



國立臺灣大學理學院氣候變遷與永續發展國際學位學程

碩士論文

International Degree Program in Climate Change and Sustainable Development

College of Science

National Taiwan University

Master's Thesis

太平洋經向模態對臺灣夏季溫度和熱浪的影響

Linkage between Temperature and Heatwaves

in Summer Taiwan to the Pacific Meridional Mode

蔡曉亭

Chieh-Ting Tsai

指導教授：曾琬鈴 博士、王懌琪 博士

Advisor: Wan-Ling Tseng, Ph.D. & Yi-Chi Wang, Ph.D.

中華民國 113 年 02 月

February 2024





致謝

謝謝琬鈴老師及懌琪老師，能擁有這兩位指導老師是我在碩士生涯最幸運的事情，因為有老師，我才有機會踏入大氣科學這個嶄新的世界，也得以用另外一個角度窺探世界運行的方式，謝謝老師這兩年予我的無盡支援與包容，讓大氣小白如我能安心地邁開步伐向前。謝謝中研院環境變遷中心四樓及 IPCS 的每一位學長及學姊們，總是在我研究大崩潰的時候，帥氣的提供專業技術支援，也謝謝學長姐們平時與我聊天、和我分享大氣世界的日常，讓我漸漸在大氣領域中找到了歸屬的一隅，希望有一天能夠跟你們一樣厲害的念頭，是我研究時的動力。謝謝師大地理的老師、同學們，在地理系的四年形塑了完整的我，你們是最厚、最溫暖的同溫層，每次的相聚就像回娘家一樣，讓我在饒富趣味的對話中充飽電，在迷惘時找回自己。也謝謝國中的小夥伴們，總是在我忘記停下來的時候，伸出手把我拉出千篇一律的生活軌道，一同相聚。

最後，謝謝嘉瑋及我的家人，你們的陪伴與支持使我能抵達今天。



中文摘要

在過去的一個世紀中，臺灣夏季溫度的上升和熱浪事件的加劇，可能對人們的日常生活造成相當大的災害，因此我們迫切的需要進一步研究它們的特徵以及對人類生活的影響。太平洋經向模態是一個發生在東太平洋南北向海平面溫度異常增溫的氣候變異，根據前人的研究，太平洋經向模態是西太平洋以及亞洲部分國家的極端高溫的主因，包括中國、印度等等，然而，太平洋經向模態和臺灣夏季溫度變化之間的關係卻仍需要更近一步的討論與研究。本研究旨在釐清太平洋經向模態與臺灣夏季溫度之間的關係與其中的物理機制，並進一步的分析太平洋經向模態增強時對臺灣的極端高溫與熱浪事件造成的影響，以及評估暴露在極端高溫之下的人口數量。我們發現太平洋經向模態是在十年的時間尺度上造成臺灣夏季溫度變化的主要因素之一，在太平洋經向模態正相位期間異常的溫暖海表面溫度將會激發向東移動的波列，延伸到北太平洋，進入東亞，引起中國東南方和臺灣附近的反氣旋環流的發展，這些環流伴隨下沉，導致更穩定的大氣，減少夏季西南季風的影響，並增強地表的短波輻射，最終導致夏季溫度的升高。這種機制可以通過使用 Taiwan Earth System Model version 1 進行實驗來驗證。在太平洋經向模態正相位期間，極端高溫 and 熱浪事件的規模變得更大、頻率增加，且持續時間延長，在對熱浪的人口暴露度部分，臺中市、彰化縣和苗栗縣等西部縣市的對熱浪的人口暴露量增加最多。本研究希望能夠增加我們對臺灣夏季溫度在年代際尺度變化的瞭解，並提供更多的資訊給各領域的專家制定中長期氣候調適計畫。

關鍵字：太平洋經向模態、年代際夏季溫度變化、遙相關、熱浪、暴露度



ABSTRACT

Over the past century, Taiwan have experienced intensifying temperatures and heatwaves in prolonged summer duration. These climatic shifts can pose considerable disasters, raising the urgency for further examination of their characteristics and impacts on human daily life. Pacific Meridional Mode (PMM), an anomalous north-south sea surface temperature gradient over the east subtropical Pacific, has been recognized influencing extreme temperatures in countries including China and India. However, the specific association between the variation of temperatures in Taiwan and the PMM remains under investigation. This study found that PMM is one of main drivers modulating summer temperatures in Taiwan on a decadal scale. The warm SST anomaly during the PMM positive phase can excite a wave train moving eastward over the Northern Pacific extends into East Asia, causing the development of anticyclonic circulations in the vicinity of southeastern China and Taiwan. These circulations are accompanied by subsidence, leading to atmospheric stabilization, diminishing the impact of southwesterly monsoon and enhances shortwave radiation at the surface. This mechanism can be reproduced by experiments using the Taiwan Earth System Model version 1 with PMM-like SST forcing. Our analysis also revealed that extremely high



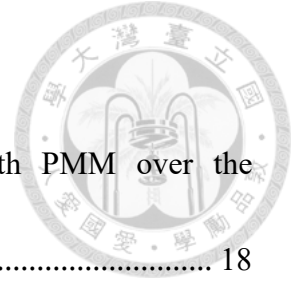
temperatures and heatwave events are more intensified, along with heightened frequency and prolonged duration of heatwaves, during the positive phase of PMM. A heightened exposure to heatwaves is evident in the northern, northwestern, and eastern regions of Taiwan. This impact extends to over 800,000 people in a single county, marking a tenfold increase compared to the effects observed in the global warming trend over one year. These findings of the relationship between summer temperatures in Taiwan and PMM on decadal scale could offer valuable insights into heatwave impact, facilitating future strategies to adapt the disaster of heatwave.

Keywords: Pacific Meridional Mode, decadal summer temperatures variation, teleconnection, heatwaves, exposure

CONTENTS



致謝	i
中文摘要	ii
ABSTRACT	iii
CONTENTS	v
LIST OF FIGURES	viii
LIST OF TABLE	xi
Chapter 1 Linking Decadal Variation of Summer Temperatures in Taiwan to PMM	1
1.1 Introduction	1
1.2 Dataset and methodology	4
1.2.1 Dataset	4
1.2.2 Methodology.....	7
1.3 Results	12
1.3.1 Linking Decadal Variation of Summer Temperatures in Taiwan with PMM	12
1.3.2 Changes of Regional Tmax/Tmin and Precipitation under PMM and Long-term Trend.....	16



1.3.3 Large-Scale Circulation Anomaly Associated with PMM over the Northern Pacific.....	18
1.3.4 Regional Features and Heat Budget Analysis.....	22
1.3.5 Surface Energy Budget Analysis	25
1.3.6 TaiESM1 Model Experiments	26
1.4 Summary.....	28
1.5 Discussion.....	30
Chapter 2 Impacts of PMM on Heatwaves and Their Exposure in Taiwan	35
2.1 Introduction	35
2.2 Dataset and Methodology	38
2.2.1 Dataset	38
2.2.2 Methodology.....	39
2.3 Results	43
2.3.1 Extreme high temperature associated with PMM	43
2.3.2 Heatwave events associated with PMM	46
2.3.3 Exposure to EHT	48
2.4 Summary.....	51
2.5 Discussion.....	53

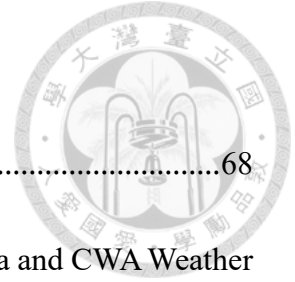
FIGURES	56
TABLES	85
REFERENCE	87



LIST OF FIGURES



Figure 1 Climate Variability Influencing Taiwan and Corresponding Forecast Time Scales.	56
Figure 2 Pattern and Time Series of Climatological SST, Horizontal Wind and JJA Tav _g in Taiwan.	57
Figure 3 Analysis of the Relationship Between PMM and JJA Tav _g in Taiwan.	59
Figure 4 Long-Term Trends and PMM Regression Analysis for JJA T _{max} , T _{min} , and Precipitation in Taiwan.	61
Figure 5 Regression Pattern of Large Circulation in the Western Pacific onto JJA Temperature and the Standardized PMM Index.	62
Figure 6 Regressed Regional Features in Southeast Asia to PMM index.	64
Figure 7 Thermodynamic Budget Analysis and Vertical Cross Section Regressed onto Standardized PMM Index.	65
Figure 8 Surface Energy Budget Analysis and Regressed onto Standardized PMM Index.	66
Figure 9 Forcing SST Anomalies and Results in PMM Experiments.	67
Figure 10 Illustration of the proposed impacts of enhanced PMM SST anomaly on	



summer surface warming in Taiwan.....	68
Figure 11 Temperatures Comparison of between TCCIP Gridded Data and CWA Weather Station Data at Six Centennial Stations in Taiwan.	69
Figure 12 Temperatures comparison of CWA Weather Station Data between Six Centennial Stations in Taiwan during 1960 and 2018.	70
Figure 13 Tav _g Comparison between TCCIP Gridded Data and CWA Weather Station Data at Six Centennial Stations in Taiwan.	71
Figure 14 T _{max} Comparison between TCCIP Gridded Data and CWA Weather Station Data at Six Centennial Stations in Taiwan. Similar to Figure 13, but for T _{max}	72
Figure 15 T _{min} Comparison between TCCIP Gridded Data and CWA Weather Station Data at Six Centennial Stations. Similar to Figure 13, but for T _{min}	73
Figure 16 Global Regression Maps of SST, Precipitation and OLR onto PC1 of Taiwan summer temperature on decadal timescales.	74
Figure 17 Population Density Across Counties and Cities in Taiwan.....	75
Figure 18 Anomaly Composites of Daily T _{max} during Positive and Negative PMM Years.	76
Figure 19 Anomaly Composite of CTX magnitude during PMM Positive and Negative Years.	77



Figure 20 Anomaly Composites of CTX Frequency during Positive and Negative Years of PMM.	78
Figure 21 Comparative Analysis of Heatwave Features Measured by the HWMD Method in PMM-Positive and PMM-Negative Years.	79
Figure 22 Feature Comparisons of the top five strongest HWMS events each year in PMM-positive (red) and PMM-negative (blue) years.	80
Figure 23 Exposure Map to Heatwave based on CTX90pt in PMM-Positive and PMM- Negative Years.	81
Figure 24 Regressed Maps of Heatwave Exposure based on CTX90pt to PMM index and Long-Term Temperature Trend in Taiwan based on the population in 2018.....	82
Figure 25 Illustration of Heatwave Changes over Taiwan in PMM-Positive and PMM- Negative Years found in this study.	84

LIST OF TABLE

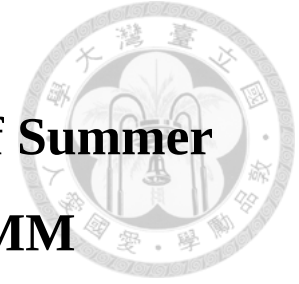


Table 1 Reference Table for County/City Names and Abbreviations in Taiwan.....85

Table 2 Weather Station Names and Locations86



Chapter 1 Linking Decadal Variation of Summer Temperatures in Taiwan to PMM



1.1 Introduction

Taiwan, as an island located between Eurasia and the western North Pacific Ocean (WNP), spans both tropical and subtropical zones (Figure 1). This unique geographical position not only positions Taiwan within the Asian monsoon region but also exposes it to climatic variabilities from both tropical and mid-latitude regions. (Central Weather Administration, 2023).

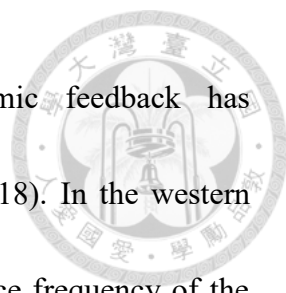
Under global warming, there has been a noticeable increase in the average temperature (T_{avg}) of 0.7°C over the globe compared with preindustrial period (IPCC, 2021). T_{avg} in Taiwan has risen by approximately 0.6°C over the past century and has become increasingly pronounced. Situated at the boundary of tropical and subtropical zones, the already hot summers in Taiwan pose a serious risk as they continue to warm, especially to ecosystems, public health, and safety, and even to economy (Taiwan Climate Change Projection and Information Platform, 2023).

Decadal climate change forecasting is important. It enables people to formulate medium to long-term adaptation strategies and develop appropriate infrastructure (Goddard, 2016; Trenberth et al., 2016). However, compared to interannual forecasting

and end-of-century projection, decadal climate prediction is a time scale that we currently find more challenging to predict accurately (Gao et al., 2018). Therefore, to improve predictive accuracy, it is essential to deepen our understanding of decadal-scale climate variability.

Climate variabilities could influence decadal climate changes in Taiwan. According to previous research, factors such as El Niño-Southern Oscillation (ENSO), the decadal Pacific-Japan pattern, SST in the Maritime Continent (MC), and even SST in the tropical Indian Ocean (TIO) have been identified as potential contributors to climate changes in the Northwest Pacific. Among them, in recent years, an increasing amount of research has shown that the Pacific meridional mode (PMM) play a crucial role in modulating climate patterns in the WNP (Kao et al., 2022).

PMM is identified to be situated in the eastern Pacific, spanning approximately 10°N-30°N and 160°E-160°W. Its positive and negative phases cycles are slightly longer than ENSO, transitioning about every 5-6 years (Chiang & Vimont, 2004). The subtropical Pacific is often regarded as a precursor to ENSO events (Chang et al., 2007). The springtime PMM in the northern region can forecast approximately 15-30% of the variance of winter ENSO (Amaya, 2019). The relationship is asymmetrical, as only the positive phase exhibits a significant correlation with ENSO, while the negative phase of PMM shows poor predictability for ENSO (Larson & Kirtman, 2014). Due to global



warming, the strengthened wind-evaporation-SST thermodynamic feedback has intensified the variability of the PMM (Liguori & Di Lorenzo, 2018). In the western Pacific region, there is a positive correlation between the occurrence frequency of the PMM and the occurrence of intense typhoons. This correlation is particularly prominent during the typhoon peak period. This relationship is attributed to the Matsuno-Gill-type Rossby wave response, resulting in weaker vertical wind shear and higher low-level relative vorticity, thereby favoring the genesis of intense tropical cyclones (Wang et al., 2023). The PMM also affects the east-west shift of the mean tropical cyclone genesis location (Hong et al., 2018). In the East Asian region, the PMM leads to a significant increase in both the intensity and frequency of extreme high temperatures in eastern China. This effect is attributed to the interaction between the East Asian jet stream and mid-latitude Rossby waves, leading to subsidence of air flow over East Asia. Concurrently, there is a significant reduction in precipitation (Liu et al., 2021; Luo et al., 2020). Furthermore, since the 1990s, with the mutually reinforcing interaction with the North Atlantic Tripole, the variability of the PMM on a decadal scale has been increasing. This might further amplify the influence of the PMM on the Northwest Pacific over a decadal scale (Amaya, 2019).

Given Taiwan's geographical proximity to the locations discussed in the studies above, however, there has yet to be a study quantifying the influence of the PMM on

summer temperature in Taiwan and elucidating the underlying physical mechanisms.

Therefore, this study aims to investigate the impact of the PMM on Taiwan in summer.

Observation data reveal that PMM likely serves as one of the dominant factors influencing summer temperatures in Taiwan on a decadal scale.

The results of this research indicate that when the PMM strengthens, there are low-pressure anomalies in the WNP, with an upward motion of air in the eastern Pacific, generating a cross-Pacific circulation pattern that leads to sinking in the western Pacific as well as East south Asia. Taiwan is situated within the central region characterized by subsidence in the East south Asia, making it the location most significantly influenced by PMM. Consequently, when PMM strengthens, it leads to a significant increase in summer temperatures in Taiwan. This process can be validated through simulation experiments using Taiwan Earth System models version 1 (TaiESM1). The simulation results reveal the large circulation in the WNP and subsidence in Southeast Asia induced by PMM.

1.2 Dataset and methodology

1.2.1 Dataset

1.2.1.1 Index For Identifying PMM

PMM is defined as a first coupled mode of the sea surface temperature (SST) and

10-m wind field in the tropical and subtropical Pacific (21°S-32°N, 74°W-15°E) through the maximum covariance analysis (Chiang & Vimont, 2004). The data is spatially averaged by 3° longitude and 2° latitude, with the removal of seasonal cycle signals and the Pacific cold tongue index (a measure of ENSO variation), detrended to remove the warming signal and then performed to a three-month running average before applying to MCA. The monthly PMM index used in this study is obtained from the NOAA Earth System Research Library, available at <https://www.esrl.noaa.gov/psd/data/timeseries/monthly/PMM/>.

This study adopts the June-August (JJA) monthly average of the PMM index for each summer during 1960 to 2018. The definition of PMM-positive years and PMM-negative years is as following: If the 5-year running averaged standardized PMM index for a given year is greater than 1, the year is classified as a PMM-positive year. If it is lower than -1, it is classified as a PMM-negative year. The PMM-positive years include 1966, 1967, 1968, 1987, 1988, 1990, 1992, 1993, 1994, 2015, 2016. The PMM-negative years include 1973, 1974, 1975, 1976, 1999, 2000, 2009, 2010, 2011, 2012. Other years are considered neutral PMM years (Luo et al., 2020).

1.2.1.2 Temperatures in Taiwan

The temperatures data for summer in Taiwan is a gridded monthly observation with

a spatial resolution of 5 kilometers, spanning from 1960 to 2018. The data is obtained at <https://tccip.ncdr.nat.gov.tw/index.aspx> (Taiwan Climate Change Projection and Information Platform, 2023).



The regions with lower weather station density, especially mountainous areas, exhibit higher data uncertainty and larger estimation errors (Taiwan Climate Change Projection and Information Platform, 2023). Therefore, this study focuses on areas below an elevation of 1000 meters. In fact, by utilizing population data from the Department of Household Registration, Ministry of the Interior, Taiwan, we found that the areas below 1000 meters cover more than 99.5% of the population distribution, effectively representing the primary residential areas in Taiwan (not shown). Consequently, we utilized data below 1000 meters and placed greater emphasis on understanding the impacts of climate variation on human populations.

1.2.1.3 Circulation Field Variables

The sea surface temperature (SST) is based on Monthly version of HadISST sea surface temperature component from Met Office Hadley Centre at <https://climatedataguide.ucar.edu/climate-data/sst-data-hadisst-v11>. Outgoing longwave radiation (OLR), geopotential high, sea level pressure (SLP), wind data are from the fifth-generation atmospheric reanalysis of the global climate (ERA5) from the European

Center for Medium-range Weather Forecasts

(ECMWF) at

<https://cds.climate.copernicus.eu/cdsapp#!/search?type=dataset>.

The horizontal

resolution is $0.25^{\circ} \times 0.25^{\circ}$ latitude-longitude, while the vertical resolution is 37 pressure

levels. The surface energy components is obtained from ERA5-Land dataset at

<https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-land?tab=overview>.

As the positive and negative phases of PMM alternate approximately on a decadal scale, this study utilizes a five-year moving average for the data. This approach helps smooth out other climate signals with periods less than five years, ensuring a more accurate representation of the influence of PMM.

1.2.2 Methodology

1.2.2.1 Empirical Orthogonal Function (EOF)

To understand the variations in the summer temperatures in Taiwan and the potential signals influencing them, this study used empirical orthogonal function (EOF) analysis. EOF, also known as Principal Component Analysis (PCA) or Eigenvector Analysis, is widely used in the atmospheric field. Given any space-time meteorological field, EOF finds a set of orthogonal spatial patterns along with a set of associated uncorrelated time series or principal components (PC). This analysis method helps reduce the dimensionality of the data and extract the patterns of variation in the climate phenomena.



The formula is as follows:

$$X(t, s) = \sum_{k=1}^M c_k(t) u_k(s) \quad (1.1)$$

The continuous space-time field that we want to achieve decomposition represented by $X(t, s)$, where t and s denote respectively time and spatial position. M is the number of modes contained in the field. $c_k(t)$ and $u_k(s)$ represent expansions functions of time and the optimal set of basic functions of spatial patterns used by each mode.

In practical terms, the EOF/PCA technique seeks to identify a new set of variables by combining the original variables linearly, with the objective of capturing the majority of the observed variability present in the data (Hannachi et al., 2007).

1.2.2.2 Correlation and Regression Analysis

In this study, Pearson correlation and linear regression are employed to quantify the impact of the PMM on the surface variables and circulation patterns in the East Pacific and Taiwan.

Pearson correlation analysis is used to explore the linear relationship between two continuous variables, x and y . The correlation coefficient measures the degree of linear association between the variables and ranges from -1 to 1. A higher absolute value of the correlation coefficient indicates a stronger mutual covariance between the variables. Generally, a positive correlation implies that as x increases, y tends to



increase as well. Conversely, a negative correlation suggests that as x increases, y tends to decrease. The formula for Pearson correlation is as follows:

$$r(x, y) = \frac{COV(x, y)}{S_x S_y} = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}} \quad (1.2)$$

where r represents the Pearson correlation coefficient, x_i and y_i denote the individual values of x and y , and $\bar{x}$ and $\bar{y}$ represent the means of x and y . (Boslaugh, 2012)

Linear regression analysis is a simple model that examines the linear relationship between an independent variable and a dependent variable. It quantifies the extent to which the dependent variable changes when the independent variable changes. The formula is as follows:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \varepsilon \quad (1.3)$$

where Y is the dependent variable, $x_1, x_2, \dots$ are the independent variables, β_0 is the intercept, $\beta_1, \beta_2, \dots$ is the regression coefficient that measures the dependence of y on x , and ε represents the residual (Boslaugh, 2012)

1.2.2.3 Thermodynamics Budget Analysis

To gain a deeper understanding of the process by which PMM leads to warming in the Northwestern Pacific, we analyze and quantify the thermodynamic processes and

energy exchange within the East Asian sinking region the equation of thermal heat budget.

The original equation is as follows (Yanai et al., 1973):

$$\left(\frac{P}{P_0}\right)^K \left(\frac{\partial \theta}{\partial t} + v \cdot \nabla \theta + \omega \cdot \frac{\partial \theta}{\partial p} \right) = \frac{Q_1}{c_p} \quad (1.4)$$

where, P represents pressure and P_0 represents the reference pressure at 1000hPa.

$K = \frac{R}{c_p}$ is the adiabatic index, defined as the ratio of the specific heat at constant pressure to the specific heat at constant volume for a gas. $\frac{\partial \theta}{\partial t}$ represents the rate of change of potential temperature θ with time t . $v \cdot \nabla \theta$ is the advective term's contribution to temperature change. $\omega \frac{\partial \theta}{\partial p}$ represents the adiabatic heating in vertical term. Lastly, $\frac{Q_1}{c_p}$ represents the non-adiabatic heating term.

However, over a five-year timescale, $\frac{\partial \theta}{\partial t}$ has reached equilibrium with an exceedingly minor change. Therefore, we rearranged the equation of thermal heat budget here, moving $\frac{\partial \theta}{\partial t}$ to the left side of the equation and the other three terms to the right side. We also broke down the advection term $v \cdot \nabla \theta$ into the zonal advection term $U \frac{\partial \theta}{\partial x}$ and the meridional advection term $V \frac{\partial \theta}{\partial y}$. This allows us to analysis how these four thermal processes individually contribute the temperature variations in this region while maintaining equilibrium in $\frac{\partial \theta}{\partial t}$. The formula is as follows:

$$\frac{\partial \theta}{\partial t} = \frac{Q_1}{c_p} - (p^* U \frac{\partial \theta}{\partial x} + p^* V \frac{\partial \theta}{\partial y} + p^* \omega \frac{\partial \theta}{\partial p}) \quad (1.5)$$

Where,

$$p^* = \left(\left(\frac{p}{p_0} \right)^k \right)^{-1} \quad (1.6)$$



In this study, we introduce specific abbreviations for key terms to enhance conciseness and clarity. These abbreviations are employed to represent crucial variables in the thermal heat budget equation. The term $p^* U \frac{\partial \theta}{\partial x}$ is denoted as "HADV_u, $p^* V \frac{\partial \theta}{\partial y}$ is represented by "HADV_v," and $\omega \frac{\partial \theta}{\partial t}$ is abbreviated as "VADV." These abbreviations facilitate a more efficient and precise representation of the associated variables in our analysis, contributing to the overall readability and comprehension of the study.

1.2.2.4 Surface Energy Budget Analysis

In the planetary boundary layer, the non-adiabatic warming component Q_1 is significantly influenced by the net upward flux through the surface (F_s) (Yanai et al., 1973). To further analyze the primary contributors to Q_1 , we utilize the Surface Heat Budget equation to break down F_s . The formula is as follows:

$$F_s = SSR + STR + SHF + LHF + G \quad (1.7)$$

The SSR and STR represent net shortwave and surface thermal (longwave) radiation at the surface, while SHF and LHF represent sensible and latent heat fluxes. The ground heat flux, G , is generally very small so is not discussed in this study. All fluxes mentioned here are positive upward.

1.2.2.5 TaiESM1 Experiments

To validate the causality between PMM and the Pacific circulation field, a series of experiments were conducted using the Taiwan Earth System Model version1 (TaiESM1).

TaiESM1 is an Earth system model used for simulating Earth's climate, considering various components of the Earth's environment, including the atmosphere, land surface, ocean, and glaciers, among others. Through TaiESM1, we were able to verify the causality between PMM and the Pacific circulation field in a simulated environment.

The region where SST increases by more than 0.1°C between 160°E and 140°W in Figure 9 is defined as the PMM-pattern in our study's definition. We conducted two experiments, called the control (CTL) and PMM experiment, each consisting of thirty simulation runs. In each simulation run, random perturbations were used to reduce the impact of model errors, resulting in initial value differences of less than 10^{-14} (Kay et al., 2015). The CTL experiment was driven by observed sea surface temperatures from 1980 to 2020, while the PMM experiment incorporated observed sea surface temperatures containing the PMM-pattern. Simulations extended from January to September. We will calculate the ensemble averages of the CTL and PMM experiments.

1.3 Results

1.3.1 Linking Decadal Variation of Summer Temperatures in

Taiwan with PMM



During the boreal summer, the temperature of the Pacific Warm Pool reaches up to 30°C, extending to around 20°N, which is the southern tip of Taiwan. The strong north-south temperature gradient results in Taiwan's sea temperatures ranging from 27°C to 30°C. Simultaneously, Taiwan, located in the region dominated by the Asian monsoon, experiences prevailing southwest winds during the summer, bringing moisture from the Pacific Warm Pool and serving as a significant source of precipitation for Taiwan (Figure 2a). Due to the high elevation of the central terrain, Taiwan exhibits a substantial temperature difference. The average summer temperature can reach up to 29°C, and with increasing elevation, temperatures tend to decrease. In areas below 1000 meters above sea level, the Tavg drops to a minimum of 20°C, creating a temperature gradient ranging from 20°C to 29°C (Figure 2b) .

Over the past century, with global temperature rise, Taiwan has witnessed an upward trend in Tavg. In the last 60 years, the trend has been an increase of 0.07°C per decade, while in the last 30 years, it has been approximately 0.03°C per decade. In the most recent decade, the upward trend has accelerated to 0.4°C (Figure 2c). The temperature trend exhibits fluctuations rather than following a straight line, possibly indicating the influence of climate variabilities or modes beyond the warming trend.

When studying interannual temperature variations in Taiwan, ENSO is considered a



crucial predictability source. However, when extending the timescale to decades, ENSO may not maintain the same level of importance due to its relatively short occurrence span. In contrast, the decadal cycle of PMM might provide a greater opportunity for a higher correlation with JJA temperature variations in Taiwan.

To compare the correlation of temperature in Taiwan with ENSO and PMM, we present a scatterplot of temperature in JJA versus PMM index from 1960 to 2018 (Figure 3a). We defined years with Oceanic Niño Index (ONI) exceeding 1 as El Niño years (blue circles), years with ONI less than -1 as La Niña years (red circles), and years with ONI between -1 and 1 as neutral years (gray circles). Notably, the circles exhibit an ascending trend, indicating that the JJA temperature tends to rise with an increase in the PMM index. The slope of neutral-year fitting line (black solid line) is steeper than that of the all-year fitting line (gray dashed line), suggesting PMM has a greater correlation with JJA Temperature without El Niño or La Niña signals. The higher R-squared value of 0.1 further supports this, meaning that the neutral-year fitting line provides a better fit. When considering all years (neutral-year, El Niño, and La Niña years), the correlation between summer temperature in Taiwan and the PMM index is 0.23. If El Niño and La Niña years are included, the correlation increases to 0.26, and both correlations pass a 10% statistical test. Consequently, PMM demonstrates a more robust correlation with summer temperature in Taiwan than ENSO.



To isolate the PMM signal from the ENSO signal, we utilize the 5-year average of the PMM index to smooth out the interannual influence of ENSO. The 5-year running averaged PMM index was then standardized to make assessments and comparisons with different variables. Regression pattern of JJA temperature onto 5-year running averaged standardized PMM index, which is referred to as "standardized PMM index" in the following study provides an assessment of the impact of PMM on JJA temperature (Figure 3b). When the PMM strengthens by one standard deviation, there is a corresponding increase in JJA temperature over Taiwan. The most significant temperature increase occurs in the northwest, southwest, and eastern regions of Taiwan, with temperatures rising by up to 0.4 °C. This is statistically significant at the 10% level.

The variation of JJA temperature in Taiwan is influenced by a multitude of factors. To isolate and analyze these factors, we apply EOF analysis to the JJA temperature data. EOF mode 1 reveals that when PMM strengthens, there is a clear upward trend in the T_{avg} over Taiwan (Figure 3d), which can explain 56.5% variance of JJA temperature. The most pronounced temperature increase trends are observed in the northwest, southwest, and eastern areas. This temperature distribution pattern closely resembles that in the regression pattern of JJA temperature and standardized PMM index (Figure 3b). We compare EOF PC1 (black line) with JJA temperature (red bars) and PMM index (black line) in Figure 3c. The patterns of each of them exhibit a remarkably similar decadal



oscillation period. From 1970 to 1980, all of them exhibit a downward trend, followed by an upward trend from 1980 to 1990. Subsequently, there is a downward oscillation from 2000 to 2010, and from 2010 onwards, an upward trend resume. This indicates that the oscillations of PMM and the primary mode of Taiwan's summer temperatures are synchronized.

1.3.2 Changes of Regional Tmax/Tmin and Precipitation under PMM and Long-term Trend

In Section 1.3.1, our exploration of summer temperatures primarily revolves around the Tav. Tav is a comprehensive metric that considers both the minimum and maximum temperatures (Tmin; Tmax). Tmax, occurring typically during the day, signifies the peak temperature influenced by factors like solar shortwave radiation, convection, and topography. In contrast, Tmin, observed at night, represents the day's lowest temperature, influenced not only by convection and topography but also by nighttime longwave radiation cooling. Moreover, external factors like precipitation, which cools surfaces through evaporation, and cloud cover, capable of blocking solar radiation, play crucial roles in shaping temperature dynamics. Therefore, when delving into discussions about summer Tav, it becomes imperative to consider not only Tmax and Tmin but also factors such as precipitation. This comprehensive analysis is essential for a better understanding

of the various factors that collectively contribute to climate variations.

To delve deeper into the regulatory process of the PMM on summer temperatures in Taiwan, we first illustrated long-term trend maps for maximum temperature, minimum temperature, and precipitation during the period from 1960 to 2018 in Figure 4a, c, e. This helps provide a general background of the overall climate change in Taiwan. Simultaneously, we plotted regression pattern for the same period, depicting the influence of PMM on maximum temperature, minimum temperature, and precipitation in Figure 4b,d,f. By comparing the intensity and distribution differences of these surface variables influenced by PMM and long-term trends, we can gain a clearer understanding of how extensively PMM affects summer temperatures and precipitation.

Regression pattern of the long-term summer Tmax in Taiwan on to the standardized PMM index in the past 60 years exhibits a rise in the north, southwest, and part of the eastern region by up to 0.03°C (Figure 4a). In contrast, when PMM is strengthening, a significant increase in summer Tmax is observed throughout Taiwan, particularly in the northern and central-western regions, with temperature increases by up to 0.3°C (Figure 4b). The impact of PMM on summer Tmax is much more pronounced than the long-term trend.

The long-term summer Tmin in Taiwan (Figure 4c) indicates a significant increase across the entire Taiwan, particularly in the north and southwest by up to 0.12°C. However,

when PMM is strengthened, although the increase of T_{min} reaches more than 0.12°C , only a few regions pass the significant testing (Figure 4d). These results suggest that global warming primarily affects T_{min} in Taiwan. Conversely, the impact of PMM enhancement on summer T_{min} in Taiwan exhibits greater variability.

The long-term trend in summer precipitation in Taiwan (Figure 4e) exhibits a weak increasing trend, passing significant testing only in very few areas, indicating considerable variability. The regions passing statistical testing are primarily located in the north and south, with an increase of up to 0.2mm. On the other hand, the enhanced PMM shows a completely different impact on summer precipitation in Taiwan (Figure 4f). It results in a significant reduction in precipitation throughout entire Taiwan, especially in the southern part of Taiwan, by up to 2mm. It is suggested that while the summer precipitation in Taiwan exhibits a great variability in the long term, the enhanced PMM cause a significant dryer climate in Taiwan.

1.3.3 Large-Scale Circulation Anomaly Associated with PMM over the Northern Pacific

In the studies, we have found that the enhancement of the PMM is highly correlated with related to the increased summer temperatures and reduced precipitation in Taiwan. These climatic factors may be influenced by large-scale circulation, surface heating, and

local circulation induced by solar energy. To explore the potential physical mechanisms of how PMM affects temperatures in Taiwan, the large-scale circulation patterns triggered by PMM enhancement in the northwest Pacific will be discussed in this chapter.

The regression map of WNP SST onto the JJA temperature in Taiwan (Figure 5a) shows that Taiwan experiences a greater SST increase compared to other coastal areas in East Asia, by up to 0.1 °C. Also, in the East Northern Pacific (ENP), a region with anomalous warming can be observed from approximately 160 °E to 120 °W, and from the Equator to around 30 °N. This anomaly aligns with the PMM, with a temperature increase up to 2.5 °C. The relationship between SST in ENP and JJA temperature in Taiwan is evident, highlighting the possible contribution from the PMM on JJA temperature increase in Taiwan.

When the PMM is enhanced, a notable warming in SST is observed in the coastal areas of East Asia, particularly in the vicinity of Taiwan. The warming intensity is up to 0.1 °C. The regression of SST near the East Asia onto standardized PMM in the pattern exhibits more areas passing the statistical test compared to that onto JJA temperature in Taiwan. In the ENP, the regression pattern illustrates a more substantial and intensified pattern associated with the PMM (Figure 5b).

The regression pattern of mean sea level pressure (MSL) and horizontal wind field at 850hPa onto the JJA temperature in Taiwan reveals that is the East Asia encounters



high-pressure anomalies, with an increase of up to 10 hPa. There is a northeastern wind anomaly over Taiwan, might indicating a weakening of the prevailing southwestern monsoon wind during JJA (Figure 5c). In the Northern Pacific, two low-pressure anomalies center are observed in 150 °E and 120 °W. The first low-pressure anomaly spans from 120 °E to 180 °W and from 15 °N to 35 °N, with MSL anomaly ranging from -20 Pa to -50 Pa. The second low-pressure anomaly extends from 180° to 120 °W, with similar MSL anomaly ranging from -20 Pa to -50 Pa.

When PMM is enhanced, a high-pressure anomaly in MSL with an anti-cyclonic anomaly at 850 hPa is observed over East Asia. In the Northern Pacific, a similar double low-pressure anomaly is observed. However, the range and intensity are broader and stronger when PMM enhanced then JJA temperature rises in Taiwan, by up to 60Pa (Figure 5d). Moreover, both Figure 5c and Figure 5d depict a westward wind anomaly in the region of 0°-10°N, 120°E to 180°E.

The regression pattern of geopotential height at 200hPa and horizontal wind field at 850hPa onto the JJA temperature in Taiwan indicates that Taiwan is within the range of positive geopotential height anomalies when the JJA temperature in Taiwan raises (Figure 5e). In the North Pacific (NP), there is a cap-shaped (lower on the sides, rising in the middle) positive geopotential height anomaly with increase up to 80 m²s⁻².

When the PMM strengthens, Taiwan falls within the scope of positive geopotential

height anomalies (Figure 5f). Similarly, a cap-shaped positive geopotential height anomaly is observed in the NP, resembling the pattern in Figure 5e with a reduction in geopotential height of up to $80 \text{ m}^2\text{s}^{-2}$. Moreover, both Figure 5e and Figure 5f depicts an eastward wind anomaly in the region of $0^\circ\text{-}10^\circ\text{N}$, 120°E to 180°E . The direction of the wind anomaly is opposite to that in Figure 5c and Figure 5d.

The regression map in Figure 5g illustrates the relationship between the vertical wind field (ω ; ω) and the June to August (JJA) temperature in Taiwan, focusing on the region between 10°N - 30°N in the Northern Pacific. The green block situated at 120°E in the map denotes the position of Taiwan. When the June to August (JJA) temperature in Taiwan increases, subsidence occurs over the region between 120°E - 130°E , spanning altitudes from 200hPa to 700hPa, with ω values reaching -0.3 Pa s^{-1} . In ENP, a significant ascending motion is observed between 160°W to 140°W , with the center of ascent located at 140°W .

When the PMM is enhanced (Figure 5h), a distinct subsidence signal is evident between 120°E - 130°E . Slightly differing from Figure 5g, subsidence anomaly extend closer to the surface, and the subsidence center coincidentally aligns with Taiwan (120°E). in the West Pacific (WP), ascending motion are observed between 160°W and 120°W , with the center of ascent also positioned near 140°W .

It's worth noting that in the vertical wind field map, there are westward wind

anomalies at 850hPa, while conversely, eastward wind anomalies are exhibited at 200hPa. (Figure 5g and Figure 5h). This aligns with the map of vertical wind at 850hPa and 200hPa (Figure 5c, Figure 5d, Figure 5e and Figure 5h). With subsidence in the WNP and ascending motion in the EWP, there is an implication of a large-scale circulation associated with the PMM over the WNP. This circulation pattern modulates convection as well as temperatures in East Asia, including Taiwan.

1.3.4 Regional Features and Heat Budget Analysis

1.3.4.1 Regional Features in East Asia Associated with PMM

In addition to the large-scale circulation, the regional features in East Asia directly affect surface temperature over Taiwan through the various heat transfer processes. Thus, we examine regional features in East Asia when PMM is enhanced, including circulations and OLR.

The regression map of mean sea level pressure and vertical wind at 850hPa in East Asia onto the standardized PMM exhibits a high-pressure anomaly and anti-cyclone centered over Taiwan (Figure 6; within the black box). The strongest high-pressure anomaly located in the northwest of Taiwan (21°N, 119°E), with MSL increase of up to 40hPa. This implicates that Taiwan is the primary influenced region in East Asia by PMM. In addition, a northeast wind anomaly over Taiwan suggests a weakening of the prevailing

northwest wind during the summer.

The OLR significantly increases along the coastal areas of East Asia when PMM is enhanced. As more long-wave radiation escapes into the atmosphere, it signals reduced cloud cover, indicating a decreased likelihood of deep convection in this region. Additionally, the northeastward moisture flux anomaly implies a reduction in moisture brought by the southwest monsoon during the summer. This may contribute to the observed decrease in precipitation when PMM is strengthened.

1.3.4.2 Near-surface thermodynamic budget analysis

As the strong high-pressure anomaly and increased OLR anomaly suggests a more stable large-scale environment over Taiwan when PMM is enhanced, we performed a thermodynamic budget analysis utilizing regressed fields from the ERA5 reanalysis dataset to further uncover how such environment affects near-surface temperature. In Figure 7, we present area-averaged results for two regions: East Asia (100°E - 135°E , 10°N - 40°N ; the black box in Figure 6) and land of Taiwan (119°E - 123°E , 21°N - 26°N ; the red box in Figure 6), respectively. These results include five key components of thermodynamic at 925hPa level, as detailed in our methodology. These components encompass temporal change in potential temperatures, the diabatic heating term Q_1 , meridional and zonal horizontal advection terms (HADV_U ; HADV_V), and the vertical

advection term (VADV).

Minimal variation in potential temperature occurs as temperatures approach equilibrium over the long-term averages throughout the entire summer season (Figure 7a and Figure 7b). The meridional and zonal horizontal advection term both play role of bringing heat into East Asia region (Figure 7a), which is consistent with the northeastward wind anomaly associated with the anticyclone seen in Figure 6a. The vertical advective term plays a primary heating role resulting from the subsidence process in this region. The diabatic cooling term Q_1 is compensated by the combined effect of all three advection terms, with magnitudes on the order of 0.01 K day^{-1} . The Q_1 terms encompass factors such as longwave radiation loss, evaporative cooling, and heat or cooling resulting from boundary layer processes.

When examining the near-surface heat budget over Taiwan (Figure 7b), the zonal horizontal advection term assumes a secondary role in transporting heat into this region, while the vertical advection term remains the primary contributor to heating. It's noteworthy that the magnitude of the vertical advection term is approximately 0.05 K day^{-1} , nearly five times greater than the thermodynamic variation observed in the entire subsidence region of East Asia, indicating that Taiwan is more sensitive to PMM compared to other regions in East Asia.

The regression map of vertical advection term and Q_1 with vertical wind field

(averaged 10°N-30°N) onto the standardized PMM is illustrated in Figure 7c and Figure 7d. The vertical wind here is easterly downward, associated with the subsidence and anticyclone over Taiwan. The vertical advection term anomaly increases over Taiwan when the PMM is enhanced, with the maximum increase located approximately 121°E (by up to 0.4Pa s⁻¹; Figure 7c).

In the other hand, Q_1 anomaly in this region decreases, reaching its minimum values of 0.3 W day⁻¹ around 121°E. The distribution pattern of Q_1 closely resembles that of the vertical adiabatic heating term in Figure 7d. It is consistent with the thermodynamic components at the 925hPa level in Figure 7b that the region near Taiwan's land is primarily warmed through the vertical advection term and cooled through the Q_1 to achieve heat equilibrium.

1.3.5 Surface Energy Budget Analysis

The inflow and outflow of energy flux are also crucial factors influencing temperature variations. As Taiwan experiences strong subsidence during the enhancement of PMM, accompanied by relatively fewer clouds and less moisture, the likelihood of Taiwan's land receiving shortwave radiation from the sun increases. To better understand the physical mechanism between temperature variation and PMM, we conducted a surface energy budget analysis using the dataset of EAR5-LAND regressed onto



standardized PMM (Figure 8). This surface energy budget contains four essential components, including surface net solar radiation flux (SSR), surface net thermal radiation flux (STR), surface latent heat flux (LHF), surface sensible heat flux (SHF). Notably that all the energy fluxes are positive (negative) downwards (upward).

The regression map shows that downward (positive) SSR flux increases throughout the entire Taiwan, particularly in the southwestern part of Taiwan, by up to $3 \text{ Wm}^{-2}\text{s}^{-1}$. SSR flux plays a crucial role in warming the land in Taiwan (Figure 8a), which means warming effects on the land. On the other hand, energy may escape through STR, LHF, SHF flux. Figure 8a show that the upward (negative) STR, LHF, SHF flux increases over nearly the entire land of Taiwan (Except for LHF at the southernmost tip of Taiwan), which means cooling effects opposite from downward SSR.

The bar chart in Figure 8b also shows the primary contribution of SSR to downward energy flux on the land, with an average of approximately $2.2 \text{ Wm}^{-2}\text{s}^{-1}$. STR, LHF, and SHF all contribute to the upward energy flux, with averages of $-0.5 \text{ Wm}^{-2}\text{s}^{-1}$, $-0.8 \text{ Wm}^{-2}\text{s}^{-1}$, and $-0.9 \text{ Wm}^{-2}\text{s}^{-1}$, respectively. The sum of all four components reaches the surface energy flux equilibrium.

1.3.6 TaiESM1 Model Experiments

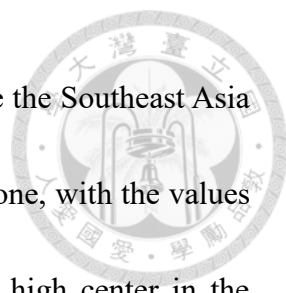
To test our hypothesis that an intensified SST anomaly associated with the PMM



could lead to a circulation response resulting in increased summer temperatures in Taiwan, we employed the TaiESM1. Our analysis focused on examining the circulation responses to PMM-like SST and their impacts on the East Asia and Taiwan region. Two simulations were conducted, labeled as ‘Control’ (CTL) and ‘PMM’ experiments. The CTL used prescribed SST based on climatological annual SST, while the PMM experiment aimed to simulate the strengthened PMM SST anomaly. Each experiment comprised 30 ensemble members and ran for 8 months from January 1st to September 1st. The initialization of each run included large-scale wind fields, temperature, and moisture based on the average over January 1st from 2004 to 2015 according to ERA5 reanalysis. The perturbation method followed the default approach used in constructing the CESM large ensemble project of CESM1 (Kay et al. 2015).

The region where the increase SST anomaly is over 0.1°C and passes the significance test in regressed field of HadISST dataset (Figure 5b) represents a PMM-like anomaly SST, which is the forcing SST in the PMM experience (Figure 9a).

The difference between CTL and PMM experience (PMM experience minus CTL experience) are illustrated in Figure 9b, Figure 9c, and Figure 9b. Large low-pressure (shading in Figure 9b) and cyclone (vector in Figure 9b) anomalies induced by PMM are observed in the NP, featuring two low-pressure and cyclone centers with values reaching as low as -200 Pa. Additionally, a high-pressure and cyclone anomaly is present over

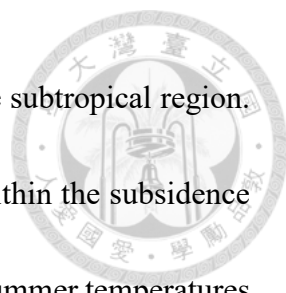


Southeast Asia, including Taiwan (Figure 9b). When further examine the Southeast Asia (Figure 9d), we found that Taiwan is in the anomaly high-pressure zone, with the values reach up to 60Pa. The model has simulated the regional anomaly high center in the Southwest East, but its location is slightly more Southeast compared to the observation data in Figure 5d. In the vertical wind field with 10°N-30°N averaged, there is an upward motion between 180°-120°W (with a slight downward motion between 160°W-130°W) and a downward motion between 120°E-160°E. These results are consistent with the observed data and validate our hypothesis that the large circulation in the NP and the regional convection in the Southeast Asia induced by PMM is the physical mechanism to make JJA temperature variation in Taiwan.

1.4 Summary

This study found that a strong correlation between the summer temperatures in Taiwan during JJA and the PMM index on the decadal timescale. This correlation is particularly pronounced in Tmax, with the most notable warming trends observed in the western, southern, and eastern regions of Taiwan.

The impact of PMM on summer temperatures in Taiwan originates from the elevated sea surface temperatures of PMM-pattern in EP triggering a westward-moving wave train extending to WNP as well as East Asia. This wave train reaches the western Pacific



around 120°E, inducing subsidence and anticyclone anomalies in the subtropical region. Taiwan, situated in the subtropical zone of the western Pacific, is within the subsidence zone caused by PMM. This explains how PMM results in a raise of summer temperatures (Figure 10).

From a thermodynamic budget perspective, the main heat source in the subsidence region induced by PMM in East Asia is the vertical advection term. Given Taiwan's central location within this subsidence, the heat brought by the vertical advection term near Taiwan is approximately five times that of the entire East Asian subsidence region. Additionally, through an analysis of Taiwan's surface energy balance, we observe an increase in SSR, possibly due to reduced convection in the subsidence area, allowing solar radiation to reach the surface more easily. This energy is primarily dissipated from the surface through LHF and SHF to maintain energy balance.

Experiments conducted with TaiESM1 validate that SST of PMM-pattern in the EP can initiates a similar eastward-moving wave train. Concurrently, subsidence anomaly is observed in the western Pacific. That is, the experiments in TaiESM1 support our inference regarding how the PMM mechanism influences temperatures in Taiwan. In summary, this study quantifies the increase in summer temperatures in Taiwan during PMM enhancement, explores its underlying mechanisms, and validates the findings using climate models.

1.5 Discussion

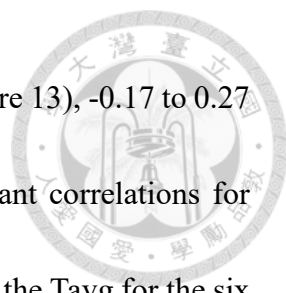


We would like to discuss the limitations of the current study in this session. We chose to use gridded observational monthly data provided by TCCIP as the foundational data for climate analysis in Taiwan. Gridded observational monthly data is obtained through mathematical interpolation of data from different weather stations. However, due to fewer weather stations numbers, weather stations over mountainous areas contain larger uncertainties. Gridded data of Tmax shows a cooling effect in some mountain areas (not shown). This phenomenon contradicts the commonly perceived global warming trend. Previous research suggests that, under global warming, enhanced convergence strengthens the hydrological cycle, leading to increased cloudiness and reduced solar radiation in Taiwan's mountainous areas, resulting in a cooling trend. Analysis using reanalysis data of ERA5 supports the observed cooling trend in mountain areas (Chen-Dau Yang, 2023). Although we cautiously avoided using TCCIP gridded data in mountainous areas in this study, in fact the data in these regions might be reasonably reliable.

Additionally, we compared gridded data with the raw data from the meteorological station set up by Central Weather Administration (CWA). Figure 11 presents temperature time series comparisons between six centennial weather stations averaged data (including Taipei station, Taichung station, Tainan station, Pingtung station, Hualien station, and



Taitung station) and gridded data based on TCCIP. While the temperature patterns of station data generally align with TCCIP data, the amplitude of temperature fluctuations in station data is larger. For instance, in 1985, weather station data was approximately 0.5°C lower than TCCIP data, and in 2016, it was about 0.5°C higher. Moreover, weather station data exhibits a stronger warming trend. Notably, Gridded data shows little upward trend in maximum temperature, whereas weather station data still demonstrates a clear upward trend. Observing the distribution of maximum temperatures at the six centennial stations, the differences in distribution are more pronounced for maximum temperatures compared to average and minimum temperatures (Figure 12). Regarding minimum temperatures, the upward trend is consistent between TCCIP data and station data. From this analysis, we conclude that while the temperature patterns of station data and gridded data are not completely opposite, there are important characteristic differences that require special attention in interpreting the analysis results. We also compared weather station data from CWA across the six centennial station and gridded data from TCCIP in the same location. In terms of the correlation between six centennial weather stations data and gridded data for different regions, Taipei, Taichung, and Tainan stations show higher correlations, ranging from 0.79 to 0.91 for T_{avg} (Figure 13), 0.39 to 0.71 for maximum temperature (Figure 14), and 0.48 to 0.8 for minimum temperature (Figure 15). These correlations are statistically significant at 10% level. Further, Hualien, Taitung, and

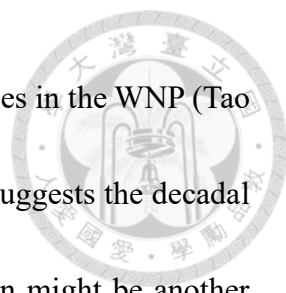


Pingtung show lower correlations, around 0.46 to 0.55 for Tav_g (Figure 13), -0.17 to 0.27 for maximum temperature (Figure 14), and no statistically significant correlations for minimum temperature (Figure 15). Regarding warming trends, while the Tav_g for the six major stations indicates an upward trend, gridded data shows a weaker warming trend compared to weather station data, especially in the Hualien, Taitung, and Pingtung. In terms of maximum temperature, except for Taipei, Taichung, and Tainan, which show weaker warming trends than Tav_g. Hualien, and Taitung in particular exhibit cooling trends in TCCIP data. Finally, in terms of minimum temperature, an upward trend is observed for all six centennial weather stations. In our hypothesis, the performance of maximum largely differs possibly due to the variability introduced by geographical factors. The warming trend in minimum temperature is consistent across all regions, as it is the primary impact of global warming. However, the differences observed may also be related to TCCIP data calculation methods, station selection, interpolation methods, or even the impact of station relocation or instrument settings. Further research and analysis are needed. In the future, we also hope to use data from weather station data and re-examine and quantify the impact of PMM on Taiwan, comparing it with the results of this study.

In addition to discussing the use of data, there is another aspect that requires discussion. This study focuses on exploring the impact of PMM on summer temperatures

in Taiwan at a decadal scale. While the importance of PMM in this study is emphasized, other factors may also influence decadal climate in Taiwan. In Figure 16a, we show the regression of global summer SST onto the EOF PC1 summer temperature in Taiwan.

When PC1 values rise, significant warming of SST occurs not only in EP (i.e. PMM-related SST anomaly), but also in the Indian Ocean (IO). Furthermore, rainfall regressed onto PC1 is showed in Figure 16b, we observe a positive-negative-positive precipitation anomaly near Taiwan (15°N - 35°N , 110°E - 130°E), resembling the decadal Pacific-Japan (PJ) pattern. In the Maritime Continent (MC) region around 0° - 15°S , 120°E - 180°E , a significant reduction in rainfall is observed. Additionally, a strip of reduced rainfall can be seen in the Central America (CA) region, approximately within the range of 15°N - 35°N , 110°E - 130°E . Thirdly, from the changes in global Outgoing Longwave Radiation (OLR) in Figure 16c, analyzed through regression with PC1, an increase in OLR is evident in MC and CA, suggesting a likely decrease in deep convection and, consequently, reduced chances of rainfall. This aligns with the analysis of reduced rainfall shown in Figure 16b. Besides PMM discussed in this study, previous research highlights the importance of the decadal PJ pattern as a major mode of East Asian summer vortex anomalies. They propose that variations in oceanic land temperatures are a source of decadal climate predictability in East Asia (Xie et al., 2022). On the other hand, some indicate that the decadal variation of PJ-like patterns is primarily influenced by SST



changes in the Tropical Indian Ocean (TIO) rather than local anomalies in the WNP (Tao et al., 2017). Therefore, consistent with previous studies, Figure 16 suggests the decadal PJ pattern, convection over the MC, and SST over the Indian Ocean might be another important factor influencing summer climate variation on decadal timescales in Taiwan. To fully understand this variability, more analysis and model experiments are necessary to delve into all potential factors affecting Taiwan's summer climate. Looking ahead, we plan to conduct further in-depth research on how the IO, MC, CA changes affects summer temperatures in Taiwan in addition to PMM variations. This will not only contribute to an overall understanding of climate variability in Taiwan but also provide a more reliable scientific basis for predicting and addressing future climate changes of Taiwan.

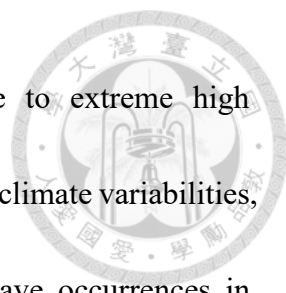
Chapter 2 Impacts of PMM on Heatwaves and Their Exposure in Taiwan



2.1 Introduction

Heatwaves can have profound impacts on human society and natural ecosystems, potentially escalating into natural disasters that threaten human life. The devastating consequences of heatwaves are exemplified by historical events, such as the 1995 Chicago heatwave, which claimed the lives of hundreds of elderlies and chronically ill individuals (Kaiser et al., 2007; Whitman et al., 1997). Similarly, the 2003 European heatwave and the 2010 Russian heatwave resulted in significant mortality rates and widespread health issues (García-Herrera et al., 2010; Mazdiyasni et al., 2017; Porfiriev, 2014). In Asia, heatwaves are a leading cause of weather-related fatalities, with notable events in China in 2013 affecting over 500 million people across nine provinces (Bai et al., 2014) and a 2018 record-breaking heatwave on the Korean Peninsula causing 4,508 cases of heat-related illnesses and 48 fatalities (Im et al., 2019). These instances underscore the perilous nature of heatwaves as natural disasters, emphasizing the critical need to understand their characteristics.

Since the Industrial Revolution in 1850s, human-induced emissions of excessive greenhouse gases have unequivocally led to global warming. Research suggests that these

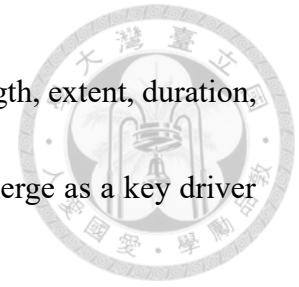


gases can alter climate patterns, fostering conditions conducive to extreme high temperatures (Cresswell-Clay et al., 2022). Beyond human activities, climate variabilities, such as ENSO and the Pacific-Japan pattern, contribute to heatwave occurrences in regions including China, India, Australia, and Taiwan (Luo & Lau, 2019; Naveena et al., 2021; Reddy et al., 2021). For instance, the Pacific-Japan pattern has been linked to droughts and heatwaves in Taiwan (Tseng et al., 2023).

While there has been extensive research on the interannual causes of heatwaves in Taiwan (Huang-Hsiung Hsu, 2017; Lin et al., 2017), understanding decadal changes remains a relatively unexplored area. Recognizing the importance of comprehending changes on a decadal scale for effective climate change adaptation, this study aims to build on the foundation laid in its first chapter. The goal is not only to delve into the physical mechanisms but also to extend scientific findings to practical societal applications.

Specifically, the study explores how the PMM influences heatwaves in Taiwan. Utilizing the calendar day 90th percentile of Tmax method (CTX90pt) as the threshold for extreme high temperatures, the research identifies a significant increase in the frequency and intensity of extreme high temperatures across Taiwan during the positive phase of PMM compared to the negative phase. Furthermore, employing Heatwaves Magnitude Scales (HWMS) as the definition for heatwave events, the study observes that

heatwaves in PMM-positive years are more intense in terms of strength, extent, duration, and frequency compared to the negative phase. PMM variations emerge as a key driver of extreme high-temperature events in Taiwan on a decadal scale.



Drawing inspiration from the work of Nishant, Ji, et al. (2022) and Tuholske, Caylor et al. (2021), which defines exposure to extreme heat as the product of the population multiplied by the number of days per year that a threshold of extreme heat is exceeded, the study calculates exposure to Extreme High Temperature (EHT) days. This assessment aims to understand the population at risk of experiencing EHT events induced by PMM.

In conclusion, the research findings of this thesis are anticipated to significantly contribute to a more comprehensive understanding of the evolving trends in extreme high-temperature events in Taiwan amid the backdrop of global warming. These findings are crucial references for shaping future responses and adaptations to climate change, emphasizing the urgency of mitigating the impacts of heatwaves on human society and the environment.

2.2 Dataset and Methodology



2.2.1 Dataset

2.2.1.1 Population Data

The population data for this study is sourced from the Department of Household Registration, Ministry of the Interior, Taiwan, with statistics compiled as of August 2018. The population in Taiwan is predominantly concentrated in the northern and western regions (Figure 17), with Taipei City, New Taipei City, Hsinchu City, and Chiayi City having the highest population densities, ranging from approximately 1810 to 9830 (*people km⁻²*). Following closely are Taoyuan City, Taichung City, Changhua County, and Kaohsiung City, with population densities ranging from 860 to 1018 (*people km⁻²*). The third-highest population densities are found in Hsinchu County, Miaoli County, Yunlin County, and Tainan City, ranging from 300 to 860 (*people km⁻²*). The least densely populated areas include Yilan County, Hualien County, Taitung County, Nantou County, Chiayi County, and Pingtung County, with population densities below 300 (*people km⁻²*). The color bar intervals in Figure 17 are based on quartiles of the total population.

2.2.2 Methodology

EHT refer to singular or short instances of unusually high temperatures, whereas a heatwave signifies a prolonged period of consistently extreme heat. In our study, to comprehensively assess the heat hazard from PMM, we are conducting an analysis of EHT, as well as heatwave events.

2.2.2.1 The 90th percentile of daily maximum temperature

The first method is the calendar day 90th percentile of daily Tmax method (CTX90pt). It characterizes the EHT by identifying days with exceeding the 90th percentile on a 15-day window for the reference period 1960-2018. A 15-day window is used since the climate characteristics of a particular day may appear a few days earlier or later. (Perkins & Alexander, 2013).

2.2.2.2 Heatwave Intensity Index

The second method is Heatwaves Magnitude Scales, also known as HWMS (Lo et al., 2021), which consists of two parts: “heatwave definition” and “daily magnitude of the heatwave”.

The heatwave definition used in HWMS is an extension of the HWMI_d proposed by Russo et al. (Russo et al., 2015), which is a period of 3 days with the Tmax above the daily threshold for the reference period 1960-2018. The threshold is defined as the



90th percentile of daily Tmax, centered on a 31-day window. The threshold is the 90th percentile of the set of data defined as following:

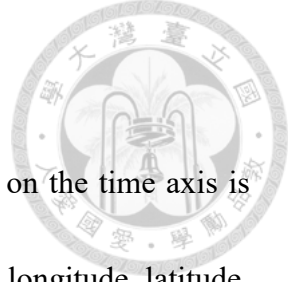
$$A_d = \bigcup_{y=1981}^{2010} \bigcup_{i=d-15}^{d+15} T_{(y,i)} \quad (2.1)$$

where $\bigcup$ denotes the union of sets and $T_{y,i}$ is the daily Tmax of the day i in the year y . Daily heatwave magnitude (M_d) was defined by the definition of grid temperature intensity is a little similar to CTX mentioned above, but the window is expanded to include the 15 days before and after the target day, resulting in a 31-day window.

If the daily maximum temperature in the grid exceeds the 25th percentile of historical maximum temperatures, the difference between the daily maximum temperature and the 25th percentile of historical maximum temperatures is divided by the difference between the 75th percentile and the 25th percentile of historical maximum temperatures, resulting in the standardized temperature intensity for that grid on the target day. If the daily maximum temperature in the grid does not exceed the 25th percentile of historical maximum temperatures, the temperature magnitude M_d is 0. The formula is as follows:

$$M_d(T_d) = \begin{cases} \frac{T_d - T_{25p}}{T_{75p} - T_{25p}}, & \text{if } T_d > T_{25p}; \\ 0, & \text{if } T_d \leq T_{25p} \end{cases} \quad (2.2)$$

M_d represents the temperature magnitude for a grid, T_d represents the maximum temperature of the grid for the given day, T_{25p} represents the 25th percentile of historical maximum temperatures for that grid, and T_{75p} represents the 75th percentile of historical



maximum temperatures for that grid.

In this approach, the maximum temperature data for each grid on the time axis is treated as a 3D volume pixel, also known as a voxel, which includes longitude, latitude, and time attributes. If the M_d values of adjacent voxels are not equal to zero, they are considered part of the same heatwave event. The M_d values of voxels within the same heatwave event are summed to obtain the Heatwave Magnitude Scale (HWMS). The formula is as follows:

$$HWMS = \sum_{t=d_1}^{d_n} \sum_{x=x_e}^{x_w} \sum_{y=y_s}^{y_n} M_d(x, y, t) \delta(x, y, t) \Delta x \Delta y \cos(\varphi(x, y)) \quad (2.3)$$

d_1 represents the first day of the heatwave event, and d_n represents the last day. x_e and x_w represent the starting and ending longitudes of the heatwave event from east to west, while y_s and y_n represent the starting and ending latitudes of the heatwave event from south to north. Δx and Δy are the cosine of latitude weights.

$$\delta(x, y, t) = \begin{cases} 1, & \text{if } M_d > 0; \\ 0, & \text{if } M_d = 0 \end{cases} \quad (2.4)$$

is used to eliminate voxels with lower Tmax values within the event.

Using the HWMS approach, various characteristics of heatwave events can be further analyzed as follows:

Heatwave Event Magnitude Volume (HWMV): This measures the overall impact of the heatwave event, focusing solely on the spatial and temporal extent without considering temperature intensity. Unit: day km²

$$HWV = \sum_{t=d_1}^{d_n} \sum_{x=x_e}^{x_w} \sum_{y=y_s}^{y_n} \delta(x, y, t) \Delta x \Delta y \cos(\varphi(x, y)) \quad (2.5)$$

Mean Magnitude of a Heatwave Event (HWMM): This calculates the average intensity per voxel by dividing the total heatwave magnitude (HWMS) by the heatwave event volume (HWV). Unit: unitless.

$$HWMM = \frac{HWMS}{HWV} \quad (2.6)$$

Mean Area of a Heatwave Event (HWMA): This represents the average spatial extent of the heatwave event per day. Unit: km²

$$HWMA = \frac{HWV}{d_n - d_1 + 1} \quad (2.7)$$

Mean Duration of Heatwave Event (HWMD): This measures the average number of days that extreme high temperatures persist in each grid within the heatwave event. Unit: day.

$$HWMD = \frac{HWV}{\sum_{x=x_e}^{x_w} \sum_{y=y_s}^{y_n} \delta_d(x, y) \Delta x \Delta y \cos(\varphi(x, y))} \quad (2.8)$$

2.2.2.3 Exposure of Extreme High Temperature

To assess the degree which individuals encounter and are affected by heatwave event, we use the following equation (Jones et al., 2015; Liu et al., 2017; Nishant et al., 2022):

$$\Delta E_c = P_1 \times \Delta C \quad (2.9)$$

ΔE_c is the exposure of climate effect, the unit is person/ day. P_1 represents the population base from 1960 to 2018, ΔC is the change of HWD from 1960 to 2018.

2.3 Results



2.3.1 Extreme high temperature associated with PMM

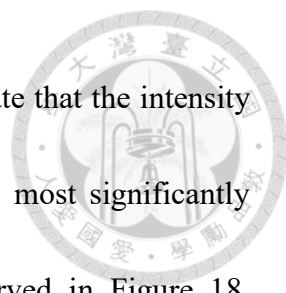
The calendar day 90th percentile of daily maximum temperature is utilized to define the extreme high temperature in this research. We conducted a probability distribution function (PDF) analysis for daily T_{max} , the frequency and magnitude of EHT in PMM-positive and PMM-negative years during the period of 1960-2018 in JJA. The detailed definition of the PMM-positive and PMM-negative phases is provided in the Section 1.2.1.1 .

A rightward shift in the probability distribution function (PDF) of T_{max} is observed during PMM-positive years compared to PMM-negative years (Figure 18a). This suggests that, during PMM-positive years, there is a tendency for higher T_{avg} , indicating an increase in the occurrence of high-temperature events. In Figure 18c, there is an increase in almost every region of Taiwan during positive years, with statistical significance at the 10% confidence level in northwest and east regions. Some minor areas in the north and south also exhibit significant warming, but statistical tests were inconclusive for most areas. On the contrary, a significant decrease in T_{max} across the entire Taiwan during PMM-negative years is shown (Figure 18d), with statistical significance at the 10% confidence level everywhere in Taiwan except for the northern



region. When moving into the difference between positive and negative years (positive minus negative; Figure 18b), an elevation in T_{max} is evident across most regions in Taiwan with the notable increase is predominantly concentrated in northwest, southwest and east region in Taiwan. The results of Figure 18 indicate that the northwest and east regions of Taiwan stand out as the most susceptible to the influence of PMM, showcasing a prominent impact on temperature variations. In contrast, the northern and southern regions, while also affected by PMM, demonstrate comparatively higher variability in their response. These findings contribute significantly to a comprehensive understanding of the intricate interaction between the PMM and the nuanced patterns of temperature variations across different regions in Taiwan.

Figure 19a show a rightward shift in the PMM-positive year compared to the PMM-negative year are also shown in the PDF of EHT magnitude, indicating that the magnitude of EHT in the PMM-positive year is stronger than that in the PMM-negative year. There is a higher magnitude of EHT over most regions in Taiwan during PMM-positive years (Figure 19c), distributed in the west and east region in Taiwan, while a decrease magnitude in southern region. During negative years, a lower magnitude of EHT appears most regions, while slightly decrease of magnitude in the minor area in the south region. (Figure 19d). The highest differences between positive years and negative years are concentrated in the northwestern, and eastern regions of Taiwan, with decrease of



magnitude in part of south region. The results from Figure 19 indicate that the intensity of extreme high temperatures in the northwest and east regions is most significantly enhanced during PMM-positive years, mirroring the trends observed in Figure 18. Additionally, the intensity of extreme high temperatures in the southern region exhibits sporadic decreases during positive phases and slight increases during negative phases of PMM. This suggests that the influence of PMM on extreme high temperatures is less pronounced in the southern region.

The PDF of EHT frequency also depicts a rightward shift in the PMM-positive year compared to the PMM-negative year (Figure 20a), which means the amount of EHT days is higher than that in the negative days. There is an increased frequency in most of the northwest and eastern and part of the north regions during positive years, while the southern region experiences a decrease in EHT frequency (Figure 20c). On the other hand, during PMM-negative years, there is a significant decrease in EHT frequency across the entire Taiwan (Figure 20d) especially in northwest region. The difference map (positive minus negative) delineates the most pronounced disparities in the northwest, east, and certain portions of the northern regions. Among these, the northwest region exhibits the most notable increase in EHT frequency (Figure 20b). In conclusion, the Figure 20 shows that the northwest and east regions exhibit a robust association between PMM and Tmax and EHT, especially in northwest, while the southern region demonstrates a



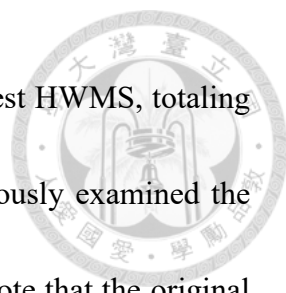
comparatively weaker impact. On the other hand, the southern region exhibits a decreasing trend in heatwave days in both positive and negative phases, suggesting a less pronounced association between PMM and heatwave occurrences in the southern part of Taiwan.

2.3.2 Heatwave events associated with PMM

To conduct a comprehensive analysis of heatwaves, we employed the HWMS (Lo et al., 2021), facilitating a decomposition of heatwaves into six key features. These features collectively quantify the characteristics of heatwaves, and their detailed definitions can be found in Section 2.2.2.2.

Figure 15 presents an insightful overview of heatwave features during both PMM-positive and PMM-negative years. Notably, all examined heatwave characteristics exhibit higher values in PMM-positive years compared to PMM-negative years. Among them, occurrence frequency is approximately 2.15 times higher during positive phases. Additionally, the values of HWMD during positive PMM years are substantial, nearly three times those of negative PMM years. This suggests that heatwaves in positive PMM phases are significantly more intense in terms of their intensity, extent, and duration, with occurrence frequency and duration being the most prominent factors.

To further evaluate the heat hazard posed by extreme heatwave events, we identified



the five most extreme heatwave events each year based on the highest HWMS, totaling 105 extreme events. Employing boxplots in Figure 22, we meticulously examined the distribution of values for each contributing factor. It's important to note that the original values of heatwave factors are substantial, and their distributions exhibit significant variability. For simplicity in analysis and interpretation, the data in Figure 22 is presented after logarithmic transformation. In the realm of extreme heatwaves, the values of HWMS components, specifically HWMV, HWMD, and HWMA, demonstrate higher magnitudes during PMM-positive years compared to PMM-negative years. Conversely, the values of HWMM are nearly identical between extreme heatwaves in PMM-positive and PMM-negative years. This suggests that, while extreme heatwaves in positive PMM years may not intensify in individual units more than those in negative PMM years, they exhibit a prolonged scope and duration. Furthermore, an examination of the interquartile range (IQR) reveals a distinct pattern. During PMM-positive years, the IQR demonstrates a higher and narrower distribution across all considered factors. This indicates a more severe and concentrated distribution of extreme heatwave characteristics compared to PMM-negative years. In summary, the PMM-positive phase not only influences the magnitude but also the duration and concentration of extreme heatwaves, setting it apart from the PMM-negative phase.

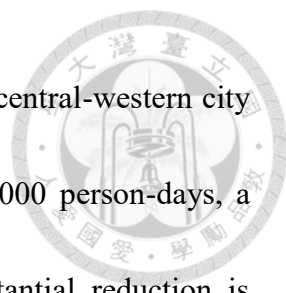
2.3.3 Exposure to EHT



2.3.3.1 Exposure Regressed to PMM and Long-Term Trend

In Figure 23a, the northern, northwestern, and eastern regions are the primary areas where exposure to EHT increases. Particularly noteworthy are Taipei City in the northern part, Taichung City in the northwestern region, and Miaoli County, where exposure sees the most significant increase. This distribution, when compared with the heatwave frequency pattern in Figure 22b, suggests that although the northern region doesn't experience the highest increase in the number of heatwave days, its densely populated areas still result in substantial exposure. Additionally, the northwest region stands out with a notably increased number of heatwave days and a substantial population, making it the location with the highest exposure. Among these areas, Taichung City is particularly with a notable amount of exposure, being a Special Municipality with a significant population. While the eastern region experiences a considerable increase in heatwave frequency, the lower population density prevents exposure from reaching particularly high levels. Conversely, in the southern region, cities such as Tainan City, Changhua County, Kaohsiung City, and Pingtung County experience a notable decrease in exposure due to a reduction in the number of heatwave days (Figure 22b).

During the PMM-negative year (Figure 23b), a decline in exposure is observed



across Taiwan, with the most significant reduction occurring in the central-western city of Taichung. The exposure in Taichung decreases by over 15,000,000 person-days, a figure at least three times higher than any other city. This substantial reduction is attributed to Taichung City being situated in the primary region where heatwave days decrease, coupled with its dense population distribution. Additionally, in the southern region, cities like Kaohsiung and Tainan also experience a reduction in exposure, although not as extensively as observed in Taichung City.

The northwest region exhibits the highest disparity between PMM-positive and PMM-negative years (Figure 23c), with Taichung City standing out the most. The exposure difference in Taichung City can reach up to 19,800,000 person-days, at least three times higher than any other city. This underscores the significant impact of PMM on exposure in urban areas, particularly making Taichung City a city of primary concern when PMM is in the positive phase. Moreover, in most other regions, exposure during PMM-positive years exceeds that of PMM-negative years, highlighting the impact of PMM on exposure levels across diverse areas. In contrast, in the southern region, exposure during PMM-positive phases is lower than during PMM-negative phases, indicating that exposure variations in the southern region may have a less direct relationship with PMM.

2.3.3.2 Exposure when PMM Enhances and in Long-Term Trend

In our exploration of exposure differences between positive and negative PMM phases, we delved deeper into understanding how exposure variations are influenced by variation in PMM and long-term warming. To provide a comprehensive perspective on the influencing factors, we employed regression analysis, linking the number of heatwave days to the standardized PMM index and quantifying exposure changes for each county and city during PMM enhancement.

With PMM enhancement, the exposure in the northwest and eastern regions demonstrates an upward trend (Figure 24). Notably, Taichung City stands out with a substantial increase in exposure, exceeding four times that of other counties and cities, consistent with the findings in Figure 23. Conversely, despite New Taipei City showing an increase in exposure in Figure 24a, it paradoxically exhibits a decreasing trend. This could be attributed to sporadic zones of exposure reduction in specific townships within the northern region. Furthermore, southern cities such as Kaohsiung and Pingtung also experience a declining exposure trend, consistent with the observations in Figure 23.

A noteworthy observation is the reversal in exposure distribution under long-term trends (Figure 24b). The northern, southern, and eastern regions emerge as the primary areas experiencing increased exposure, with New Taipei City and Taipei City in the north, and Tainan City and Kaohsiung City in the south, showing particularly significant

increases. This points to a robust correlation between exposure in these areas and the long-term warming trend. In contrast, the central region, especially the Taichung area, does not display an increasing exposure trend and, in fact, shows a slight downward trend.

Figure 24c illustrates that all counties and cities are distributed in the first, second, and fourth quadrants, suggesting that at least one factor is contributing to increased exposure in these areas, whether influenced by PMM or long-term trends. It's notable that Taichung City, marked with a yellow circle in the chart, represents a conspicuous extreme value situated in the fourth quadrant. This signifies that, during PMM strengthening, Taichung experiences a significant increase in exposure, while under long-term trends, there is a subtle downward trend. Additionally, some extreme values are distributed in the first and second quadrants, including New Taipei City, Taipei City, Kaohsiung County, and Tainan County. These areas exhibit a considerable increase in exposure under long-term warming trends, although their response to PMM is comparatively minor.

2.4 Summary

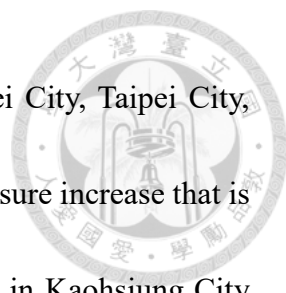
In Chapter 2, this study investigates the impact of the PMM on extreme high temperatures and heatwave events in Taiwan. CTX90pt is used as the threshold to assess extreme high temperatures, and the HWMS method is employed to analyze the spatial, intensity, and temporal characteristics of heatwave events. We especially focus on

explores the relationship between PMM and extreme high temperatures and heatwaves in Taiwan (Figure 25).



When CTX90pt is used as the threshold for heatwaves, the probability distribution chart indicates that, during the positive phase of PMM, Taiwan experiences higher extreme high temperatures. Furthermore, the probability distribution chart for heatwaves with CTX90pt as the threshold reveals that the positive phase of PMM is associated with more intense and prolonged heatwaves, with an increased frequency of extreme long-duration and high-intensity heatwaves. In terms of heatwaves, this study comprehensively assesses their distribution in time and space using the HWMS. The study calculates the frequency of heatwaves occurring in PMM-positive and PMM-negative years. Simultaneously, five key metrics of heatwave events are analyzed: overall magnitude (including intensity, duration, and extent), average intensity, heatwave volume (including duration and extent), heatwave duration, and heatwave extent. In PMM-positive years, there is an increase in the frequency of heatwaves, and the overall magnitude becomes stronger, mainly due to the increase in heatwave duration. The study further analyzes the top five extreme heatwave events each year, revealing that heatwaves in PMM-positive years are stronger in all metrics compared to events in PMM-negative years.

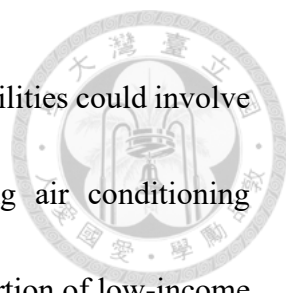
To assess the direct impact of PMM-induced heatwaves on the population, the study calculates the population exposure for each county and city. The results indicate that,



when PMM strengthens, the highest exposure occurs in New Taipei City, Taipei City, Taoyuan City, and Taichung City. Taichung City experiences an exposure increase that is more than three times that of other cities. Conversely, the exposure in Kaohsiung City and Tainan City is less affected by the strengthening of PMM. In conclusion, this study provides valuable insights for medical resource allocation, agriculture, industry, energy, and various other sectors, aiding in the formulation of more effective adaptation strategies in the face of PMM-induced heatwaves in Taiwan.

2.5 Discussion

The results of this study have implications for diverse sectors. In the context of human health and safety, the decadal-scale exposure to EHT presented in this study guides our understanding of which areas may have a higher risk of residents being affected by EHT, which can be applied in the development of medium to long-term adaptation strategies. Local healthcare institutions can proactively engage in construction and preparation, utilizing the decadal-scale exposure as a reference. With a more precise assessment of potential increases in heat-related illnesses under heightened exposure, healthcare facilities can undertake construction of additional hospital beds, staff allocation, stocking of medicines, and even enhance backup energy facilities several years in advance to meet the anticipated rise in demand for medical resources. In counties or



cities with high exposure, strategies to improve heat adaptation capabilities could involve establishing air-conditioned centers in public spaces or lowering air conditioning temperatures. This is especially important in areas with a high proportion of low-income or elderly populations, where encouraging air conditioning installation and providing relevant subsidies could be beneficial. Additionally, implementing a notification system for heat injuries, compiling concern lists of high-risk groups (elderly individuals, low-income households, solitary residents), conducting heat warnings and public health education, such as promoting indoor activities and providing reminders of heatstroke symptoms, are effective strategies. (Zuo et al., 2015).

In addition to its implications for human health, this study extends its applications to the field of agricultural resources. Various studies suggest that heat can have diverse impacts on crops, including reduced photosynthesis, leaf senescence, diminished pollen production and viability, seed abortion, and ultimately resulting in lower grain number and weight (Siebert and Ewert 2014). The insights gained from understanding the future trends of heatwaves over the next decade enable informed proper decisions or implementing enhanced agricultural practices. For instance, selecting heat-tolerant crop varieties, enhancing irrigation efficiency, and implementing site management strategies to improve soil health through increased organic matter and microbial biomass can be considered. All these measures require long-term investment in technology or

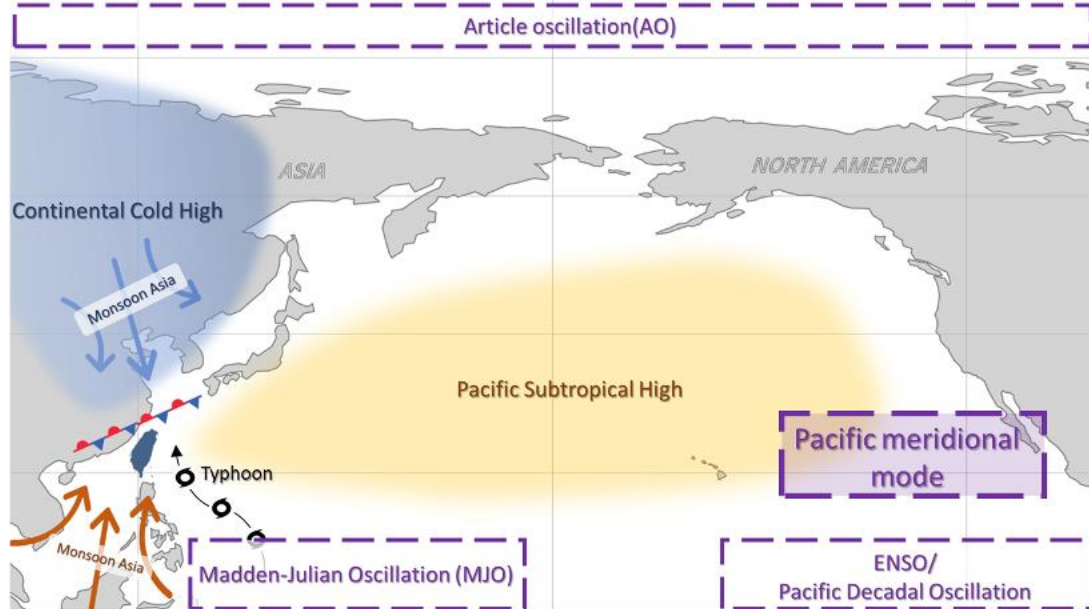
infrastructure development, highlighting the need of decadal heatwaves information.

The insights from this study are not confined to agriculture and healthcare but can also be applied to areas such as energy demand management and urban planning. By comprehending the relationship between PMM and heatwaves, we can boost societal adaptability and effectively mitigates the potential impacts of heatwaves on both public health and facilities for the upcoming decade.

FIGURES



(a) Climate variabilities



(b) Climate Predictability sources

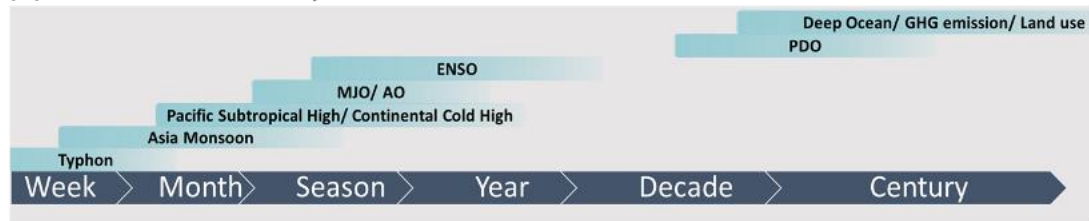


Figure 1 Climate Variability Influencing Taiwan and Corresponding Forecast Time Scales.

(a) Illustration of Taiwan's location at the juncture of the subtropical and tropical regions in the northwest Pacific, and climatic variabilities that impact Taiwan's climate. (b) Representation of the periodicities of climatic variabilities influencing Taiwan, along with their corresponding predictabilities time scales. The figure is adapted from Hoskins (2013).

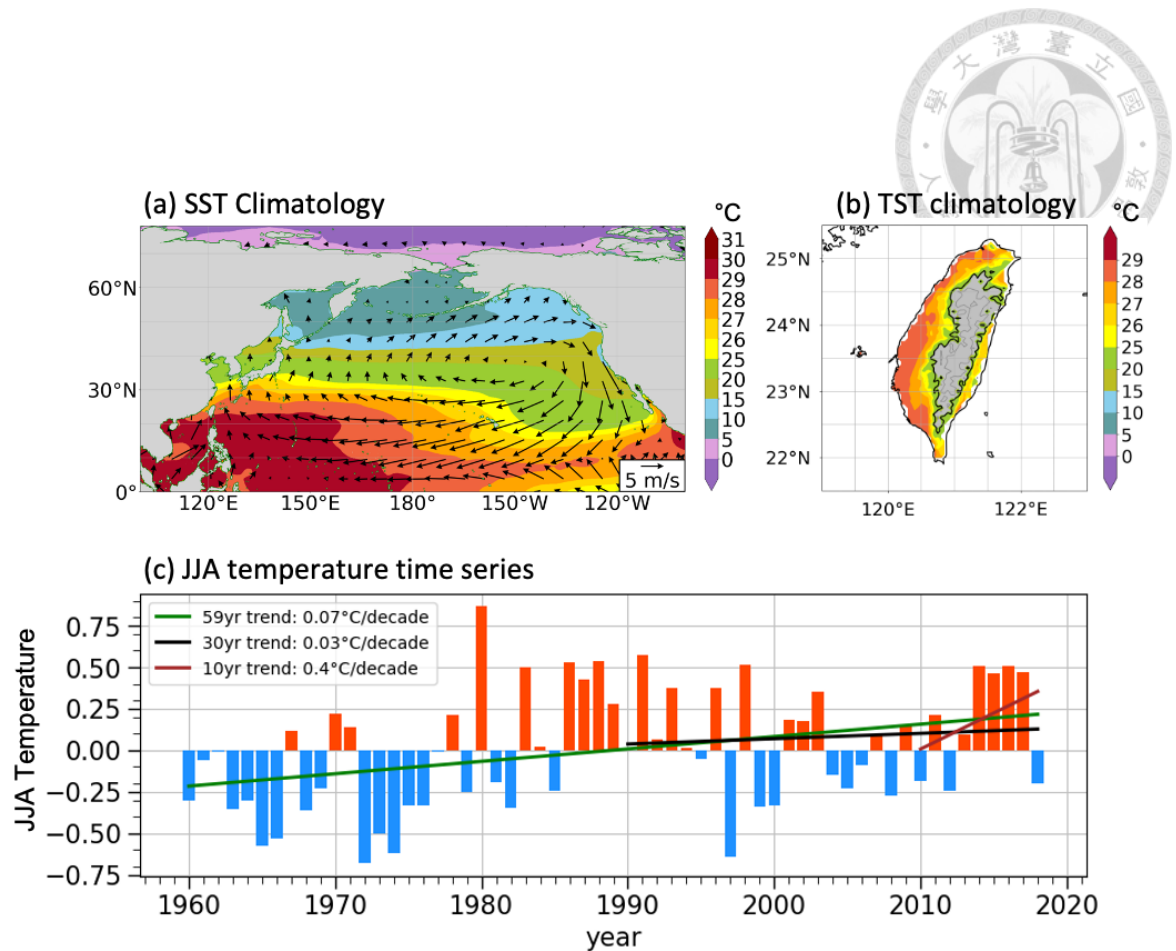


Figure 2 Pattern and Time Series of Climatological SST, Horizontal Wind and JJA Tavg in Taiwan. (a) illustrates the climatological SST (shading; °C) and horizontal wind (vector; ms⁻¹) at 850 hPa in JJA over the NP. SST is derived from the Monthly version of HadISST sea ice component, and horizontal wind is based on ERA5 reanalysis. (b) depicts the climatology of JJA Tavg (shading; °C) in Taiwan, utilizing TCCIP monthly observation grid data. The gray shading denotes regions above an altitude of 1000 meters. Topographic data is sourced from the ETOPO1 1 Arc-Minute Global Relief Model by NOAA. (c) presents a time series of JJA Tavg in Taiwan. The green line represents the 59-year trend, the black line indicates the 30-year trend, and the red line shows the 10-

year long-term trend ($^{\circ}\text{C}$). The data presented in figure 2 spans the period from 1960 to 2018.



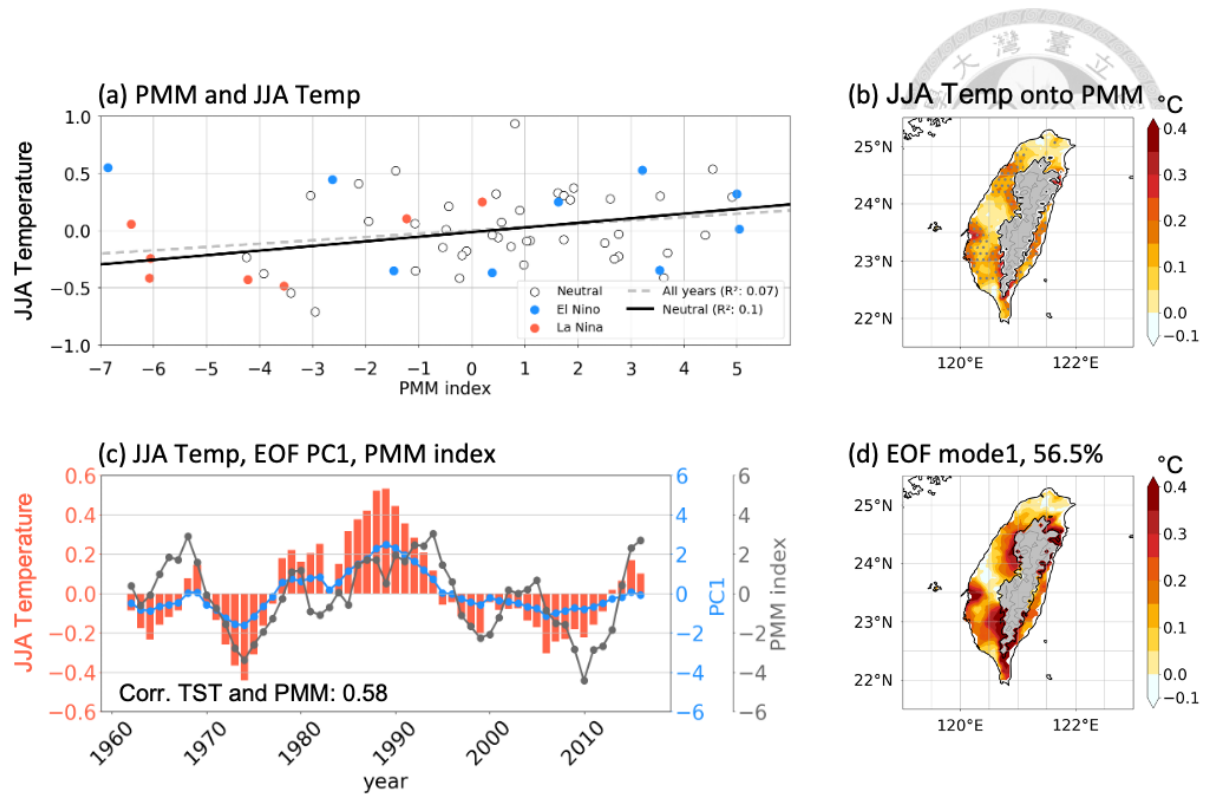


Figure 3 Analysis of the Relationship Between PMM and JJA Tavg in Taiwan. (a) is the scatter plot depicting the relationship between the PMM index (unitless) and JJA a Tavg (°C) in Taiwan. The PMM index is sourced from the NOAA Earth System Research Library and the JJA temperature is from TCCIP. El Niño years are represented by blue circles (ONI exceeding 1), La Niña years by red circles (ONI lower than -1), and neutral years (ONI ranges from -1 to 1) by black-bordered circles. The fitting lines are included for neutral (solid black line) and all years (gray dashed line). (b) is the regression map of the standardized PMM index on JJA temperatures (°C) in Taiwan. Significance dots at the 10% level highlight notable points in the data. (c) is the yearly time series displaying JJA temperature (red bars; °C), EOF PC1 of the JJA temperature in Taiwan (blue line; unitless), and standardized PMM (black line; unitless). (d) is the EOF Mode1 of the JJA

temperature (°C) in Taiwan. The data presented in figure 3 spans the period from 1960 to 2018.



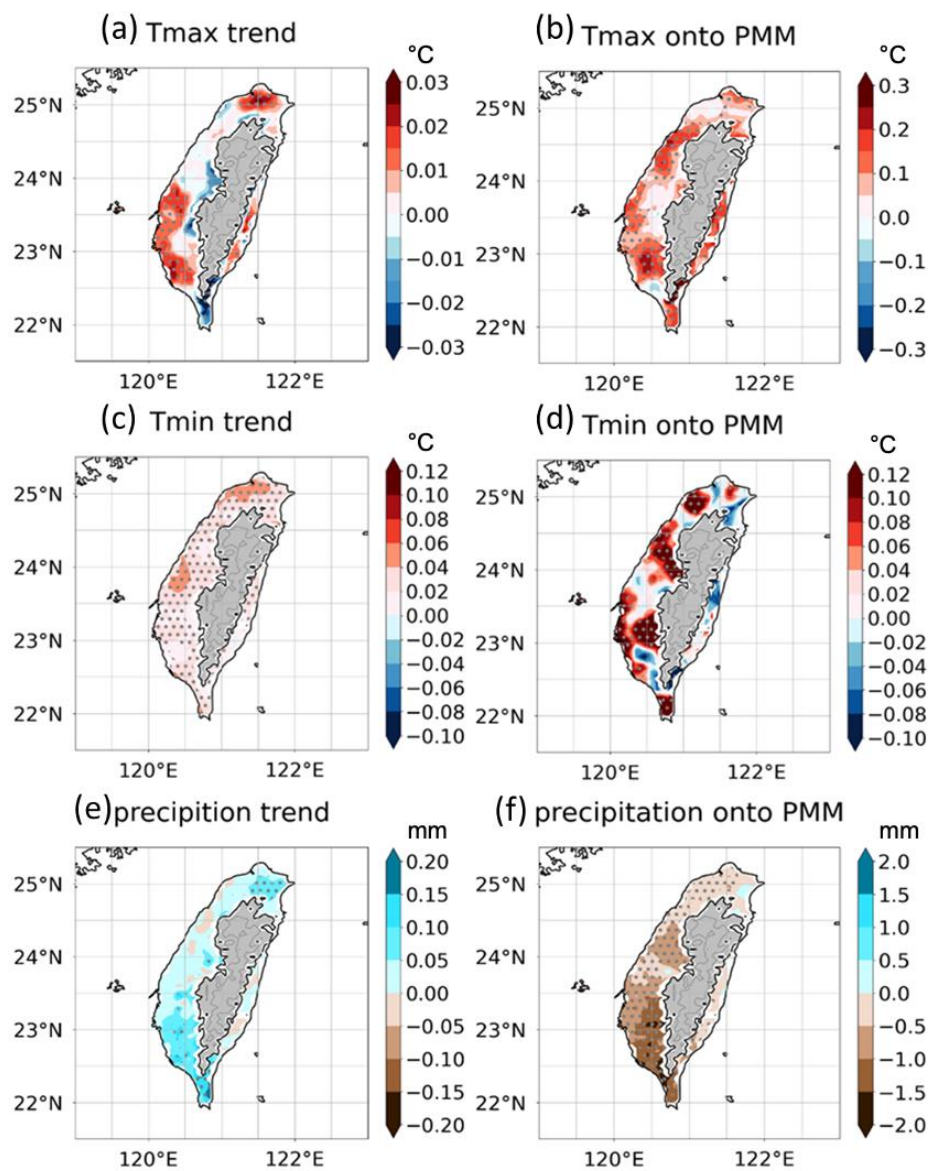


Figure 4 Long-Term Trends and PMM Regression Analysis for JJA Tmax, Tmin, and Precipitation in Taiwan. (a), (b), and (c) illustrate the trends in Tmax (°C), Tmin temperature (°C), and precipitation (mm) in JJA. (d), (e), and (f) present regression maps of the same variables but onto the standardized PMM Index. Significance is denoted by dots at the 10% level. The data for all variables are sourced from the TCCIP monthly observation grid data. The data presented in figure 4 spans the period from 1960 to 2018.

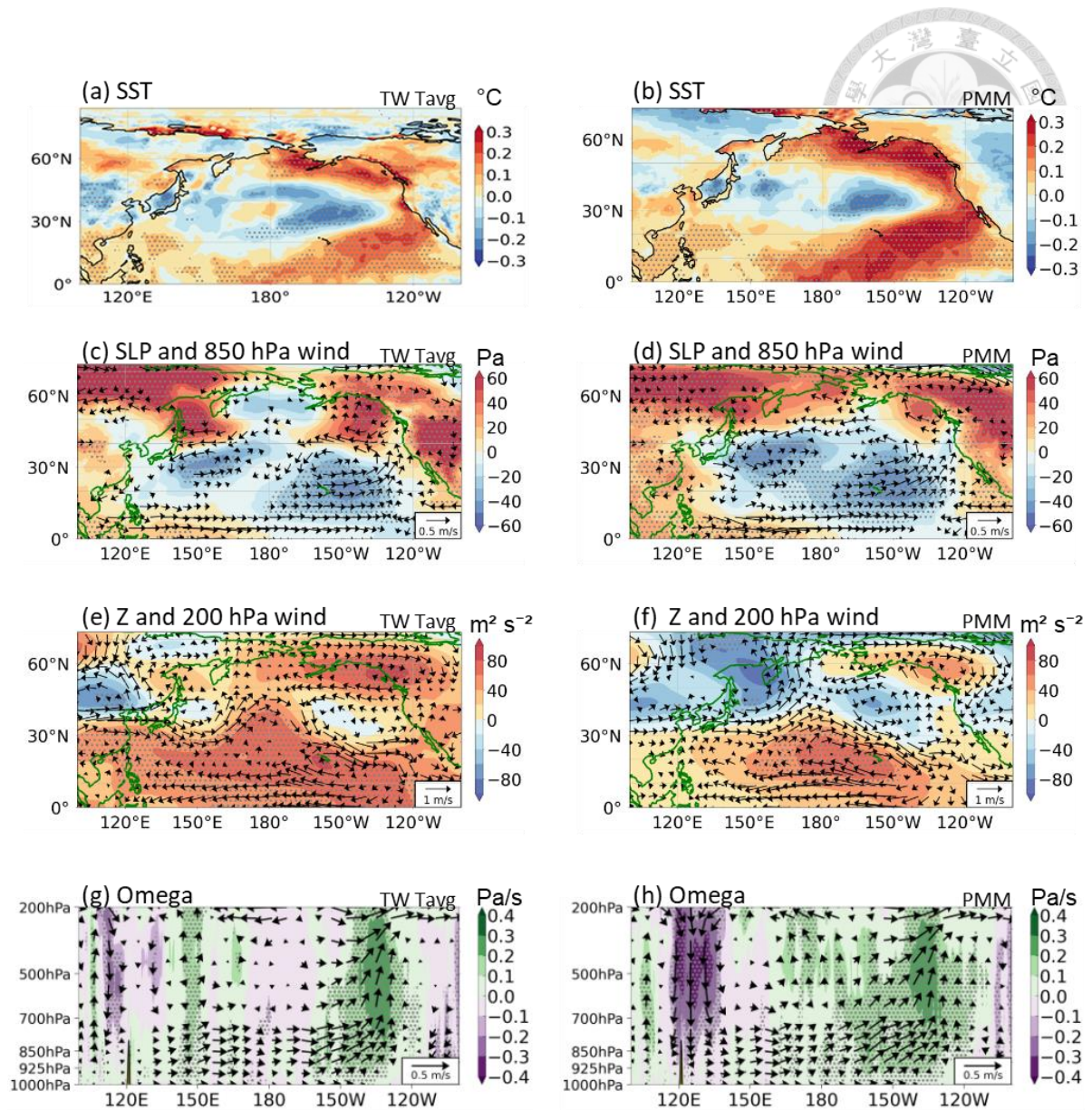
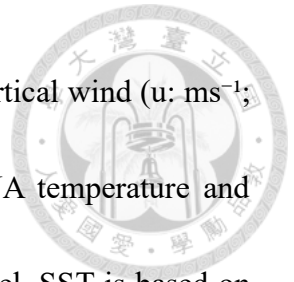


Figure 5 Regression Pattern of Large Circulation in NP onto JJA Temperature and the Standardized PMM Index. (a) and (b) are T2m ($^{\circ}\text{C}$; land only) and SST ($^{\circ}\text{C}$) regressed onto JJA temperature in Taiwan and standardized PMM index. (c) and (d) are wind at 850hPa (ms^{-1} ; vector) with sea level pressure (SLP; Pa; shading) regressed onto JJA temperature in Taiwan and standardized PMM index. The (e) and (f) are wind (u: ms^{-1} ; omega: 10^2Pa s^{-1} ; vector) and geopotential height (Z; m^2s^{-2} ; shading) at 200hPa regressed

onto JJA temperature and standardized PMM index. (g) and (f) is vertical wind (u: ms^{-1} ; omega: 10^2Pas^{-1} ; vectors) with omega (shading) regressed onto JJA temperature and standardized PMM index. Dots indicate significance at the 10% level. SST is based on the Monthly version of HadISST, and the rest of the data is based on ERA-5 Reanalysis. The data presented in figure 5 spans the period from 1960 to 2018.



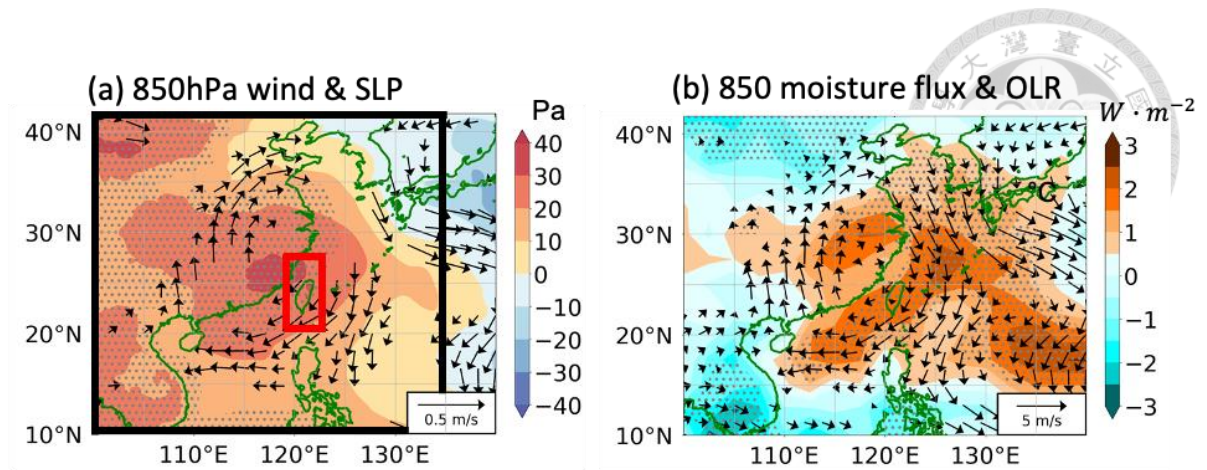


Figure 6 Regressed Regional Features in Southeast Asia to PMM index. (a) illustrates horizontal wind at 850hPa (v : ms^{-1} ; vector) and SLP (Pa; shading) in Southeast Asia based on ERA-5 reanalysis data from 1960 -2018, regressed onto the standardized PMM index. (b) displays OLR based on NOAA observation data from 1980-2018 (Wm^{-2} ; shading) and moisture flux based on ERA-5 reanalysis data from 1960-2018 (gkg^{-1} ; vector), regressed onto the standardized PMM index. Dots indicate significance at the 10% level.

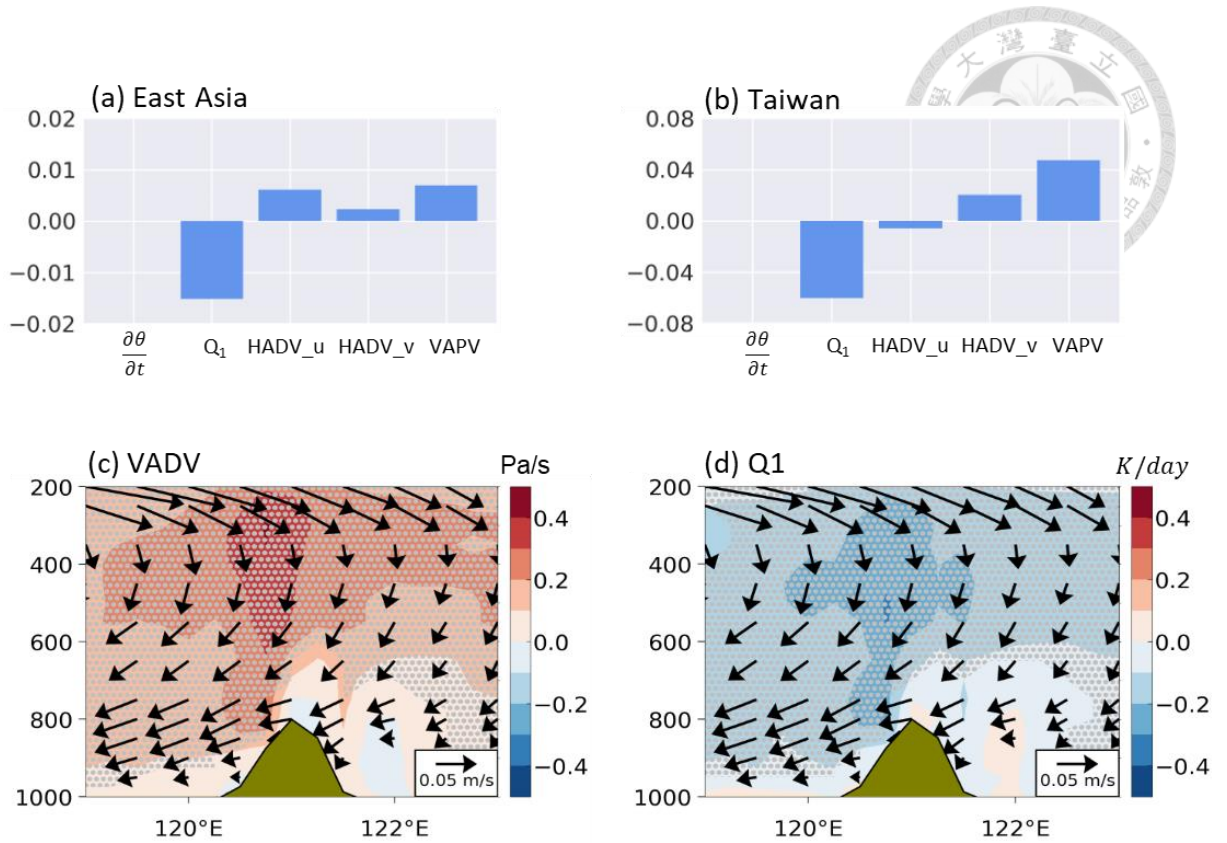


Figure 7 Thermodynamic Budget Analysis and Vertical Cross Section Regressed onto Standardized PMM Index. (a) Displays the average of each component in the Thermodynamic Budget Analysis near the land of Taiwan. (red box in Figure 6; 119°E-123°E, 21°N-26°N). Components include $\frac{\partial \theta}{\partial t}$ (temporal change of potential temperature), Q_1 (diabatic heating term), HADV_u (zonal horizontal advection term: $pU \frac{\partial \theta}{\partial x}$), HADV_v (meridional horizontal advection term, $pV \frac{\partial \theta}{\partial y}$), and VADV (adiabatic term: $p\omega \frac{\partial \theta}{\partial x}$). The unit of all components: $Kday^{-1}$. (b) Similar to (a), but in the southeast Asia (black box in Figure 6; 100°E-135°E, 10°N-40°N). (c) vertical cross section of VADV ($Kday^{-1}$; shading) and wind (u : ms^{-1} ; ω : $10Pas^{-1}$; vector) regressed onto standardized PMM index. (d) Similar to (a), but Q_1 ($Wday^{-1}$, shading) and wind (u : ms^{-1} ; ω :

10Pas⁻¹; vector). The data presented in figure 7 spans the period from 1960 to 2018.

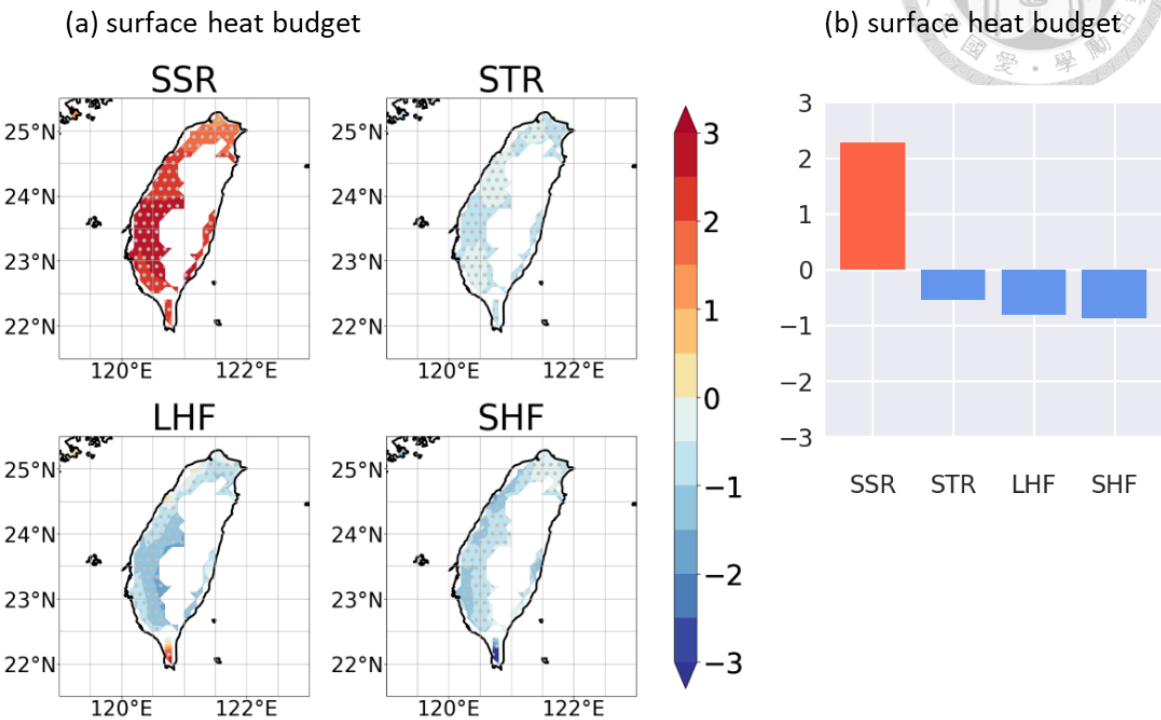


Figure 8 Surface Energy Budget Analysis and Regressed onto Standardized PMM Index.

(a) Each component of surface energy budget regressed onto the standardized PMM, including components as surface net solar radiation (SSR), surface net thermal radiation (STR), surface latent heat flux (LHF), and surface sensible heat flux (SHF). The data are sourced from ERA-Land, with the units of each component expressed in $\text{Wm}^{-2}\text{s}^{-1}$. (b) Presents the average of each component in the Surface Heat Budget Analysis over the land of Taiwan. The data presented in Figure 8 is based on ERA-LAND data and from 1960 to 2018.

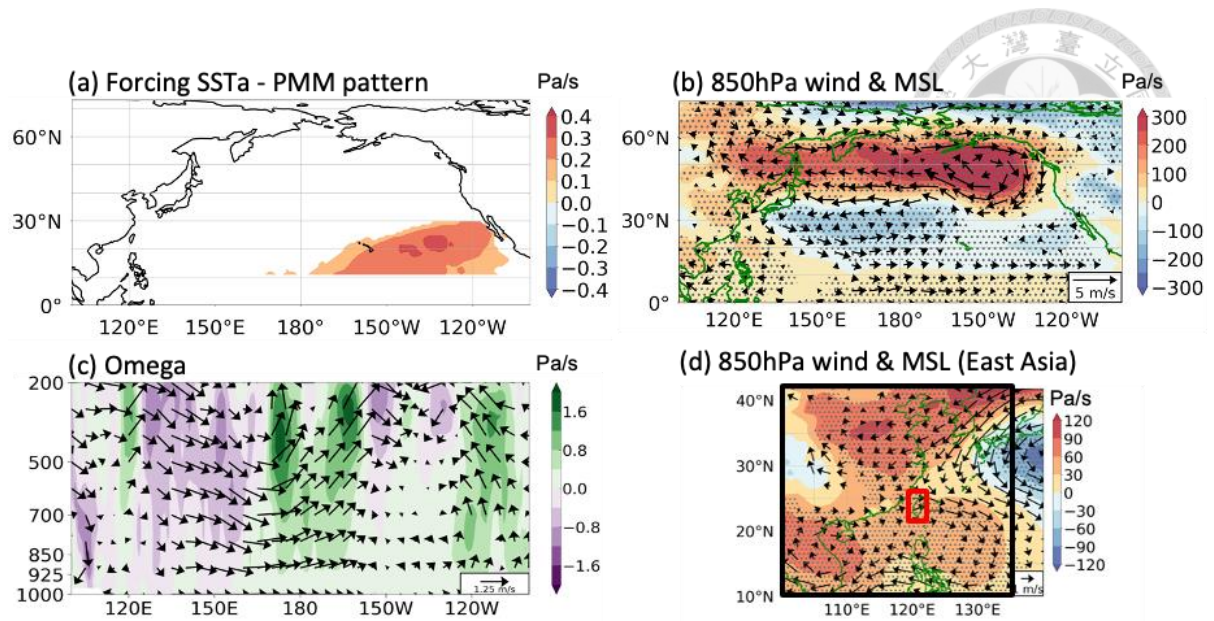


Figure 9 Forcing SST Anomalies and Results in PMM Experiments. (a) Forcing SST anomalies with the PMM pattern ($^{\circ}\text{C}$; shading) in the PMM Experiments are illustrated, defined as the region where SST increases by more than 0.1°C between 160°E and 140°W when regressed onto the standardized PMM index. (b) The differences in wind (ms^{-1} ; vector) and MSL (Pa s^{-1} ; shading) at 850hPa between the CTL experiment and PMM experiment are showed. (c) The differences in vertical wind (u : ms^{-1} ; omega: 10^2Pa s^{-1} ; vector) and omega (shading) between the CTL experiment and PMM experiment are depicted. (d) Similar to (b) but focusing on East Asia.

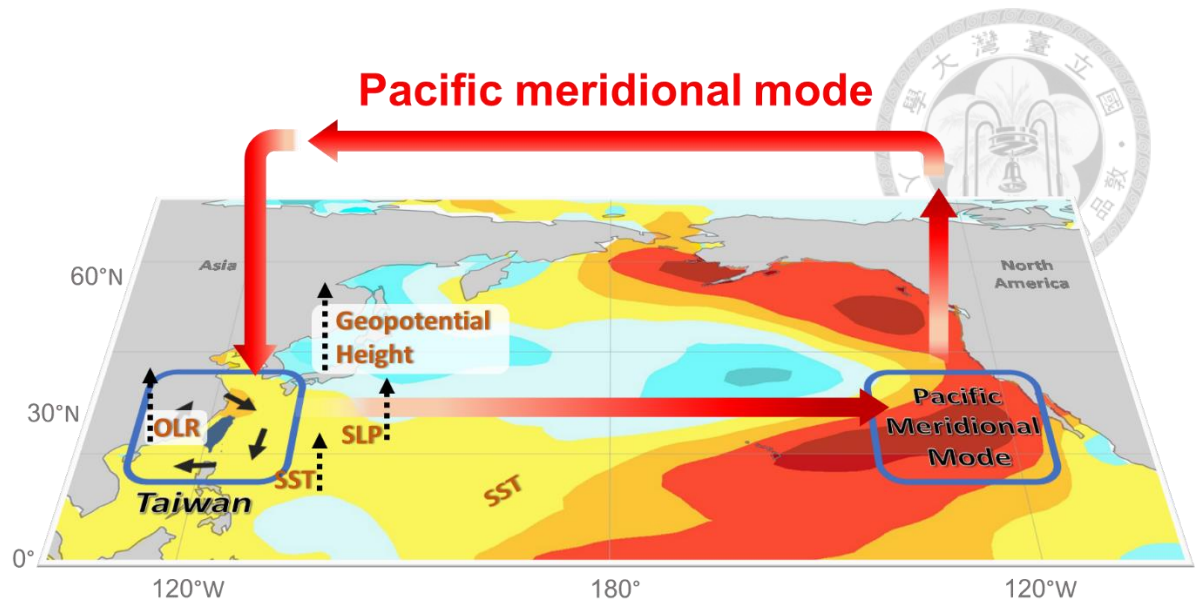


Figure 10 Illustration of the proposed impacts of enhanced PMM SST anomaly on summer surface warming in Taiwan.

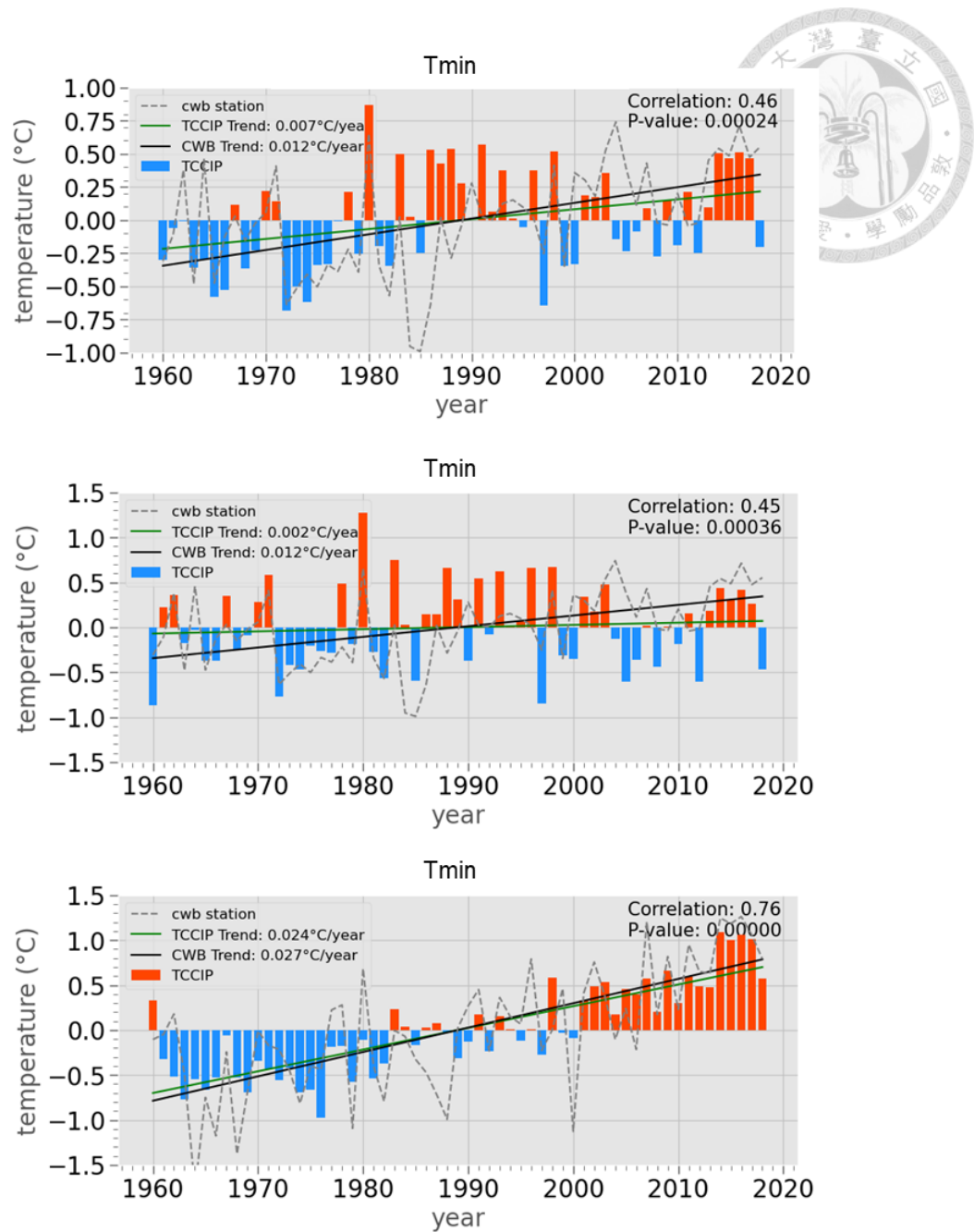


Figure 11 Temperatures Comparison of between TCCIP Gridded Data and CWA Weather Station Data at Six Centennial Stations in Taiwan. The bar chart represents TCCIP gridded data, while the gray dashed line corresponds to CWA Weather Station data. The green line means the trend of TCCIP gridded data, and the black line is CWA Weather Station Data. The data presented in figure 11 spans the period from 1960 to 2018. The weather station

names and locations are detailed in Table 2. Unit: °C.

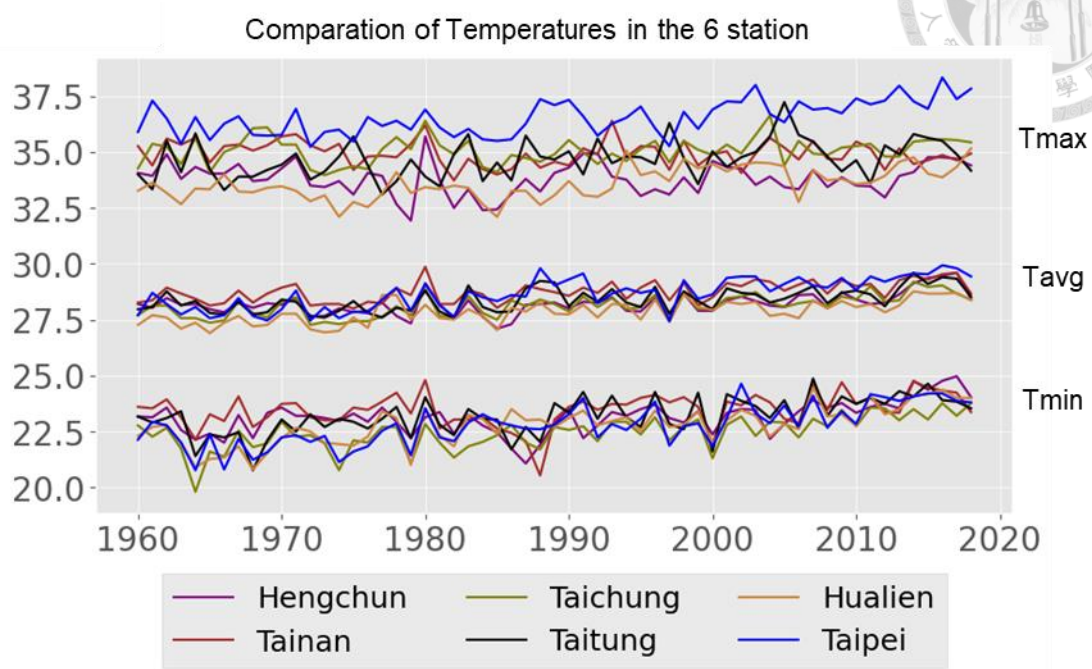


Figure 12 Temperatures comparison of CWA Weather Station Data between Six Centennial Stations in Taiwan during 1960 and 2018. Unit: °C.

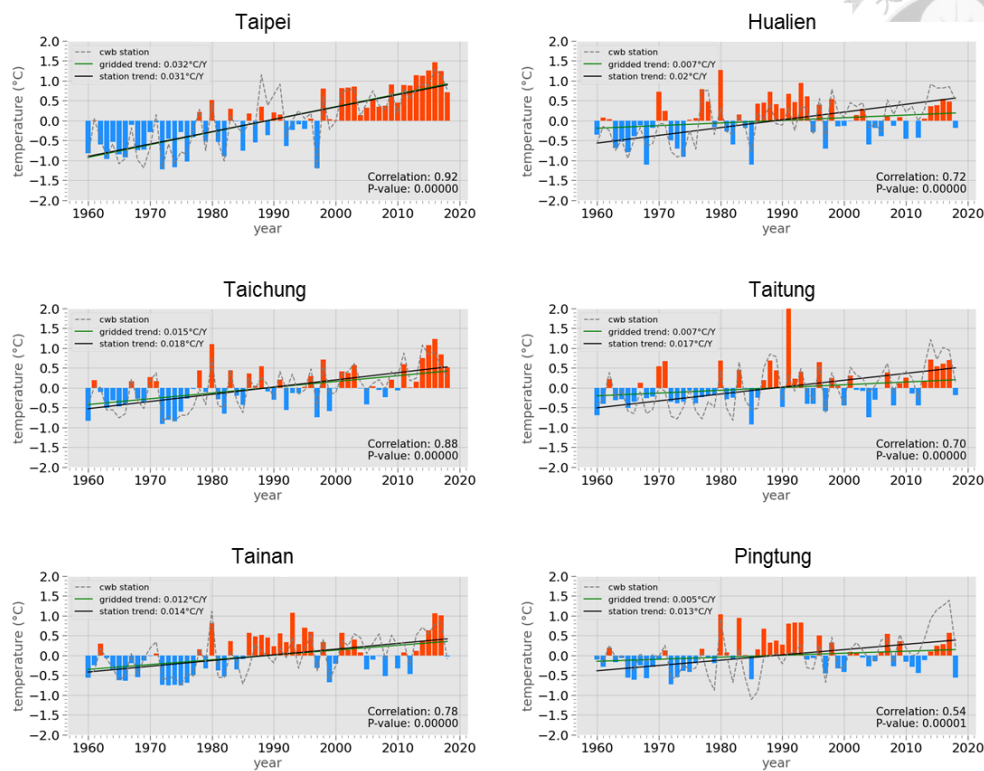


Figure 13 Tavg Comparison between TCCIP Gridded Data and CWA Weather Station Data at Six Centennial Stations in Taiwan. The bar chart represents TCCIP gridded data, while the gray dashed line corresponds to CWA Weather Station data. The green line means the trend of TCCIP gridded data, and the black line is CWA Weather Station Data. Unit: °C.

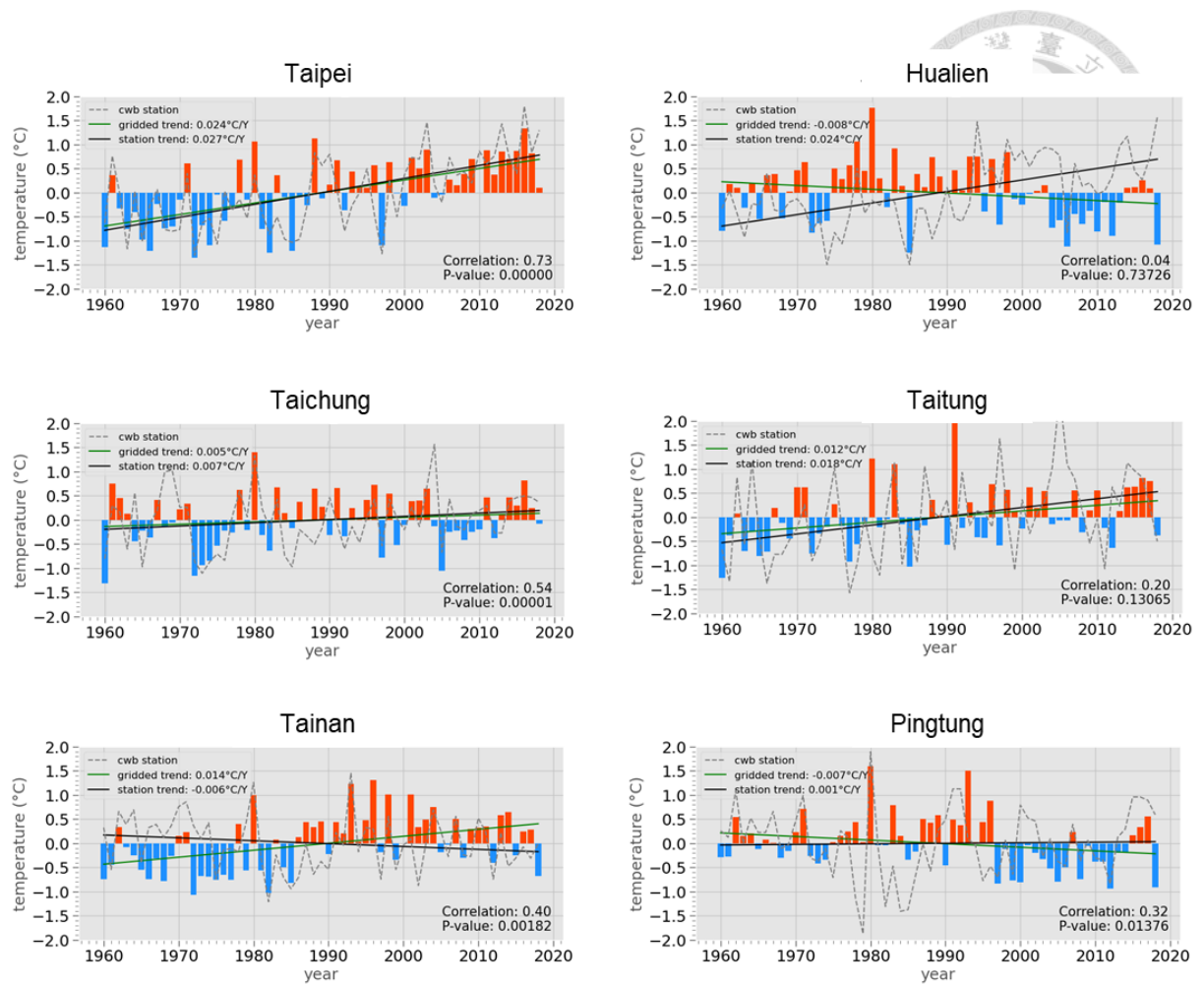


Figure 14 Tmax Comparison between TCCIP Gridded Data and CWA Weather Station

Data at Six Centennial Stations in Taiwan. Similar to Figure 13, but for Tmax. Unit: °C.

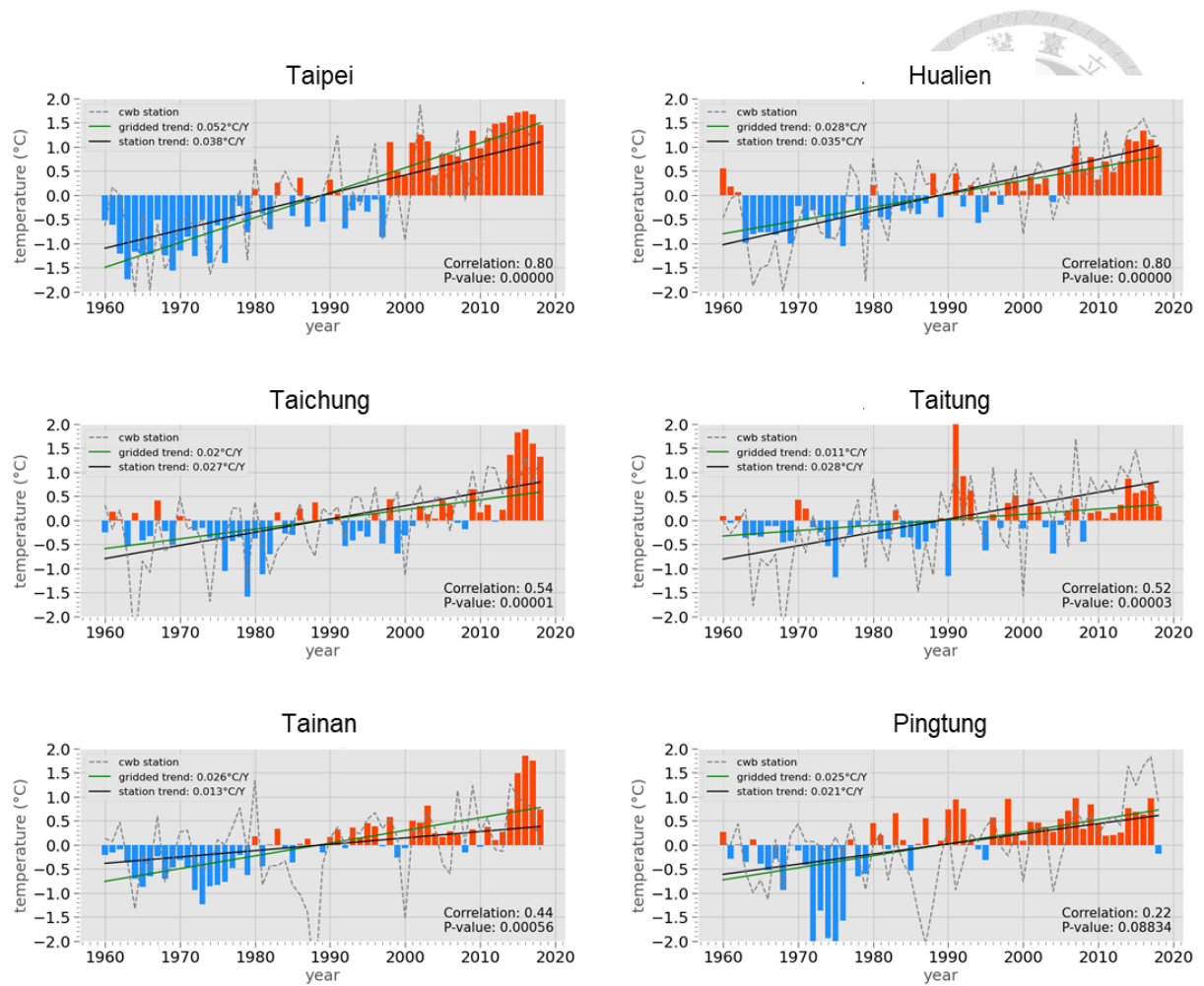


Figure 15 Tmin Comparison between TCCIP Gridded Data and CWA Weather Station

Data at Six Centennial Stations. Similar to Figure 13, but for Tmin. Unit: °C.

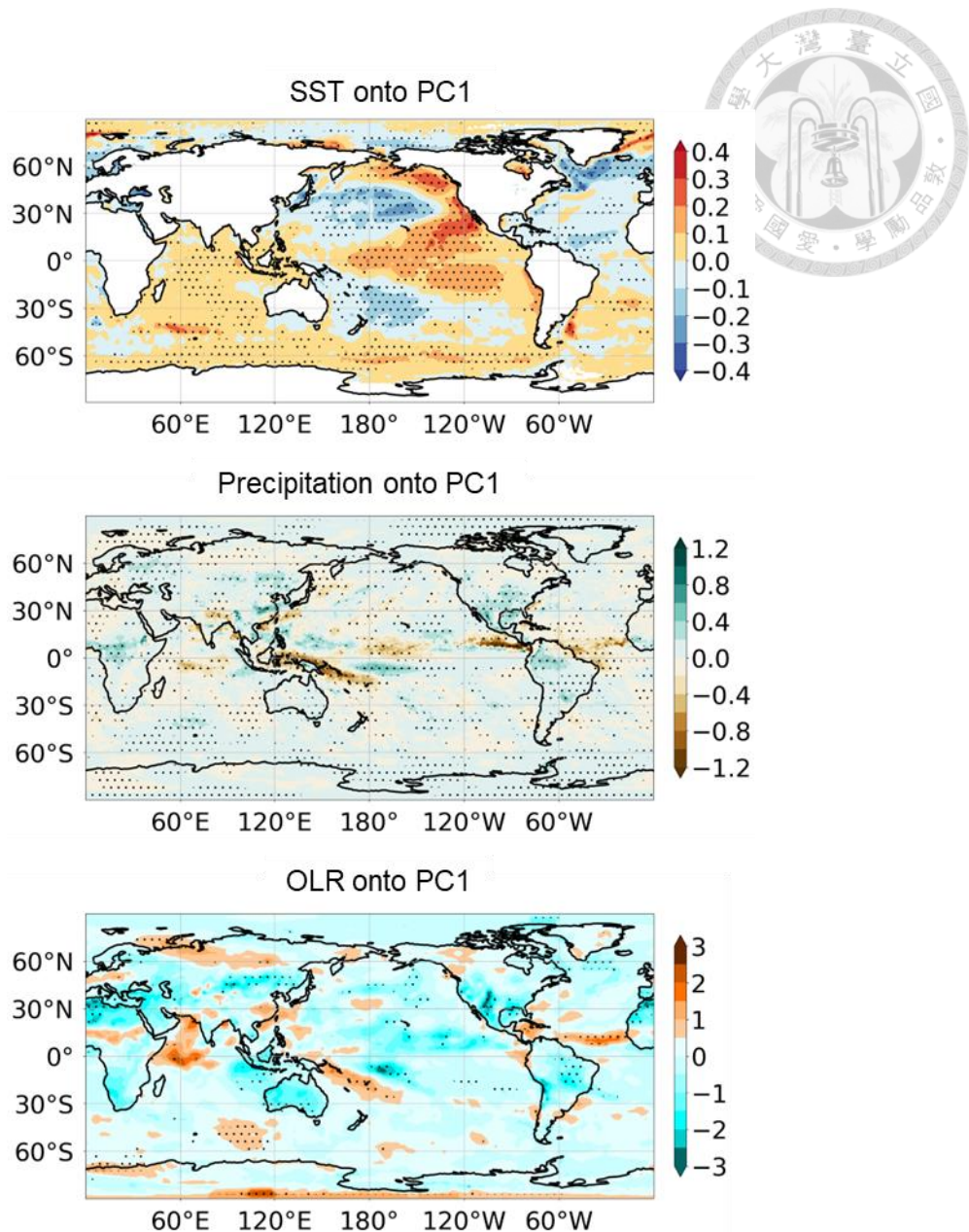


Figure 16 Global Regression Maps of SST, Precipitation and OLR onto PC1 of Taiwan summer temperature on decadal timescales. (a) SST Monthly version based on HadISST ($^{\circ}\text{C}$; shading) (b) precipitation based on ERA5 reanalysis data (mm; shading) and (c) OLR based on NOAA observation data (Wm^{-2} ; shading) regressed onto the EOF PC1 of the JJA temperature in Taiwan. Dots indicate significance at the 0.1 level. The data presented in figure 16 is from 1960 to 2018.

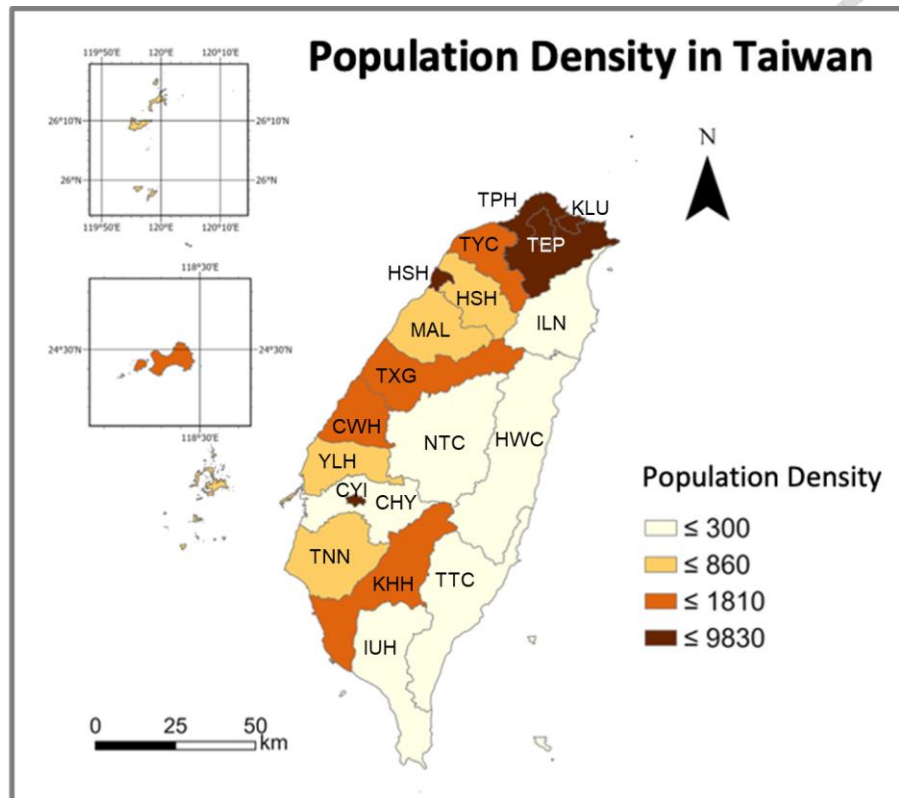


Figure 17 Population Density Across Counties and Cities in Taiwan. Population density (people/ km^2) in each county and city in Taiwan are depicted in the shading. The color bar intervals are based on quartiles of population density. The data is sourced from the Department of Household Registration, Ministry of the Interior, with statistics updated as of August 2018.

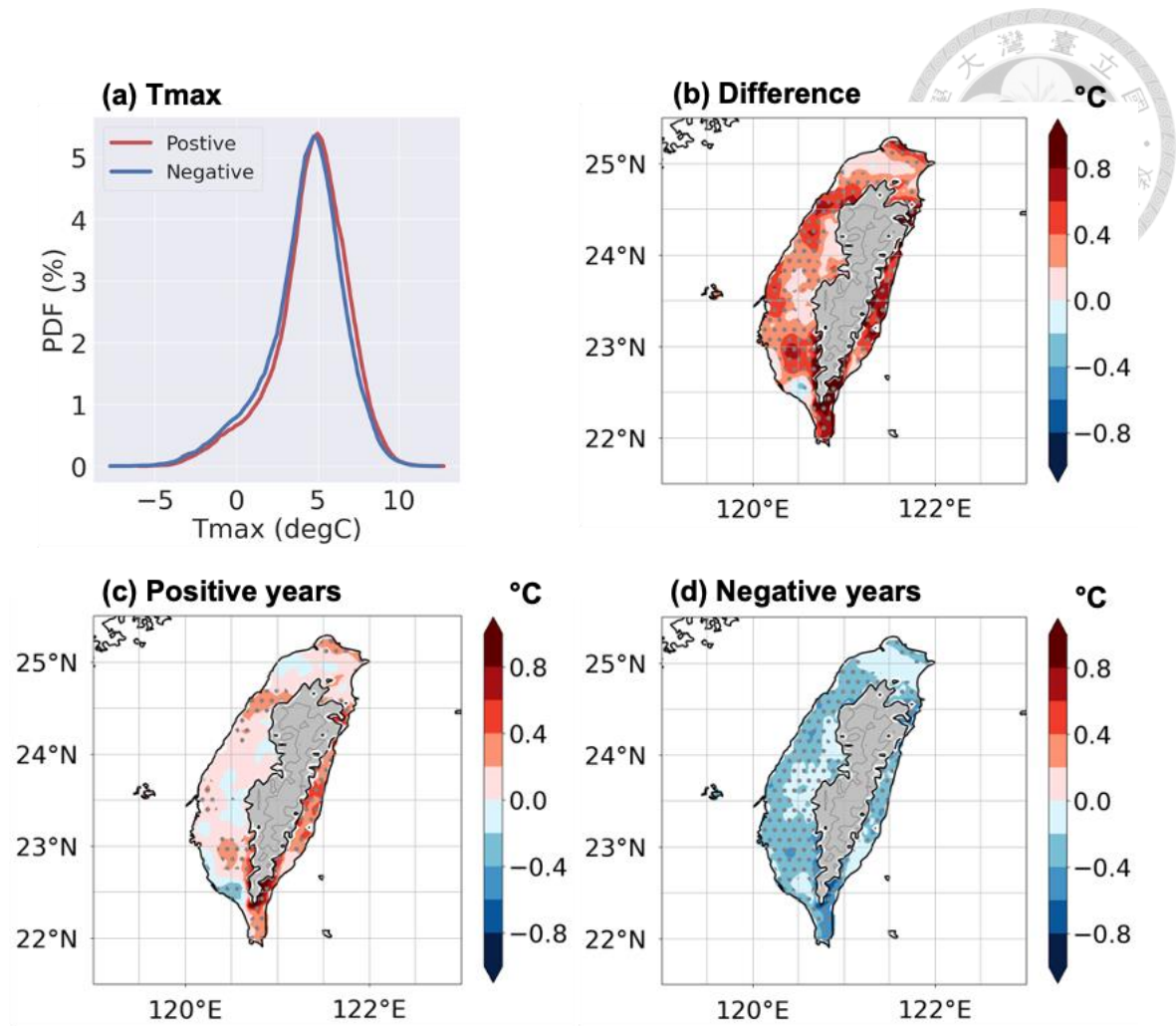


Figure 18 Anomaly Composites of Daily Tmax during Positive and Negative PMM Years.

(a) Probability Density Function (PDF) of Tmax during positive (red line), and negative (blue line) PMM phases. (c) presents the Tmax composite for PMM-positive years, and (d) displays the Tmax composite for PMM-negative years. (b) illustrates the temperature difference between PMM-positive and PMM-negative years (positive minus negative).

The data presented in figure 18 is based on TCCIP gridded data and spans from 1960 to 2018. Unit: °C.

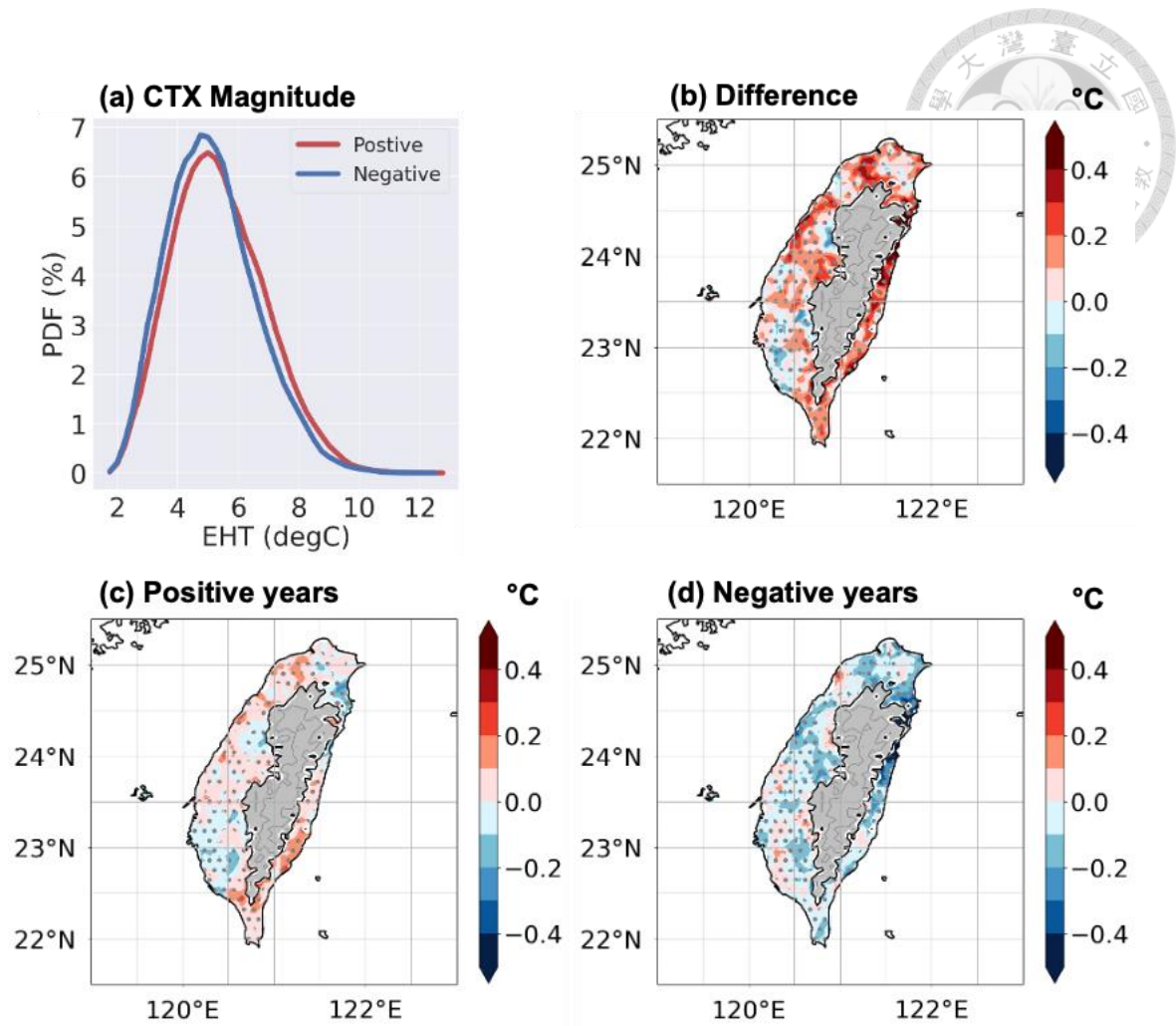


Figure 19 Anomaly Composite of CTX magnitude during PMM Positive and Negative Years.

(a) Probability Density Function (PDF) of CTX magnitude during positive (red line), and negative (blue line) PMM phases. (c) Presents the composite CTX magnitude for PMM-positive years, and (d) displays the composite CTX magnitude for PMM-negative years. (b) Illustrates the temperature difference between PMM-positive and PMM-negative years (positive minus negative). The unit of CTX magnitude is °C. The data presented in figure 19 is based on TCCIP gridded data and spans from 1960 to 2018. Unit: °C.

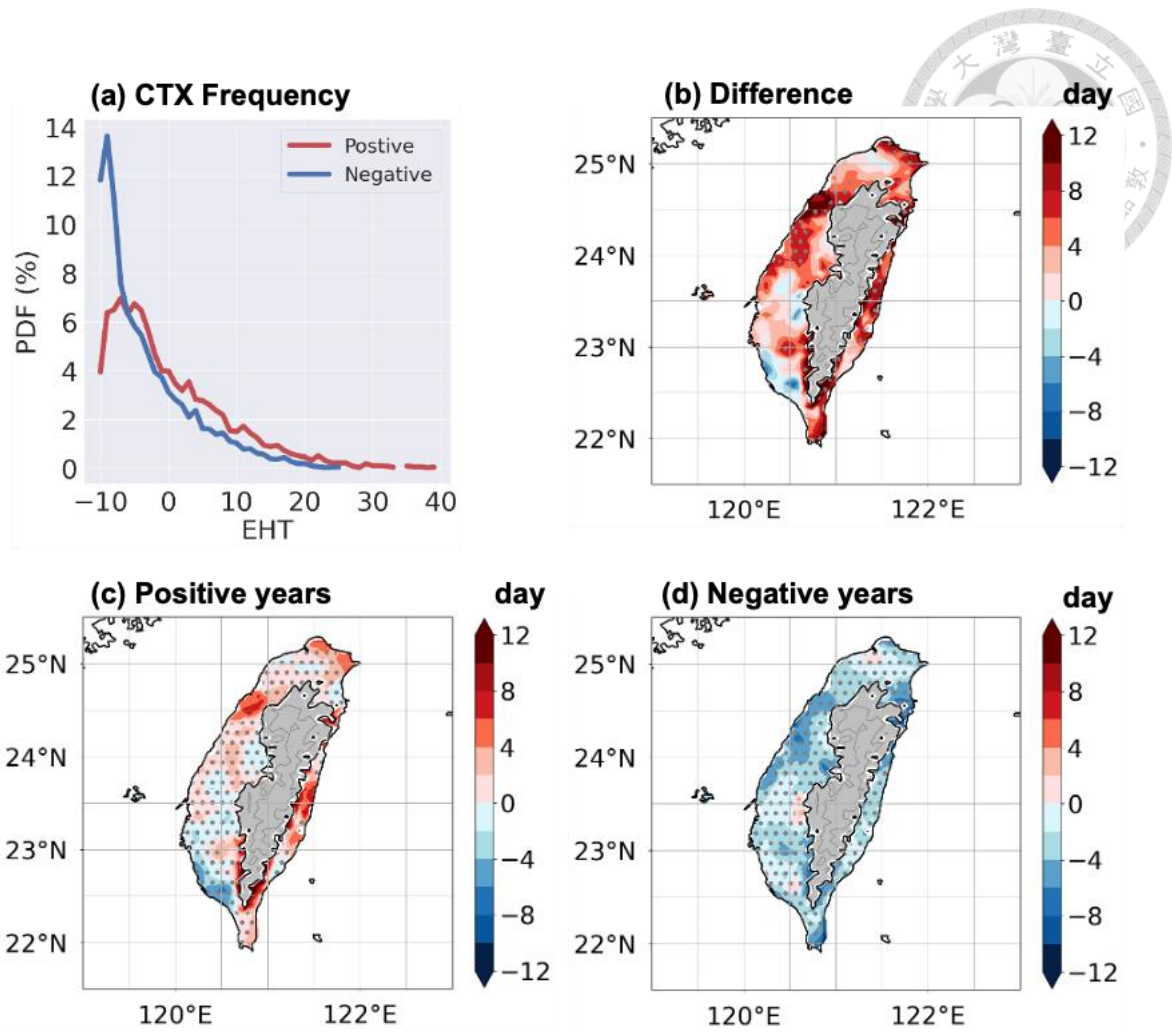


Figure 20 Anomaly Composites of CTX Frequency during Positive and Negative Years of PMM. (a) Probability Density Function of CTX frequency during positive (red line) and negative (blue line) PMM phases. (c) Composite of CTX frequency during PMM-positive years, and (d) Composite of CTX Magnitude during PMM-negative years. (b) The difference of CTX frequency between PMM-positive and PMM-negative years (positive minus negative). The data presented in figure 20 is based on TCCIP gridded data and spans from 1960 to 2018. Unit: day.

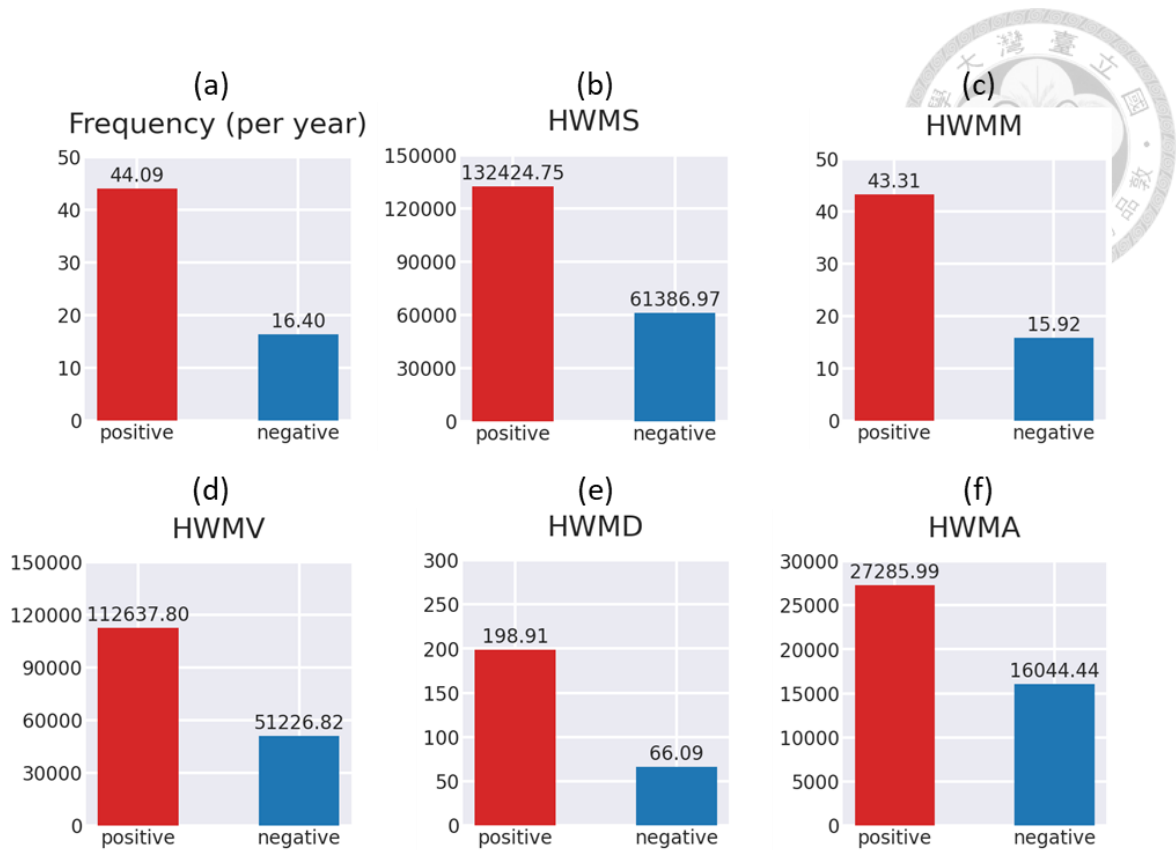


Figure 21 Comparative Analysis of Heatwave Features Measured by the HWMD Method in PMM-Positive and PMM-Negative Years. This figure illustrates heatwave features, encompassing (a) Frequency of heatwaves, (b) Heatwave Magnitude Scale (HWMS; day km^2), (c) Mean Magnitude of a Heatwave Event (HWMM; unitless), (d) Heatwave Event Volume (HWMV; day km^2), and (e) Mean Duration of Heatwave Event (HWMD; day), and (f) Mean Area of a Heatwave Event (HWMA; km^2), in PMM-positive years (red bars) and PMM-negative years (blue bars). Refer to section 2.2.2.2 for detailed definitions. All the data in figure 21 is from 1960 to 2018.

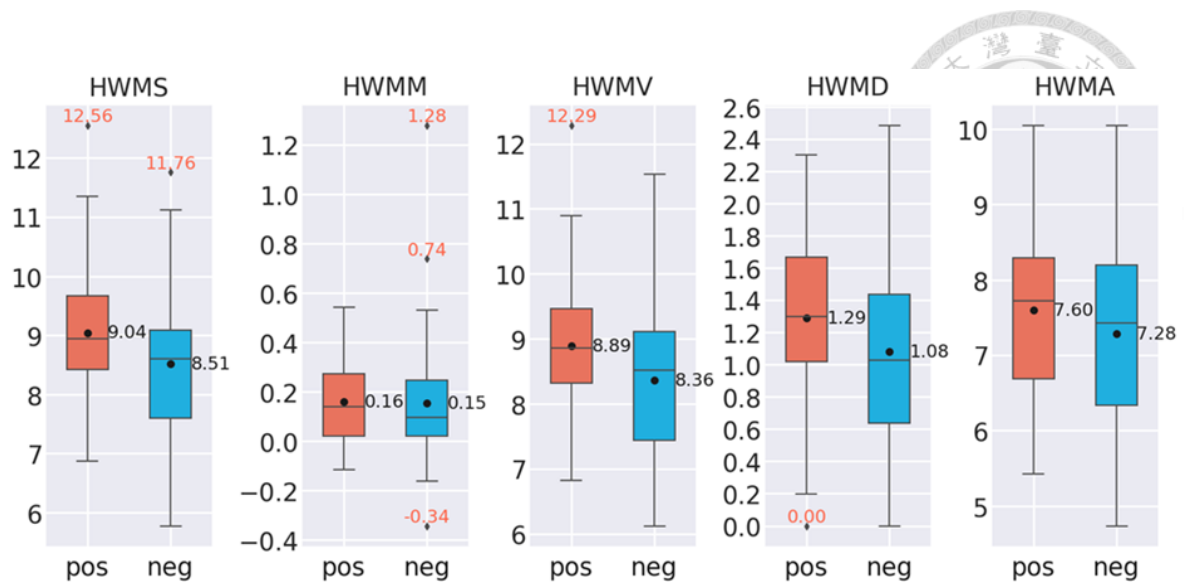


Figure 22 Feature Comparisons of the top five strongest HWMS events each year in PMM-positive (red) and PMM-negative (blue) years. This figure represents the top five strongest HWMS (day km²) each year in PMM-positive (red) and PMM-negative (blue) years, totaling 105 events. Definitions of plotting symbols are illustrated at the upper-right corner of the figure. The data presented in figure 22 is from 1960 to 2018.

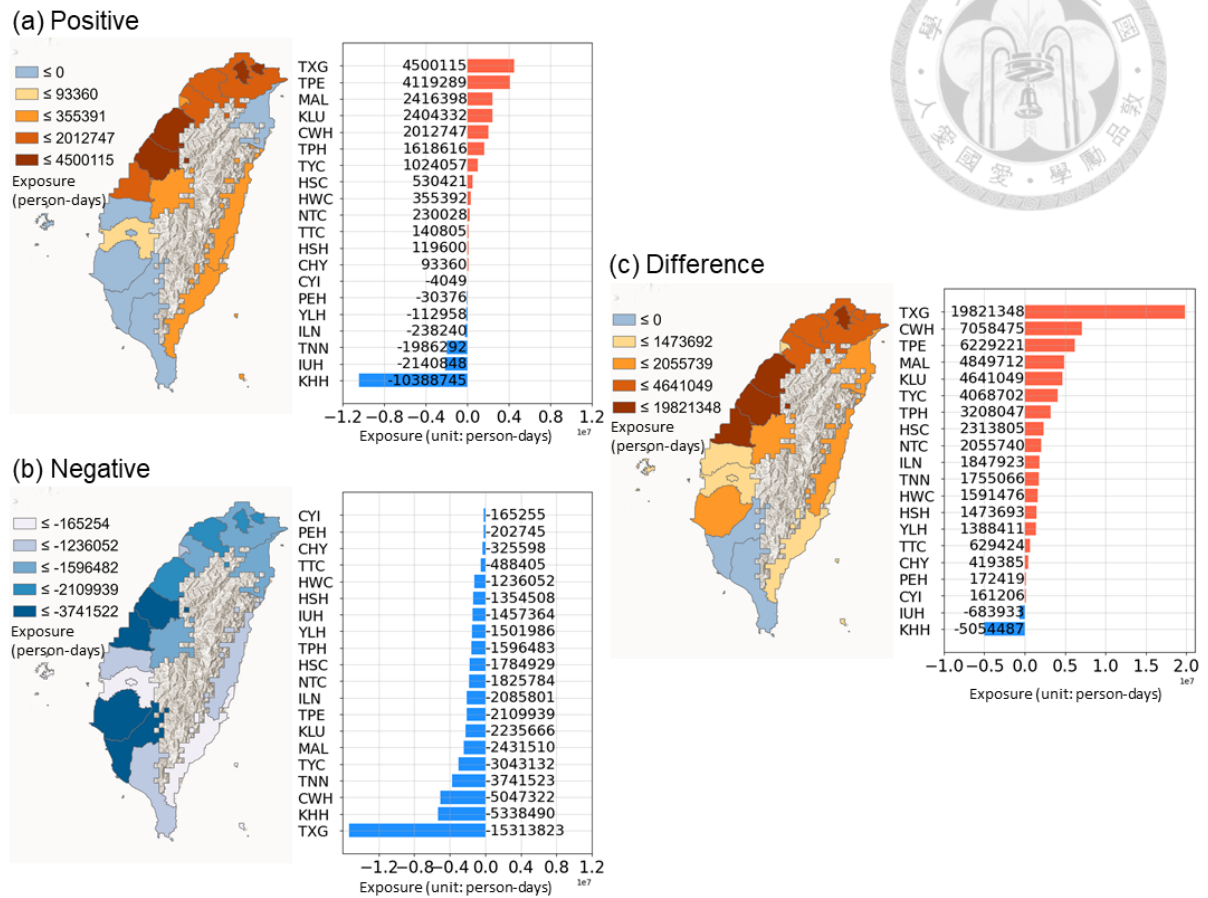


Figure 23 Exposure Map to Heatwave based on CTX90pt in PMM-Positive and PMM-Negative Years. (a) represents the exposure to heatwaves (person-day; shading) during PMM-positive years. (b) represents corresponding figure during PMM-negative years. (c) is the difference between positive years and negative years (positive minus negative). The color bar of each figure intervals is based on quartiles of exposure to heatwaves. Definition of exposure is $\Delta E_c = P_1 \times \Delta C$. ΔE_c is the exposure of climate effect, P_1 represents the population base from 1960 to 2018, and ΔC is the change of HWD from 1960 to 2018. The population density data is from the Department of Household Registration, Ministry of the Interior, with statistics updated as of August 2018.

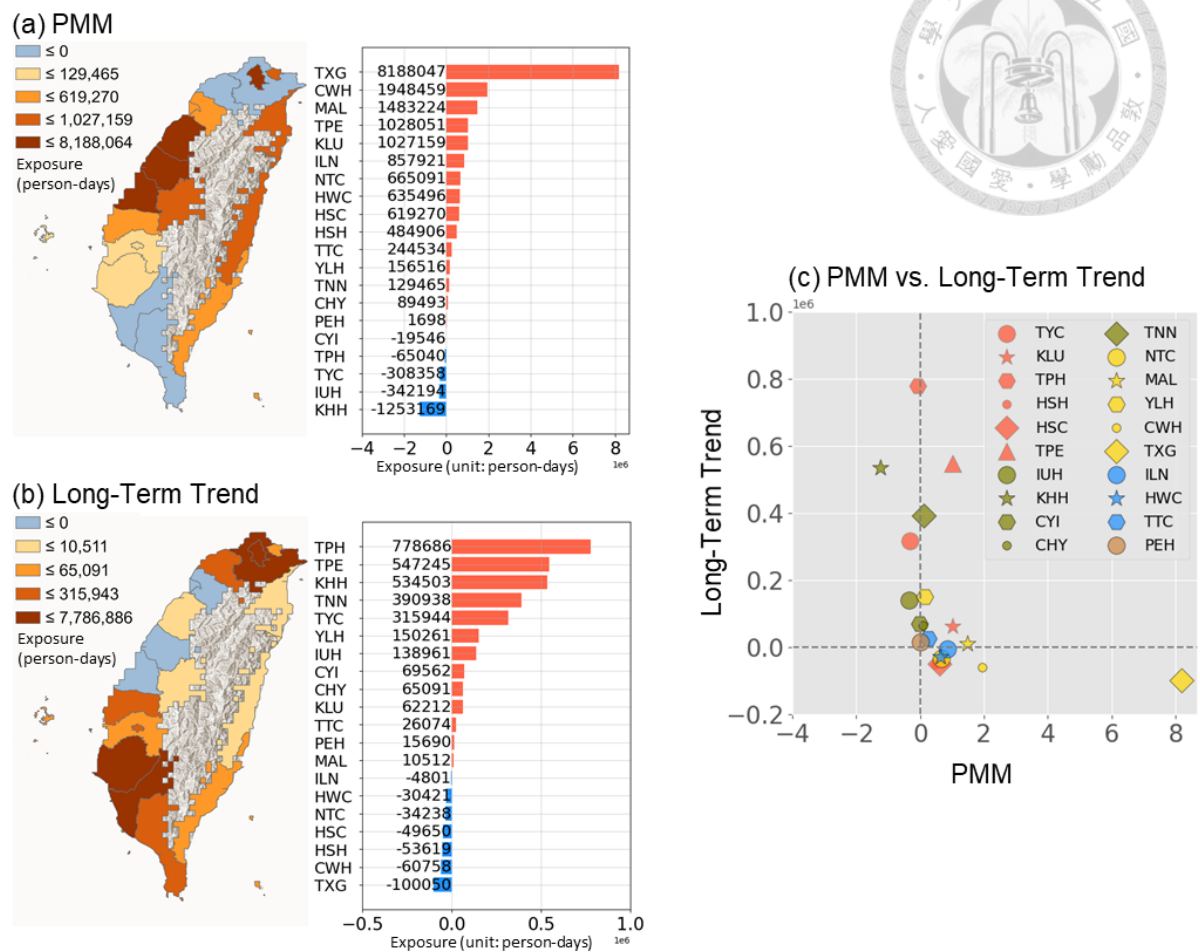


Figure 24 Regressed Maps of Heatwave Exposure based on CTX90pt to PMM index and Long-Term Temperature Trend in Taiwan based on the population in 2018. This figure is same with Figure 23 but (a) represents the regression map of exposure to heatwaves (person-day; shading) onto standardized PMM. (b) represents the long-term trend of exposure to heatwaves. (c) The scatter plot illustrates the regression of exposure to heatwaves onto the standardized PMM index in comparison to the long-term trend of heatwave exposure. The color bar of each figure intervals is based on quartiles of exposure to heatwaves. The population density data is from the Department of Household

Registration, Ministry of the Interior, with statistics updated as of August 2018.



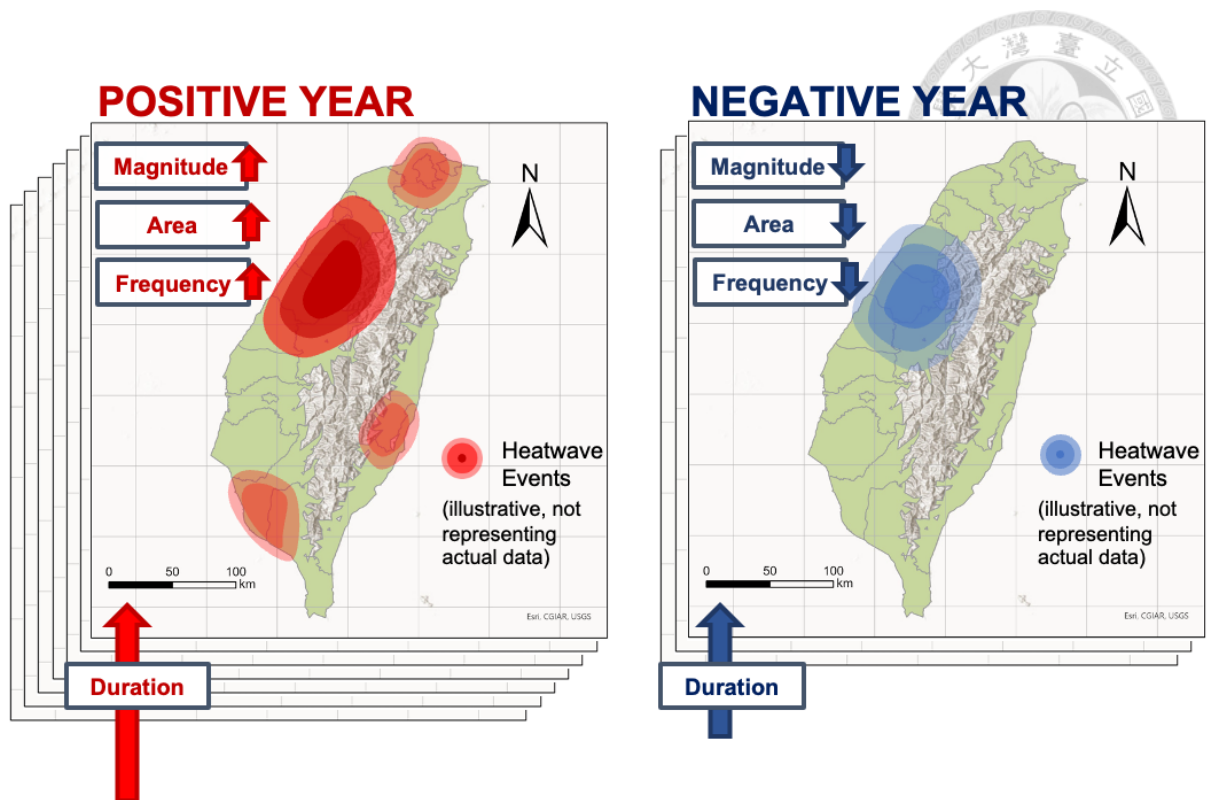


Figure 25 Illustration of Heatwave Changes over Taiwan in PMM-Positive and PMM-Negative Years found in this study.

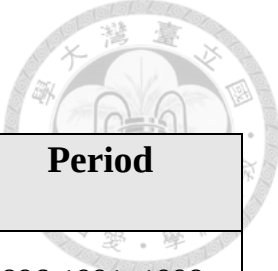
TABLES



Table 1 Reference Table for County/City Names and Abbreviations in Taiwan

County name	Abbreviation
Taipei City	TPE
Taichung City	TXG
Keelung City	KLU
Tainan City	TNN
Kaohsiung City	KHH
New Taipei City	TPH
Yilan County	ILN
Taoyuan City	TYC
Chiayi City	CYI
Hsinchu County	HSN
Miaoli County	MAL
Nantou City	NTC
Changhua County	CWH
Hsinchu City	HSC
Yunlin County	YLH
Chiayi County	CHY
Pingtung County	IUH
Hualien City	HWC
Taitung City	TTC
Penghu County	PEH

Table 2 Weather Station Names and Locations



Station	Number	Latitude (°N)	Longitude (°E)	Period
Taipei	466920	25.037658	121.514853	1896-1991, 1998-
Taipei (shi-yuan)	466921	25.036275	121.513225	1992-1997
Taichung	467490	24.145736	120.684075	1897-
Tainan	467410	22.993239	120.204772	1897-1997, 2002-
Tainan (Yong-kang)	467411	23.038386	120.2367	1998-2001
Hualien	466990	23.975128	121.613275	1910-
Taitung	467660	22.752211	121.154586	1901-
Hengchun	467590	22.003897	120.746339	1896-

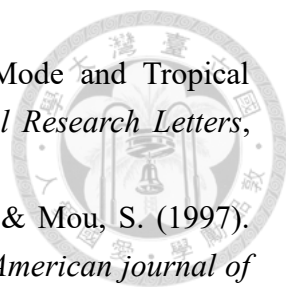
REFERENCE



- Amaya, D. J. (2019). The Pacific Meridional Mode and ENSO: a Review. *Current Climate Change Reports*, 5(4), 296-307. <https://doi.org/10.1007/s40641-019-00142-x>
- Bai, L., Ding, G., Gu, S., Bi, P., Su, B., Qin, D., Xu, G., & Liu, Q. (2014). The effects of summer temperature and heat waves on heat-related illness in a coastal city of China, 2011–2013. *Environmental research*, 132, 212-219.
- Boslaugh, S. (2012). *Statistics in a nutshell: A desktop quick reference*. " O'Reilly Media, Inc."
- Central Weather Bureau. (2023). *Global Warming and Climate Change*. Retrieved 08/29 from https://www.cwb.gov.tw/V8/C/C/Change/change_1.html
- Chang, P., Zhang, L., Saravanan, R., Vimont, D. J., Chiang, J. C., Ji, L., Seidel, H., & Tippett, M. K. (2007). Pacific meridional mode and El Niño—Southern oscillation. *Geophysical Research Letters*, 34(16).
- Chen-Dau Yang, R.-C. C., Shu-Ping Weng (2023). The Construction and Long-term Trend Analysis of Daily Gridded Temperature Dataset in Taiwan. 78, 75-109. [https://doi.org/10.6234/JGR.202311_\(78\).0004](https://doi.org/10.6234/JGR.202311_(78).0004)
- Chiang, J. C., & Vimont, D. J. (2004). Analogous Pacific and Atlantic meridional modes of tropical atmosphere–ocean variability. *Journal of Climate*, 17(21), 4143-4158.
- Cresswell-Clay, N., Ummenhofer, C. C., Thatcher, D. L., Wanamaker, A. D., Denniston, R. F., Asmerom, Y., & Polyak, V. J. (2022). Twentieth-century Azores High expansion unprecedented in the past 1,200 years. *Nature Geoscience*, 15(7), 548-553.
- Gao, S., Zhu, L., Zhang, W., & Chen, Z. (2018). Strong modulation of the Pacific meridional mode on the occurrence of intense tropical cyclones over the western North Pacific. *Journal of Climate*, 31(19), 7739-7749.
- García-Herrera, R., Díaz, J., Trigo, R. M., Luterbacher, J., & Fischer, E. M. (2010). A review of the European summer heat wave of 2003. *Critical Reviews in Environmental Science and Technology*, 40(4), 267-306.
- Goddard, L. (2016). From science to service. *Science*, 353(6306), 1366-1367. <https://doi.org/doi:10.1126/science.aag3087>
- Hannachi, A., Jolliffe, I. T., & Stephenson, D. B. (2007). Empirical orthogonal functions and related techniques in atmospheric science: A review. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 27(9), 1119-1152.
- Hong, C.-C., Lee, M.-Y., Hsu, H.-H., & Tseng, W.-L. (2018). Distinct influences of the ENSO-like and PMM-like SST anomalies on the mean TC genesis location in the

- western North Pacific: The 2015 summer as an extreme example. *Journal of Climate*, 31(8), 3049-3059.
- Huang-Hsiung Hsu, T.-H. L. (2017). Characteristics of Taiwan Heat Wave and Future Projection. *Atmospheric Sciences*, 45, 281-304.
<https://doi.org/10.3966/025400022017124504001>
- Im, E.-S., Thanh, N.-X., Kim, Y.-H., & Ahn, J.-B. (2019). 2018 summer extreme temperatures in South Korea and their intensification under 3° C global warming. *Environmental Research Letters*, 14(9), 094020.
- Jones, B., O'Neill, B. C., McDaniel, L., McGinnis, S., Mearns, L. O., & Tebaldi, C. (2015). Future population exposure to US heat extremes. *Nature Climate Change*, 5(7), 652-655.
- Kaiser, R., Le Tertre, A., Schwartz, J., Gotway, C. A., Daley, W. R., & Rubin, C. H. (2007). The effect of the 1995 heat wave in Chicago on all-cause and cause-specific mortality. *American journal of public health*, 97(Supplement_1), S158-S162.
- Kao, P.-k., Hong, C.-C., Huang, A.-Y., & Chang, C.-C. (2022). Intensification of Interannual Cross-Basin SST Interaction between the North Atlantic Tripole and Pacific Meridional Mode since the 1990s. *Journal of Climate*, 35(18), 5967-5979.
- Kay, J. E., Deser, C., Phillips, A., Mai, A., Hannay, C., Strand, G., Arblaster, J. M., Bates, S., Danabasoglu, G., & Edwards, J. (2015). The Community Earth System Model (CESM) large ensemble project: A community resource for studying climate change in the presence of internal climate variability. *Bulletin of the American Meteorological Society*, 96(8), 1333-1349.
- Larson, S. M., & Kirtman, B. P. (2014). The Pacific meridional mode as an ENSO precursor and predictor in the North American multimodel ensemble. *Journal of Climate*, 27(18), 7018-7032.
- Liguori, G., & Di Lorenzo, E. (2018). Meridional Modes and Increasing Pacific Decadal Variability Under Anthropogenic Forcing. *Geophysical Research Letters*, 45(2), 983-991. <https://doi.org/10.1002/2017gl076548>
- Lin, C.-Y., Chien, Y.-Y., Su, C.-J., Kueh, M.-T., & Lung, S.-C. (2017). Climate variability of heat wave and projection of warming scenario in Taiwan. *Climatic Change*, 145, 305-320.
- Liu, Z., Anderson, B., Yan, K., Dong, W., Liao, H., & Shi, P. (2017). Global and regional changes in exposure to extreme heat and the relative contributions of climate and population change. *Scientific Reports*, 7(1), 43909.
- Liu, Z., Gao, T., Zhang, W., & Luo, M. (2021). Implications of the Pacific meridional mode for summer precipitation extremes over China. *Weather and Climate Extremes*, 33, 100359.
- Lo, S.-H., Chen, C.-T., Russo, S., Huang, W.-R., & Shih, M.-F. (2021). Tracking heatwave

- extremes from an event perspective. *Weather and Climate Extremes*, 34, 100371.
- Luo, M., & Lau, N.-C. (2019). Amplifying effect of ENSO on heat waves in China. *Climate Dynamics*, 52(5-6), 3277-3289.
- Luo, M., Lau, N.-C., Zhang, W., Zhang, Q., & Liu, Z. (2020). Summer high temperature extremes over China linked to the Pacific meridional mode. *Journal of Climate*, 33(14), 5905-5917.
- Mazdiyasni, O., AghaKouchak, A., Davis, S. J., Madadgar, S., Mehran, A., Ragno, E., Sadegh, M., Sengupta, A., Ghosh, S., & Dhanya, C. (2017). Increasing probability of mortality during Indian heat waves. *Science advances*, 3(6), e1700066.
- Naveena, N., Satyanarayana, G. C., Rao, K. K., Umakanth, N., & Srinivas, D. (2021). Heat wave characteristics over India during ENSO events. *Journal of Earth System Science*, 130, 1-16.
- Nishant, N., Ji, F., Guo, Y., Herold, N., Green, D., Di Virgilio, G., Beyer, K., Riley, M. L., & Perkins-Kirkpatrick, S. (2022). Future population exposure to Australian heatwaves. *Environmental Research Letters*, 17(6), 064030.
- Perkins, S. E., & Alexander, L. V. (2013). On the measurement of heat waves. *Journal of Climate*, 26(13), 4500-4517.
- Porfiriev, B. (2014). Evaluation of human losses from disasters: the case of the 2010 heat waves and forest fires in Russia. *International Journal of Disaster Risk Reduction*, 7, 91-99.
- Reddy, P. J., Perkins-Kirkpatrick, S. E., & Sharples, J. J. (2021). Interactive influence of ENSO and IOD on contiguous heatwaves in Australia. *Environmental Research Letters*, 17(1), 014004.
- Russo, S., Sillmann, J., & Fischer, E. M. (2015). Top ten European heatwaves since 1950 and their occurrence in the coming decades. *Environmental Research Letters*, 10(12), 124003.
- Taiwan Climate Change Projection and Information Platform. (2023). *Interannual Variation of Past Temperature in the Entire Taiwan Region*. Retrieved 08/30 from https://tccip.ncdr.nat.gov.tw/ds_01_grid_1.aspx
- Tao, L., Li, T., Ke, Y.-H., & Zhao, J.-W. (2017). Causes of interannual and interdecadal variations of the summertime Pacific–Japan-like pattern over East Asia. *Journal of Climate*, 30(22), 8845-8864.
- Trenberth, K. E., Marquis, M., & Zebiak, S. (2016). The vital need for a climate information system. *Nature Climate Change*, 6(12), 1057-1059.
- Tseng, W. L., Lin, S. Y., Wang, Y. C., Lo, S. H., Lo, M. H., Lee, S. Y., Tsai, C. T., & Hsu, H. H. (2023). Impact of Pacific–Japan pattern on temperature and heatwave events in summer over Taiwan. *International Journal of Climatology*.
- Wang, C., Fu, M., Wang, B., Wu, L., & Luo, J. J. (2023). Pacific Decadal Oscillation

- 
- Modulates the Relationship Between Pacific Meridional Mode and Tropical Cyclone Genesis in the Western North Pacific. *Geophysical Research Letters*, 50(5). <https://doi.org/10.1029/2022gl101710>
- Whitman, S., Good, G., Donoghue, E. R., Benbow, N., Shou, W., & Mou, S. (1997). Mortality in Chicago attributed to the July 1995 heat wave. *American journal of public health*, 87(9), 1515-1518.
- Xie, M., Wang, C., & Chen, S. (2022). The role of the Maritime Continent SST anomalies in maintaining the Pacific–Japan pattern on decadal time scales. *Journal of Climate*, 35(3), 1079-1095.
- Yanai, M., Esbensen, S., & Chu, J.-H. (1973). Determination of bulk properties of tropical cloud clusters from large-scale heat and moisture budgets. *Journal of Atmospheric Sciences*, 30(4), 611-627.
- Zuo, J., Pullen, S., Palmer, J., Bennetts, H., Chileshe, N., & Ma, T. (2015). Impacts of heat waves and corresponding measures: a review. *Journal of Cleaner Production*, 92, 1-12.