Climate variability of heat waves and their associated diurnal temperature range variations in Taiwan

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Abstract

This study investigates heat waves in Taiwan and their maintenance mechanism, based upon observations and dynamically downscaled simulations. A 95th percentile threshold is used for identifying hot extremes over a period of consecutive days. Heat waves are forecast to become more severe in the future projection. Daily minimum temperatures are generally high and diurnal temperature ranges (DTR) are relatively large. The daily minimum temperature serves as the primary control in the variation in DTR during heat waves. An apparent increase in the daily minimum temperature suggests elevated heat stress at nighttime during future heat waves. Heat waves in Taiwan are associated with abnormal warming and drying atmospheric conditions under the control of an enhanced western North Pacific subtropical high. The surrounding waters serve as a vast moisture source to suppress the drying magnitude in the surface layer as the temperature rises, thereby ensuring a high humidity level during the hot spell. The subsidence and adiabatic warming above can trap the warm and humid air in the surface layer, leading to positive feedback to the abnormally hot surface condition. The associated warming and drying atmospheric conditions cover certain spatial extents, suggesting that the extreme situation identified here is not confined to just an island-wide hot spell; the abnormal hot weather can take place across a broad geographical area.

1. Introduction

Severe hot temperatures contribute to human mortality and cause widespread impacts on natural and socio-economic environments. The fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC 2013) indicated that the number of warm days and nights has increased on the global scale and the frequency of heat waves has increased in large parts of Europe, Asia and Australia. The report declared a high human contribution to the observed global-scale changes in the frequency and intensity of daily temperature extremes since the mid-20th century, and to the increased occurrence of heat waves in some locations. Extensive studies have indicated a high probability of more intense, longer lasting and/or more frequent heat waves in the future (Meehl and Tebaldi 2004, Schär et al 2004, Della-Marta et al 2007, Kuglitsch et al 2010, Perkins et al 2012, IPCC 2013, Lewis and King 2015). Heat waves are generally associated with persistent high-pressure and anticyclonic circulation patterns that dynamically produce large-scale subsidence, and thereby facilitate prolonged hot conditions at the surface (Meehl and Tebaldi 2004, Lau and Nath 2012, Pezza et al 2012, Lee and Lee 2016, Wang et al 2016, Wang et al 2017). The western North Pacific subtropical high (WNPSH), an important component of the East Asian summer monsoon system, plays a major role in regulating the summer monsoon rainfall and tropical storm activities over the western North Pacific (e.g. Tao and Chen 1987, Kurihara 1989, Chang et al 2000, Ding 2007, Huang et al 2012). The anomalous WNPSH is a major cause of climatic extremes, such as flooding, drought, and heat waves in the region. The summer high temperature extremes in China have been attributed to the variation of WNPSH (Hu et al 2011, Hu et al 2013, Wang et al 2014, Wang et al 2016, Wang et al 2017),
which could be further linked to the El Niño–southern oscillation as well as the tropical Indian Ocean warming (Hu et al 2011, Hu et al 2013, Wang et al 2014). However, studies of WNPSH in the future climate based on model projections are inconclusive (e.g. Li et al 2012, Seo et al 2013, He et al 2015). Understanding the source of variability and predictability of WNPSH is important for predicting the climate and weather, as well as climatic extremes in East Asia (e.g. Park and Schubert 1997, Kosaka et al 2012, Wang et al 2013).

Relatively little work has been done in relation to the heat waves in the coastal areas and islands of subtropical Asia, where the climate is warm and humid, and the majority are at elevated risk of increased population density and energy demand over the last decade. More specifically, there is still a gap in the scientific analysis of the occurrences and physical causes of present day and future heat waves to provide information for proposing mitigation and adaptation strategies to cope with the increasing threat of climate change. In this work, Taiwan is taken as an example for investigating the heat waves in the heavily urbanized coastal zones of subtropical Asia. Taiwan is a mountainous island located off the southeast coast of China in the East Asia monsoon region. With more than 200 mountain summits at over 3000 meters above sea level, the island has the most precipitous and complex terrains of the area (figure 1, top).

![Figure 1](image.png)

**Figure 1.** Top panel: location and topography of Taiwan. Bottom panel: composite daily maximum temperature of all heat wave days among four data sets. From left to right, composite temperature of heat waves obtained from the gridded observation data set (TCCIP), and WRF dynamically downscaled simulations driven by NCEP/CFSR or ECHAM5/MPIOM. The right most is for future projection (2075–2099) and the rest are for recent past (1979–2003) simulations.
models (GCMs) at hundreds, or even tens, of kilometers resolution. Regional high-resolution downscaling of coarse GCMs can generate more detailed information regarding local climate and high-impact weather events, and their potential future changes, by accounting for topographical influences from mountains, lakes, and coastlines (Leung and Wigmosta 1999, Salathe et al 2008, Feser et al 2011, Lin et al 2015, Notaro et al 2015, Kitoh et al 2016). The present study intends to identify the heat waves in Taiwan and their relevance to the anomalous WNPSH using observations and dynamically downscaled simulations and future projection. We will also explore the extent to which the anomalous conditions identified here are not confined to just an island-wide hot spell, but that the abnormal hot weather can take place across a broad geographical area.

2. Data and method

The downscaling is performed using the weather research forecasting (WRF) model (Skamarock et al 2008) with 5 km grid spacing. Both recent past (1979–2003) and future (2075–2099) simulations are conducted. Taking the National Centers for Environmental Prediction/Climate Forecast System Reanalysis (NCEP/CFSR, Saha et al 2010) and the IPCC AR4 global simulation with the ECHAM5/MPIOM model system at T63 resolution (Roecckner et al 2003) as boundary conditions, two sets of downscaled simulations are carried out respectively for the recent past period, and are hereafter referred to as NCEP-wrf and ECHAM5-wrf. The ECHAM5 model output under the A1B emissions scenario is used as the global driver for the downscaled future projection, and is hereafter referred to as ECHAM5-wrf.future. Details of the model description and downscaling configuration can be found in Lin et al (2015), in which the authors reveal both altitudinal and latitudinal variations in the warming trend over Taiwan. Although the set of models used in AR4 (the CMIP3 models) have been superseded by the CMIP5 models and the SRES scenarios have been replaced by the four RCPs in AR5, some of the AR5’s contents is still referenced to the CMIP3 simulations. Using radiative forcing (RF) as a metric, the AR5 report shows that the RF for several of the SRES (e.g. A1B) and RCP scenarios (i.e. RCP 6.0 and RCP 8.5) are similar over time (Cubasch et al 2013, their figure 1.15). In addition, the global climate model ECHAM5 has been upgraded to ECHAM6 for CMIP5. The response of ECHAM6 to increasing concentrations of greenhouse gases is, however, similar to that of ECHAM5 (Stevens et al 2013). Thus we believe that the use of a future projection conducted with an old scenario (A1B) and an old version of the global climate model should still provide results that can be used to compare climate modelling studies. A set of uniform gridded surface temperatures over the island provided by the Taiwan Climate Change Projection and Information Platform (TCCIP, https://tccip.ncdr.nat.gov.tw/ds/) project is employed as reference data for the downscaled simulations for the recent past. This dataset, provided at 1 km resolution, is constructed using more than 300 monitoring stations from multiple data sources (Central Weather Bureau, Water Resources Agency, Irrigation Association, and Taiwan Power Company). The dataset is hereafter referred to as TCCIP.

A percentile-based definition is applied for identifying heat waves from across the four datasets (TCCIP, NCEP-wrf, ECHAM5-wrf, and ECHAM5-wrf.future). We use the downscaled temperature at two meters to represent surface temperature. For each dataset, a set of daily maximum temperature index ($T_{\text{max}}$) is derived by averaging the daily surface maximum air temperature over plain areas (altitude < 500 m) in Taiwan. A hot day threshold is then determined upon the respective 95th percentile of this set of $T_{\text{max}}$. A subset of hot days is found as the corresponding $T_{\text{max}}$ exceeding their respective 95th percentile for the period. From across each subset of hot days, any hot spell lasting at least three consecutive days is defined as a heat wave event. Consequently, four subsets of heat waves can be identified from among the four sets of $T_{\text{max}}$ figures, and we term the days within each subset as heat wave days. The use of the threshold calculated from each individual dataset allows us to identify heat waves apart from the usual weather and normal temperatures for that particular dataset. In addition, four sets of daily minimum temperature index ($T_{\text{min}}$) are calculated as of the $T_{\text{max}}$, but using the plain-averaged daily surface minimum air temperature from each dataset. The $T_{\text{max}}$ and $T_{\text{min}}$ are then used for calculating the diurnal temperature range (DTR) for their respective dataset. For each dataset, there are 457 hot days defined from 9131 daily $T_{\text{max}}$ samples. The resulting numbers of heat wave days are 324 (TCCIP), 272 (NCEP-wrf), 268 (ECHAM5-wrf), and 276 (ECHAM5-wrf.future). The heat waves identified in this work occur primarily in the summer (June–August, JJA) despite the use of $T_{\text{max}}$ from across all seasons in our definition. Daily anomaly fields are all calculated with respect to their summer (JJA) climatology upon the respective study period. Finally, we follow Grotjahn and Faure (2008) in the use of the bootstrap method to assess the statistical significance of the composite fields of heat wave days.

3. Temperature distribution

The composite daily maximum temperature of heat waves presents a pattern that mirrors the topography (figure 1), with relatively high maximum temperatures found over plains, a strong gradient, and altitude over mountains. The temperature distribution is apparently shaped by the topography. The coarse resolution of the
global model is inadequate to resolve the complex geographic nature of Taiwan. The dynamic downscaling employed here achieves a fine-scale representation of the complex relief in Taiwan, and the response of topographical forcing as well. Further details regarding the improved simulation of surface temperatures resulting from the more accurate representation of the fine-scale topography can be found in Lin et al. (2015), our previous article based on the same set of downscaled simulations as used here. A high similarity is found among the four composites of temperature, indicating that the downscaled simulations can reproduce the spatial pattern of daily maximum temperatures during heat wave events in Taiwan. Among the three simulations, however, NCEP-wrf produces strikingly similar spatial features at the localized scale. We conducted the significance test for each composite map; 1000 bootstrap samples were generated from JJA for each grid at its native resolution. For all composite maps, all the Taiwanese land points pass their respective 99% significance test, including the mountain area (figure not shown). Therefore, the use of the plain-averaged $T_{\text{max}}$ can identify an island-wide high temperature event. As compared with the heat wave composite in the recent past (ECHAM5-wrf), the dominant features of the spatial pattern remain similar and become much warmer in the projected composite (ECHAM5-wrf future). This result suggests that the localized distribution of temperature along with the island-wide warming is not overly affected by the large-scale boundary forcing, but is controlled by interactions between the large-scale circulations with the local geographical features. Questions thus arise as to whether a consistent circulation regime in association with heat waves exists among the four datasets, and to whether the heat wave mechanism changes in response to climate warming.

A high similarity in the probability distribution shapes are again found among the four datasets (figure 2,
The $T_{\text{max}}$ distributions of heat waves exhibit a strong right-skewed pattern (solid lines), whereas those of the summertime present a slight left-skewed pattern (hatched areas). Moreover, the $T_{\text{max}}$ distributions of the four heat waves have been shifting to the high temperature spectrum in their respective summertime distribution. The $T_{\text{min}}$ of the heat waves show distinct variability from that of the $T_{\text{max}}$ presenting a slightly left-skewed or nearly symmetric distribution (dashed lines). This discrepancy in variability results in a distinct dependence of the diurnal temperature range (DTR) on the $T_{\text{max}}$ and $T_{\text{min}}$. We will address this in a later paragraph. The major differences in the temperature distribution among the four datasets are the shift along the axis, not the shape. The distinct warm shift of the projected distributions is indicative of the future changes in summertime and heat waves, which we may ascribe to the changes in the mean but not in higher moments at this island-wide scale. Several recent studies have also demonstrated that changes in high temperature extremes are primarily as a result of the shift in the mean and not a result of changes in higher moments (Lau and Nath 2012, Rhines and Huybers 2013, Weaver et al 2014).

We further quantitatively inspect the temperature distributions with box-and-whisker plots (figure 2, bottom). First look at the similarity among datasets. The distributions of heat waves and hot days reside above their respective 75th percentile (the third quartile) of summertime temperatures, indicating that their occurrences are abnormal and temperatures are high. Their highly overlapping distributions clearly reveal that our definition attempts to separate heat waves from short lasting hot days, but not to identify the most extreme hot days from across the dataset. We then draw our attention to the difference in the hot-day thresholds (i.e. the 95th percentile of $T_{\text{max}}$, see the lowest temperature end of the whiskers in hot-days subsets). The warm shift in the future hot-day threshold is obvious. Should a unique hot-day threshold based upon the past climate from either TCCIP or ECHAM5-wrf be adopted, then up to 70% of the future summer days would count as hot days, suggesting that the current abnormal conditions would become normal in the future. A flexible hot-day threshold, perhaps, is appropriate for proposing mitigation strategy for future extreme conditions under a changing climate where socio-economic status and human physiological acclimatization also change. Although the frequency of heat wave occurrence cannot be assessed here, owing to our definition, the apparent warm shift of the future temperature distribution indicates that heat waves are becoming more severe. We found a small increment of about 0.13°C for the inter-quartile in the future $T_{\text{max}}$ as against that in the past. The degree of this variability increase is much smaller than the increments of 2.7°C, 2.6°C and 2.9°C for the corresponding mean, median and 95th percentile, respectively. Recent studies have indicated that small temperature variability changes can play an important role in intensifying future heat waves (Schär et al 2004, Fischer and Schär 2010); our finding is, however, inconclusive for the issue. For the differences among the three recent past datasets, the NCEP-wrf presents a cold bias and ECHAM5-wrf shows a comparable temperature spectrum against the TCCIP. A close inspection of the dates of heat waves in NCEP-wrf reveals that nearly 57% (70%) of them are also listed in the TCCIP heat waves (hot days) subset. Whereas less than 20% of the heat waves in ECHAM5-wrf match the hot days in TCCIP. The highly overlapping heat wave dates indicate that dynamically downscaled NCEP reanalysis can well reproduce the heat waves in Taiwan, despite the relatively cold JJA climate. The ECHAM5-wrf provides a comparable temperature spectrum, but may only be able to poorly simulate the temporal phase of synoptic activities and thus result in a low hit rate of the heat wave dates.

4. Diurnal temperature range

We use the DTR as a metric to assess the heat waves and the future change (figure 3). On the basis of JJA distribution, the DTR increases with $T_{\text{max}}$, demonstrating that solar heating is the primary driver. The relationship between summertime DTR and $T_{\text{min}}$ is less clear. During heat waves, $T_{\text{max}}$ are generally high and the monotonic relationship with DTR is no longer observed, and $T_{\text{min}}$ serve as the primary control of DTR variation instead. We note the relatively large DTR and high $T_{\text{min}}$ found during heat waves. The nighttime temperatures are also high during an abnormal hot spell, implying that a DTR in which people experiencing normal weather consider moderate can become uncomfortable under the stress of heat waves. The means of downscaled DTR during heat waves are all smaller than that of the TCCIP (indicated by vertical grey lines in each panel). We find no trend in the DTR in the future projection, given the similar increasing magnitudes of $T_{\text{max}}$ and $T_{\text{min}}$. The underestimated $T_{\text{max}}$ and overestimated $T_{\text{min}}$ is the major source for the biased DTR in NCEP-wrf and ECHAM5-wrf, respectively. As a subtropical island, hot nights in Taiwan are usually humid because warmer air can carry more water vapor than cooler air, and there is plenty of water available in the surroundings. We speculate that the model representations of cloud cover and surface processes are responsible for such biases. For example, the cloud cover can suppress solar heating in the daytime but increase long wave radiation at nighttime. The incorporation of urbanization scenarios in simulating a changing climate would also improve the diurnal variations during heat waves. Recently, Wang et al (2017) revealed that the urbanization effects on the warming in daily minimum temperature are amplified during heat waves. Furthermore, projections of both
the possible future scenario and climate change using a fully coupled economics-earth system model would be of help to account for human activities in a warming climate, as suggested by Yang et al. (2016).

Heat waves are becoming more frequent and severe. During future heat waves, a large majority of $T_{\text{min}}$ fall within the lower spectrum of daytime maximum, as shown in figure 3. This could have more serious impacts because people in this area are not currently as well adapted to such hot nights. A high daily minimum temperature suggests insufficient relief of heat stress at nighttime during an abnormal hot spell. Anderson and Bell (2009) suggested that a sustained period of extreme heat presents an elevated risk over single days of high temperatures, and therefore both the duration and intensity of the heat wave can increase the risk of mortality. When extreme maximum temperatures are coupled with extreme high dew point temperatures, the nighttime recovery is reduced. As human heat stress is associated with atmospheric heat content contributed by both temperature and humidity, deaths can be attributed to abnormally hot and humid nights, and nighttime urban warming can enhance the heat stress during a heat wave. Consecutive days of high temperatures further increase the risk of heat-related morbidity and mortality and incidences of heat stress and stroke. In short, the combination of high temperature and high humidity can provide a relatively complete description of hot extremes in humid regions, such as Taiwan, and the apparent increase in the daily minimum temperature suggests elevated heat stress at nighttime during future heat waves.

5. Circulation regime

Heat waves in Taiwan are associated with abnormal warming and drying atmospheric conditions under the control of enhanced WNPSH. Figure 4 presents the composite meteorological fields of heat waves, the major spatial patterns generally consistent across datasets. During heat waves, the westward intrusion (TCCIP and NCEP-wrf) or southwestward retreat (ECHAM5-wrf and ECHAM5-wrf.future) of the ridge of WNPSH results in a positive geopotential height anomaly centered near Taiwan (figure 4, bottom panels). The height anomaly shows boarder coverage, compared with the small island of Taiwan, extending from southeastern China to the seas south of Japan.
A comparable area of warm temperature anomaly, with the anomalous center shifts slightly northward from Taiwan, is accompanied by the height anomaly. A drying (negative) relative humidity anomaly is found to be centered at Taiwan. These major anomalous patterns are all statistically significant at 99% of the confidence level (figure S1 in the supplementary information available at stacks.iop.org/ERL/12/074017/mmedia). The abnormal warming and drying conditions also exhibit a certain vertical extension (figure 4, top panels). The positive height anomaly found throughout the troposphere is presumably a combined consequence of the westward intrusion of WNPSH in the mid- to low-levels and the eastward extension of the South Asian High above (figures not shown). The enhanced summertime high pressure systems both accompany this with enhanced large-scale subsidence (figure not shown) and warm temperature anomalies in the vertical. Relative humidity exhibits a deep layer of drying structure. In the free atmosphere above the boundary layer, the relative humidity reduction can be ascribed to adiabatic warming and drying due to large-scale subsidence and insufficient horizontal moisture supply. In the lower boundary layer, the specific humidity increment can suppress the reduction of relative humidity as the temperature rises. The largest specific humidity increment appears at the surface, of which the coverage area is nearly overlapping that of the warm temperature anomaly over the East Asian sector (see also figure S1 in supplementary information). We speculate that the moisture content increase is in response to temperature rise in the boundary layer, and the vast majority is supplied from the underlying surface. The specific humidity increment in the surface layer is supporting evidence that hot conditions in Taiwan are accompanied by high moisture content, as previously mentioned. The subsidence and adiabatic warming above can however act to stabilize the lower atmosphere and trap the warm and humid air in the surface layer, leading to positive feedback to the abnormally hot surface condition. This thermodynamic regime ensures the maintenance of consecutive days of high temperature and high humidity, leading to an accumulated risk of human heat stress. The major anomalous pattern, as well as the dominance of WNPSH variation, and the relevant thermodynamic processes remain true for all datasets, including that of the future, suggesting a robust mechanism of heat waves in Taiwan.

Figure 4. Composite anomalies of all heat wave days for each dataset (from left to right). Top panels: vertical profiles of geopotential height (m), specific humidity (g kg⁻¹), relative humidity (%), and temperature (°C) anomalies averaged over an area centered at Taiwan (118–125°E, 19–27°N). Here the values of temperature and specific humidity anomalies have been increased by a factor of ten for the purpose of plotting. Middle panels: 850 hPa temperature (shaded) and relative humidity (green and yellow contours for positive and negative values, respectively, starting with +4 and −4 at an interval of 2%) anomalies. Bottom panels: 850 hPa geopotential height (shaded) anomalies. The thick contours in the middle and bottom panels are composites of geopotential height for heat wave days (black) and JJA geopotential height climatology (grey); selected contour lines shown are 1490, 1500, 1510, and 1520 m. Daily anomalies are calculated relative to 1979–2003 and 2075–2099 mean summer (JJA) values for recent past and future, respectively. Statistical significances of these composite anomalies are given in figure S1 in the supplementary information; the locations of the averaged area for top panels are shown therein.
In a recent study, Wang et al (2016) proposed that heat waves in southeastern China are associated with southward intensification of the WNPSH and southward displacement of the East Asian jet stream. Their heat waves of 2003 are found in our heat waves listed in TCCIP and NCEP-wrf. Therefore, the associated large-scale anomalous pattern identified in our work is not confined to local heat waves at an island-wide scale, but can be applied to a broader area in the East Asian monsoon region. Moreover, the positive height anomaly found in this work is associated with a negative height anomaly to the north (figure 4, bottom). Although the magnitudes of these anomalies vary across the datasets, a north–south dipole structure can still be identified. A similar height anomalous pattern, but with a reversal of the signs in the dipole structure, has been related to anomalous hot and dry days in South Korea (Lee and Lee 2016). This dipole structure, or teleconnection pattern, is closely related to WNPSH variability, and can be ascribed to a Rossby wave train that is generated by deep convection in the tropical western Pacific (e.g. Park and Schubert 1997, Huang et al 2012, Kosaka et al 2012). This teleconnection pattern has long been recognized as a cause of the extreme summers in Japan (e.g. Wakabayashi and Kawamura 2004, Kosaka et al 2012). In this context, weather anomalies and/or extremes in adjacent regions or remote areas may be connected through some recurrent teleconnections. The extreme temperatures in Taiwan possibly occur simultaneously with some weather anomalies, or even weather extremes, in other places in the East Asian summer monsoon region, in the same context of anomalous circulation backgrounds. Any potential precursors associated with the relevant teleconnection can be of high practical value in predicting persistent temperature extremes in Taiwan and its surrounding areas.

6. Conclusions

This study investigates the heat waves in Taiwan and their maintenance mechanism, based upon observations and dynamically downscaled simulations and future projections. The downscaling is performed using the weather research forecasting (WRF) model with a 5 km grid spacing, and both recent past (1979–2003) and future (2075–2099) simulations are conducted. A percentile-based heat wave definition is utilized for defining the heat wave from each dataset. We suggest a flexible hot-day threshold upon the climate of the study period as this is appropriate for documenting the respective extreme conditions, and thus facilitates the formulation of a mitigation strategy for future extreme conditions in a changing climate.

Heat waves are forecast to become more severe in future. This future change is primarily as a result of the shift in the mean daily maximum temperature and not a result of change at higher moments. During heat waves, daily minimum temperatures are generally high and DTR is relatively large; the daily minimum temperature serves as the primary control of the variation in DTR. No trend in the DTR was found, but the extremely hot days and nights imply that a moderate DTR during normal weather can become uncomfortable or even harmful under the stress of heat waves. The combination of high temperature and high humidity can provide a relatively complete description of hot extreme in humid regions, such as Taiwan, and the apparent increase in the daily minimum temperature suggests that there will be elevated heat stress at nighttime during heat waves in the future.

Heat waves in Taiwan are associated with abnormal warming and drying atmospheric conditions under the control of an enhanced western North Pacific subtropical high. The surrounding waters, however, serve as a vast moisture source to suppress the drying magnitude in the surface layer as temperatures rise, thereby ensuring a high humidity level during the hot spell. The subsidence and adiabatic warming above can trap the warm and humid air in the surface layer, leading to positive feedback to the abnormally hot surface condition. This thermodynamic regime ensures the maintenance of consecutive days of high temperature and high humidity, leading to the accumulated risk of human heat stress. The anomalous warming and drying patterns cover certain spatial extents and with substantial vertical extension, suggesting that the extreme situation identified here is not confined to just an island-wide hot spell, but that the abnormal hot weather can take place across a broad geographical areas. The major anomalous pattern, as well as the dominance of WNPSH variation, and the relevant thermodynamic processes remain true for the future, suggesting a robust mechanism of heat waves in Taiwan. The potential precursors of this relevant teleconnection can be of high practical value in predicting persistent temperature extremes in Taiwan and the surrounding areas.

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