increased. Consistent with the increased SSTs over the two basins is the increased omega (descending anomalies) over the central North Pacific. The anomalous descending motion suppressed the convection and cloud, thus leading to increased downward solar radiation, which warmed the Hawaiian Islands after the early 1980s. Figure 8b shows the composite difference (the 1985–2015 mean minus the 1948–78 mean) of the longitude–vertical section (10°–25°N) of circulation (m s⁻¹; vectors) during summer (JASO). The omega is multiplied by −100 to denote the vertical motion, which is the vertical direction of the vector, whereas the horizontal direction of the vector is the zonal wind; shading is the omega significant at the 95% confidence level. The red triangle indicates the location of Hawaii.
oceans around Mexico, whereas pronounced descending motion appears over the central North Pacific, where the Hawaiian Islands are located. Again, the suggestion is that the interdecadal increase in HST is related to the increase (decrease) in downward solar radiation (cloudiness), via the anomalous zonal circulation driven by the elevated SSTs over the IPW and TNA.

To validate this IPW–TNA SSTA remote forcing mechanism, we carried out an AGCM sensitivity experiment (sen_ID) with imposed SSTAs forcing over both the IPW and TNA. Figure 9a plots the atmospheric response to the IPW–TNA SSTA forcing. As expected, enhanced convection (negative OLR anomalies) appears over the Maritime Continent and oceans around Mexico/the TNA, with pronounced westerly flow over the central/eastern equatorial Pacific and easterlies over the tropical Indian Ocean and continental Africa. Because of the enhanced convection over these two basins, suppressed convection appears over the central North Pacific, leading to increased downward solar radiation there and thus a warming over the Hawaiian Islands. Figure 9b shows the zonal profile (averaged over 10°–25°N) of the circulation response to the IPW–TNA SSTA forcing. Albeit not exactly the same as the observation shown in Fig. 8b, the AGCM generally reproduced the two branches of ascending motion over the Maritime Continent and Atlantic Ocean, and the descending motion in between.

Thus, from both observation and simulation, we suggest that the interdecadal increase in HST was mainly driven by the increased SSTs over the IWP and TNA through anomalous zonal circulation. Note, however, that in our sensitivity experiment, since only the IPW and TNA SSTA forcing were added, some differences existed in the convection pattern compared with that observed. And because no boundary forcing over land was specified, the weakened East Asian monsoon with dominant northeasterly flow could not be captured by the AGCM.

5. Conclusions and discussion

The surface air temperature in the summer (July, August, September, and October) of 2015 in Hawaii was the highest since records began in 1948. The summer-mean surface temperature was about 1.5°C warmer than the climatological mean. Furthermore, during that summer, there were 98 local heatwave days, which was also the highest number for nearly seven decades. The extremely hot summer of 2015 over the Hawaiian Islands came about as a result of the combined contribution of a positive phase of interdecadal variability and a positive peak of interannual variability of HST. The interannual component was the leading factor, accounting for a large part of the abnormally high HST that year, while the interdecadal component was the secondary factor. The interannual variability of HST is linked to positive SSTAs over the tropical central/eastern Pacific and subtropical/midlatitude eastern North Pacific and negative SSTAs over the western North Pacific. The interdecadal variability of HST, meanwhile, is associated with a uniform positive SSTA pattern over the tropics, with significantly large amplitude appearing in the IPW and TNA. From observational diagnosis, we hypothesized that the positive interannual HST is related to the weakened trade winds over the tropical central North Pacific, driven by the Pacific SSTA pattern, whereas an interdecadal increase in HST is caused by reduced cloudiness and increased downward solar radiation.
radiation over the central North Pacific, driven by warm SSTAs in both the IPW and TNA.

Numerical experiments were carried out to validate the physical mechanisms for the variability of HST on these two different time scales. For the interannual time scale, because HST is influenced by the trade winds over the Hawaiian Islands via the ventilation effect/cold advection, four sensitivity experiments were performed to understand the relative roles of tropical and extratropical SSTAs in inducing anomalous low-level wind over the Hawaiian Islands. The simulations showed that the warming in the subtropical and midlatitude eastern North Pacific, rather than warming at the equator, is crucial in determining the trade wind anomalies over the Hawaiian Islands. Thus, the interannual variability of HST and the associated trade winds is mainly determined by the SSTAs over the subtropical and midlatitude eastern North Pacific. For the interdecadal variability of HST, one sensitivity experiment with imposed SSTAs over both the IPW and TNA was performed. The result showed that the IPW and TNA SST warming enhances the convection over these two regions, leading to a subsidence anomaly over the central North Pacific. The subsidence further reduces the total cloud cover and increases the amount of downward solar radiation, thus creating a warming over the Hawaiian Islands.

The present study provides two useful clues for the seasonal prediction of HST. First, because the interdecadal variability of HST is closely related to the SSTAs over the IPW and TNA, attention should be paid to the secular change of SSTs over these two basins when conducting an empirical model for the seasonal prediction of HST. Second, because of the high TCC (0.54) between SSTs in the Niño-3.4 region and HST, El Niño may be wrongly selected as a potential predictor for HST. During the Hawaiian local summer (JASO), although the Niño-3.4 SSTs have a significant relationship (0.62) with local trade winds over Hawai‘i, the Niño-3.4 SSTs are not necessarily the origin of the variation in the trade winds and surface air temperature in summer over Hawaii. As indicated in the present study, from both observation and simulation, it is in fact the SSTAs over the subtropical eastern North Pacific, rather than the Niño-3.4 region, that determine the central North Pacific trade winds and HST.

Of note is that our conclusions regarding the roles of SSTAs in driving the large-scale circulations are based solely on the Hawaiian summer season (JASO). The atmospheric responses to the same SSTAs can be quite different during different seasons because of the independent seasonal-mean states (Zhu et al. 2014; Zhu and Li 2016). So far, the causality between the SSTAs over the Niño-3.4 region and the subtropical eastern North Pacific remains unknown. Is the subtropical eastern North Pacific warming a result of El Niño discharging from the equator (Jin 1997)? Why are the SSTAs over the Niño-3.4 region and subtropical eastern North Pacific out of phase in certain years? Understanding the formation of the subtropical midlatitude SSTAs remains a challenging issue.

Previous studies have mainly focused on the climatic influence of tropical SSTAs. However, as demonstrated in the present study, subtropical SSTAs may also exert considerable impacts. The effects of regional SSTAs may partially explain why El Niño or the PDO are not always correlated with Hawaiian rainfall and temperature, as mentioned in many previous studies (Chu 1989; Giambelluca et al. 2008; Jayawardena et al. 2012; Safeeq et al. 2013; O’Connor et al. 2015). It is anticipated that the subtropical eastern North Pacific SSTAs could not only influence Hawaii but also have an impact on the west coast of North America. Whether there is a link between the subtropical eastern North Pacific warming and the recent California droughts (Swain 2015) is an interesting topic that merits further investigation.

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