Short- and long-term prediction of extremely hot days due to climate change and related attributable mortality

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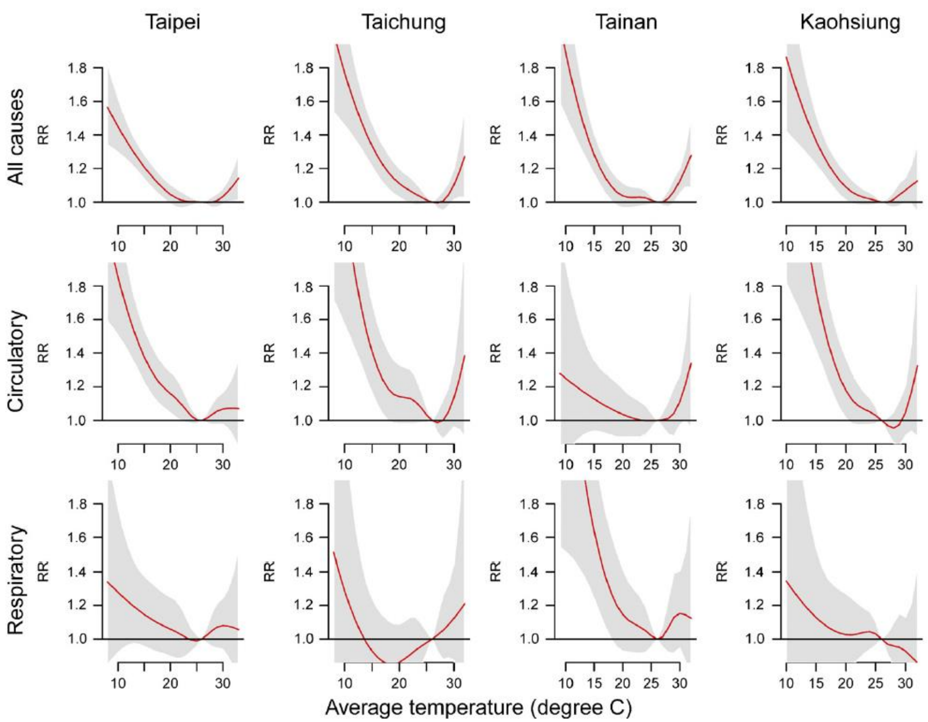
Temperature and prolonged extremes & mortality in elderly

Lin et al. (2011) Environ Res

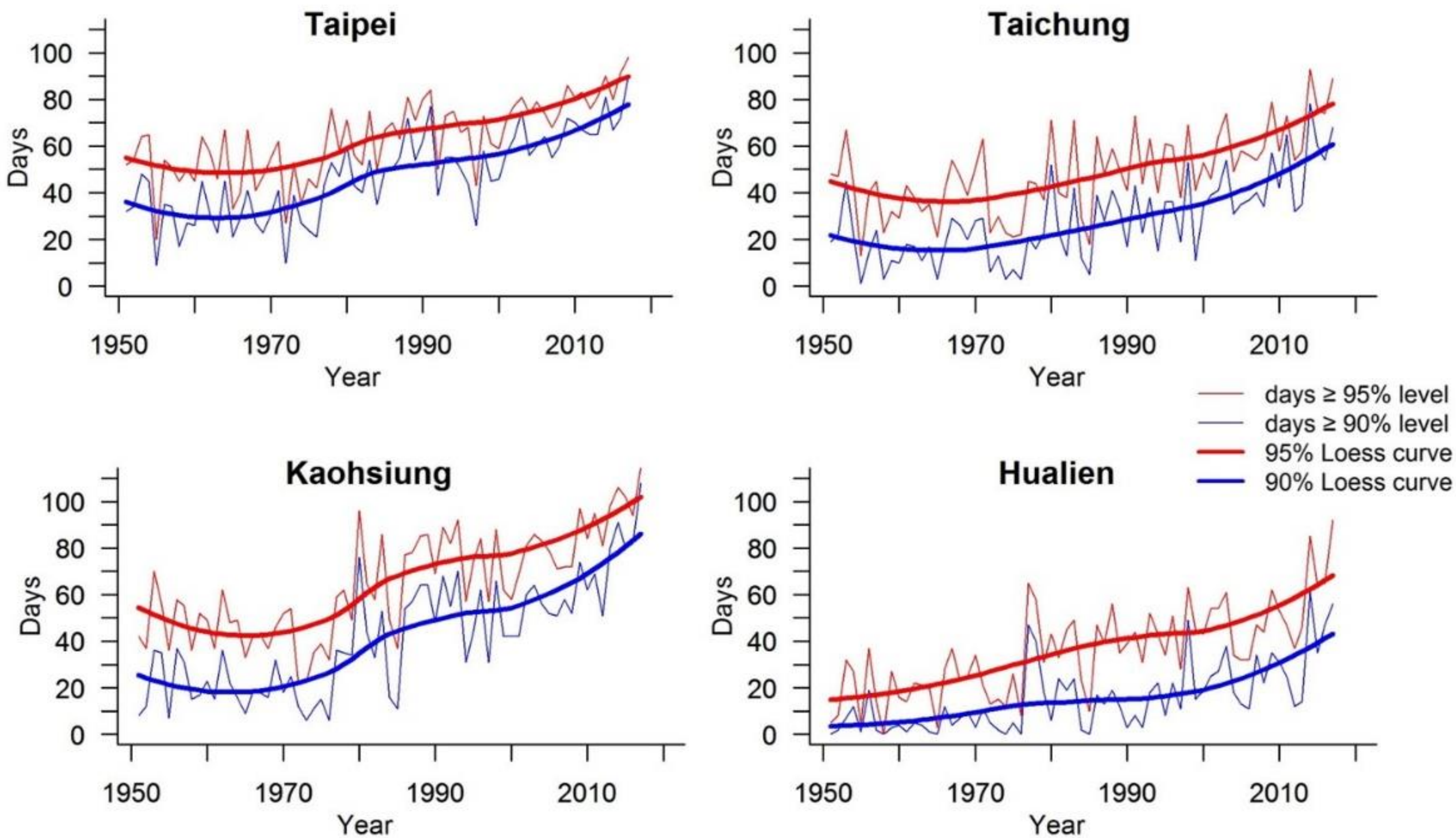
Statistical model: DLNM

Data: 1994-2007, age ≧65 y

RR: daily mean temp.

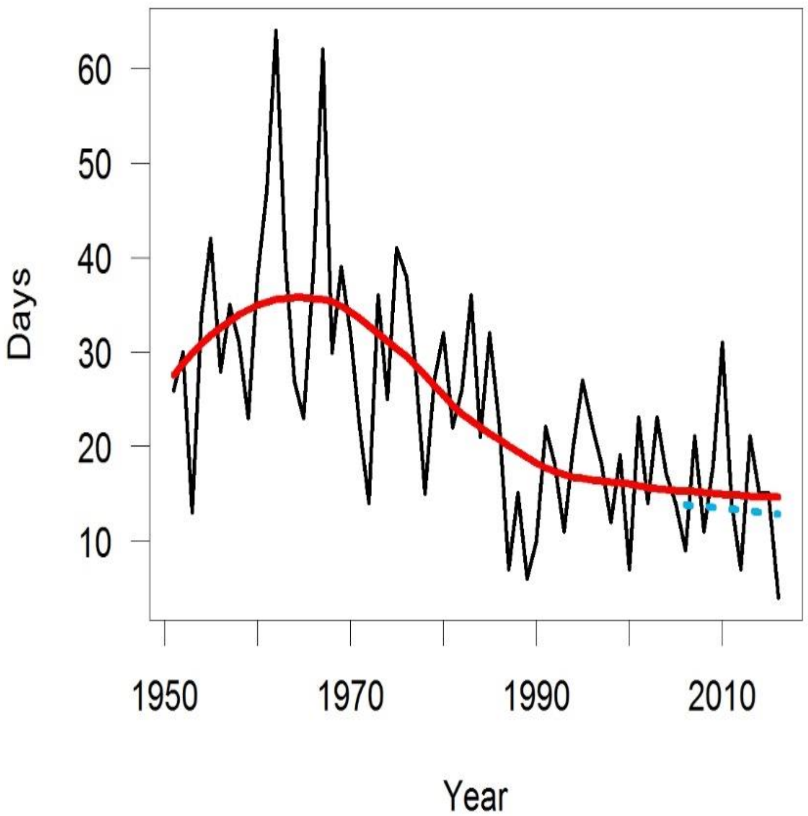


Hot days during June-September in Taiwan since 1951 (baseline period 1961-1990)

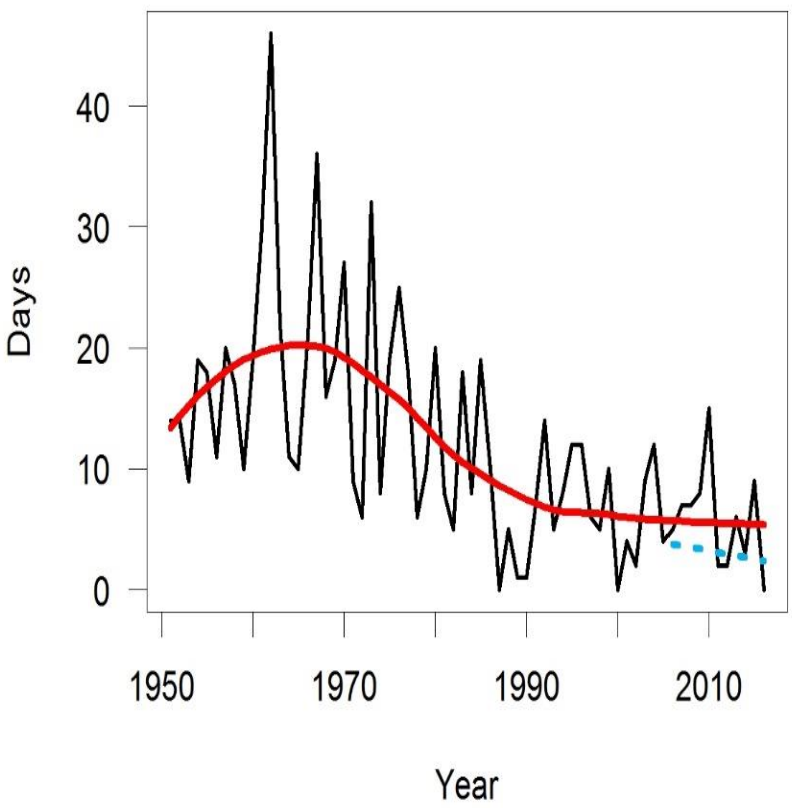


Trend of cold days (daily minimum) in winter (Dec.-Feb.) due to climate change (Taipei)

winter days ≤ 5% level 10.3℃

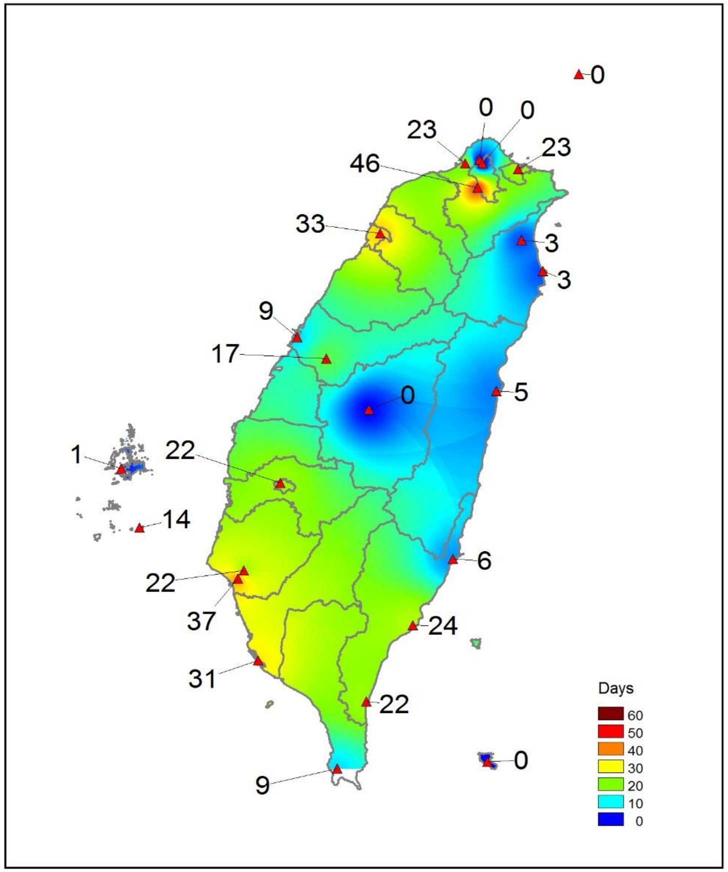


winter days ≤ 10% level 12.5℃



Why short-term prediction?

Actual 2010 Hot days (> 30 °C) in summer



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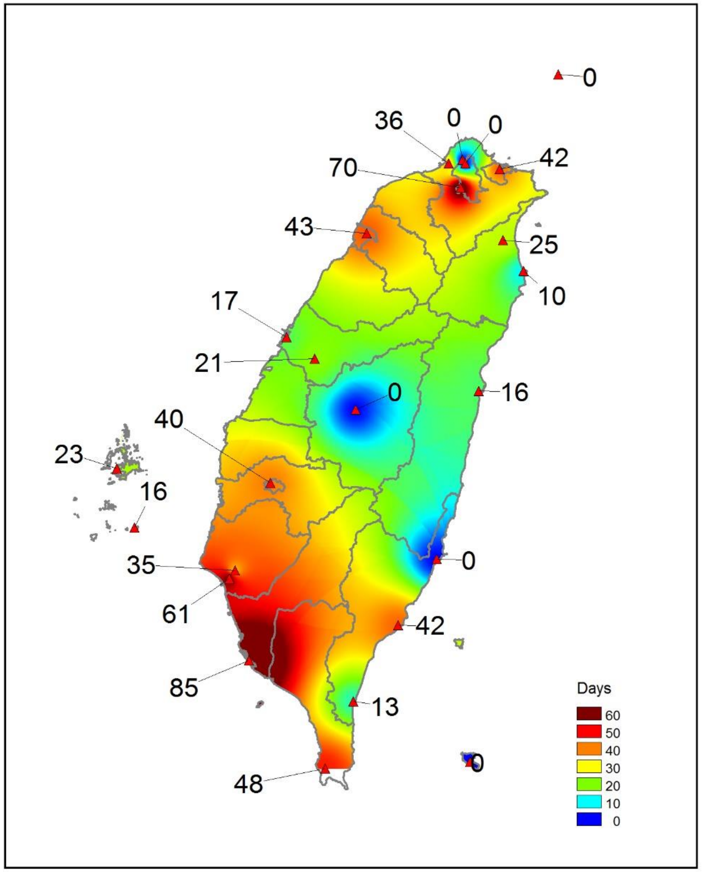

Summer: June - September

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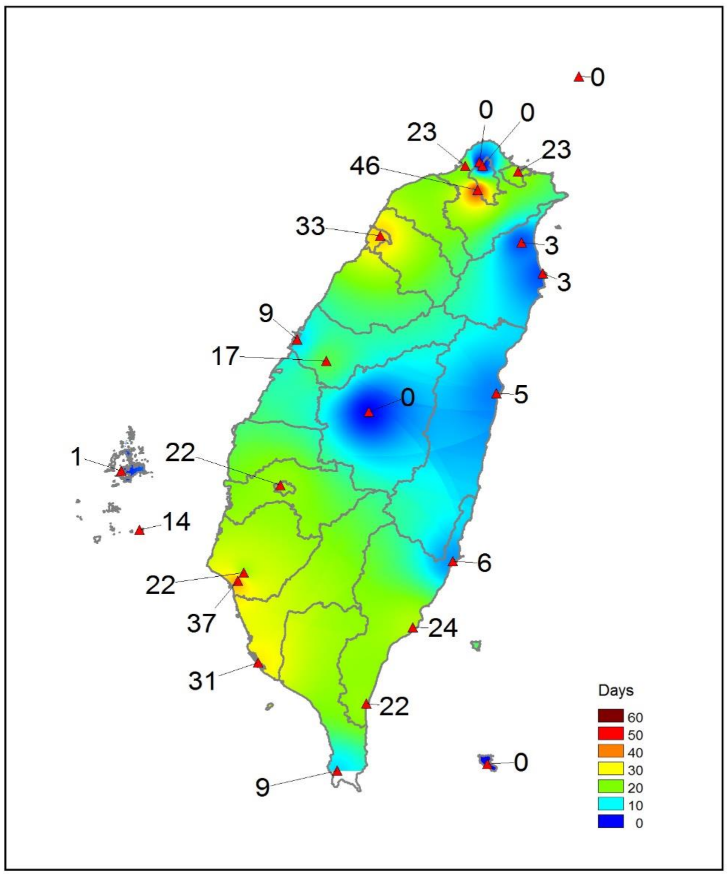
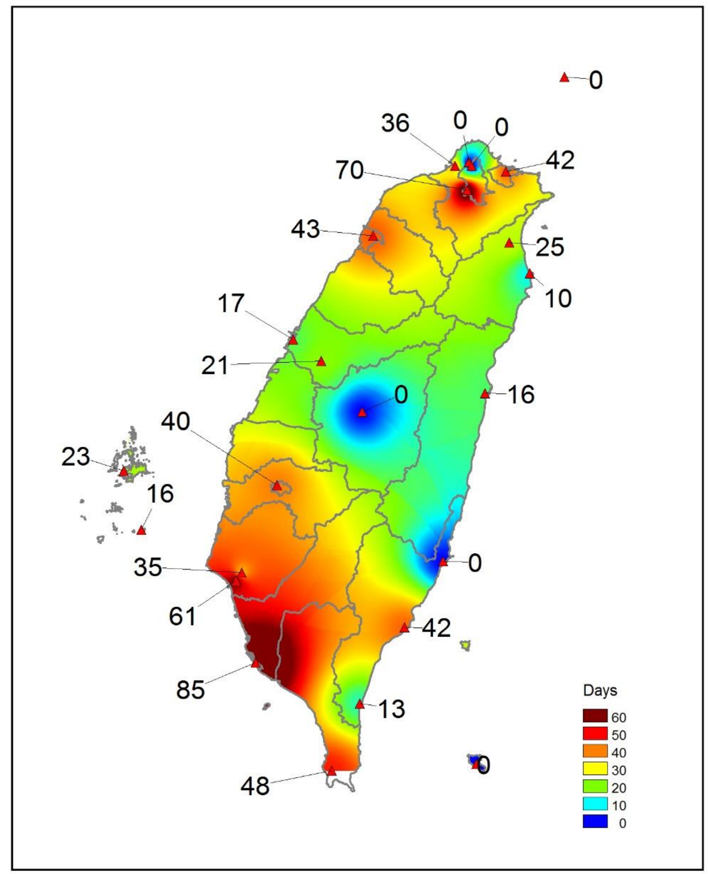


Actual 2017 Hot days (> 30 °C) in summer

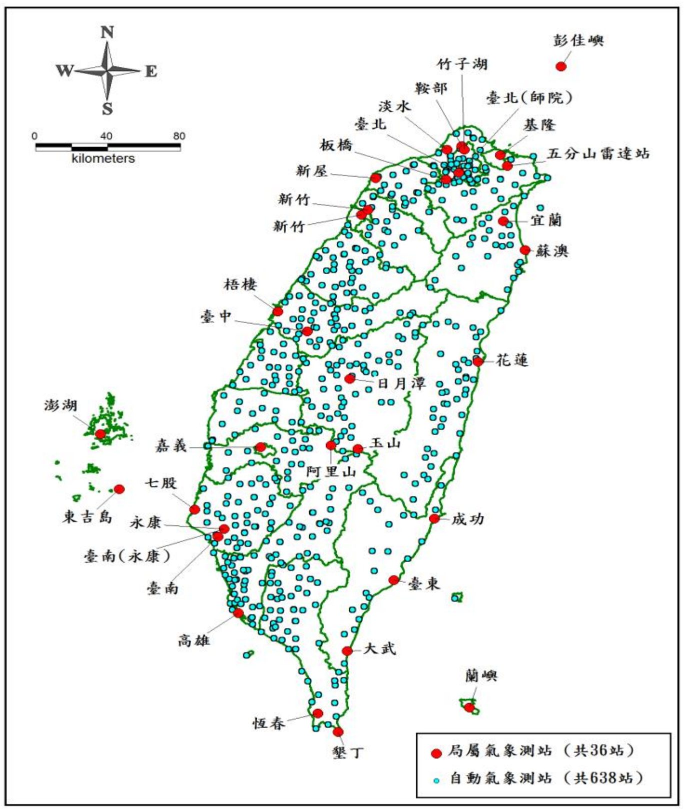


Summer: June - September

Data sources

- 台灣颱風洪水研究中心 Data Bank for Atmospheric & Hydrologic Research service, Taiwan Typhoon and Flood Research Institute, National Applied Research Laboratories – daily 24 hr temperature 1951-2017
- 臺灣氣候變遷推估與資訊平台 Taiwan Climate Change and Information Platform (TCCIP) – IPCC RCP8.5 simulation outcomes for daily maximum temp (personal communication)
- 中央氣象局 Central Weather Bureau of Taiwan – monthly Nino3.4 index
- 內政部 Ministry of Interior of Taiwan -- population size during 2010-2017 and national mortality data during 1995-2008
- 王玉純教授 Prof. Yu-Chun Wang -- City/county-specific relative risks (RRs) of all-cause, cardiovascular, and respiratory mortality per 1°C increase

Meteorological stations and historical data in Taiwan



Background: Daily meteorological measurements of a total of 36 Central Weather Bureau (CWB) stations in Taiwan since 1890.

Data: Hourly temperature records of 24 CWB stations with complete data and monthly nino3.4 indices during 1951-2016 were used for the analysis.

Percentiles of the reference period 1961-1990

95%: 33.4℃

90%: 32.5℃

10%: 12.5℃

5%: 10.3℃

Prediction of days with high temperature extremes

Short-term prediction (2018-2020): using time-series statistical model based on historical observation data from 1951-2016 from 36 CWB stations across Taiwan.

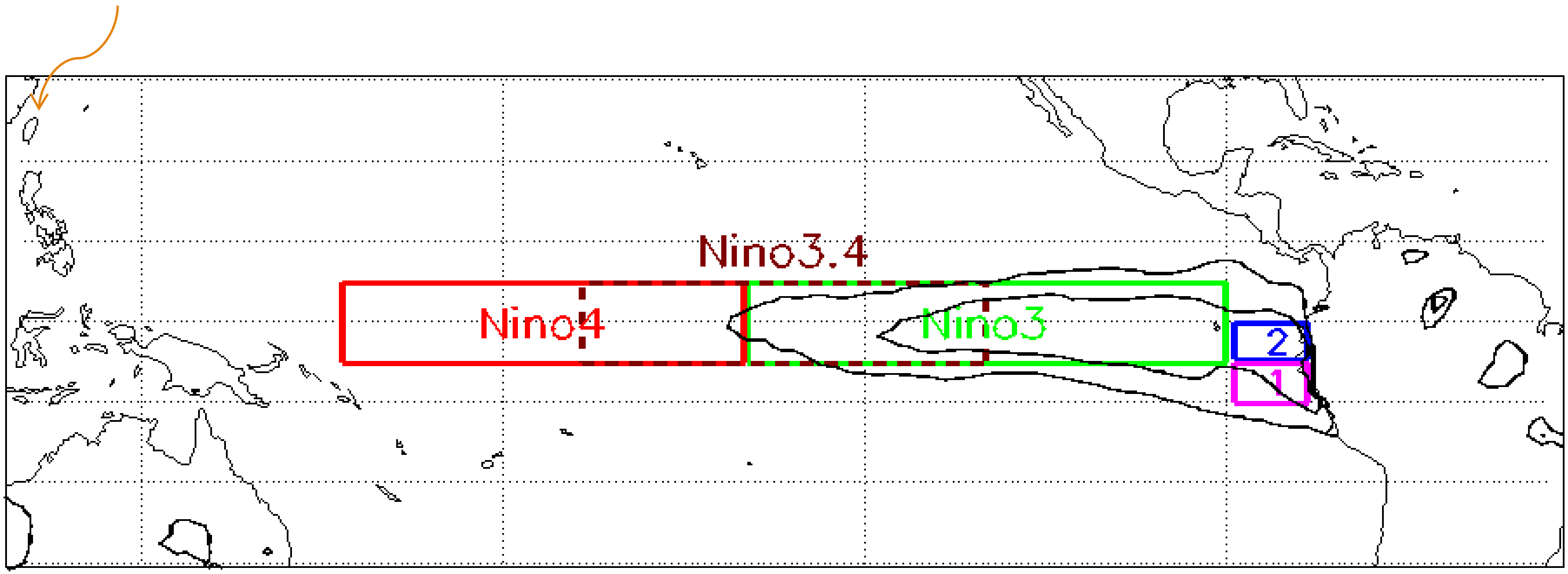
Mid- & long-term prediction (2021-2060): using statistical downscaling based on IPCC AR5 climate model simulations for scenarios rcp2.6, 4.5, 6.0 & 8.5.

Reference period: 2000-2010

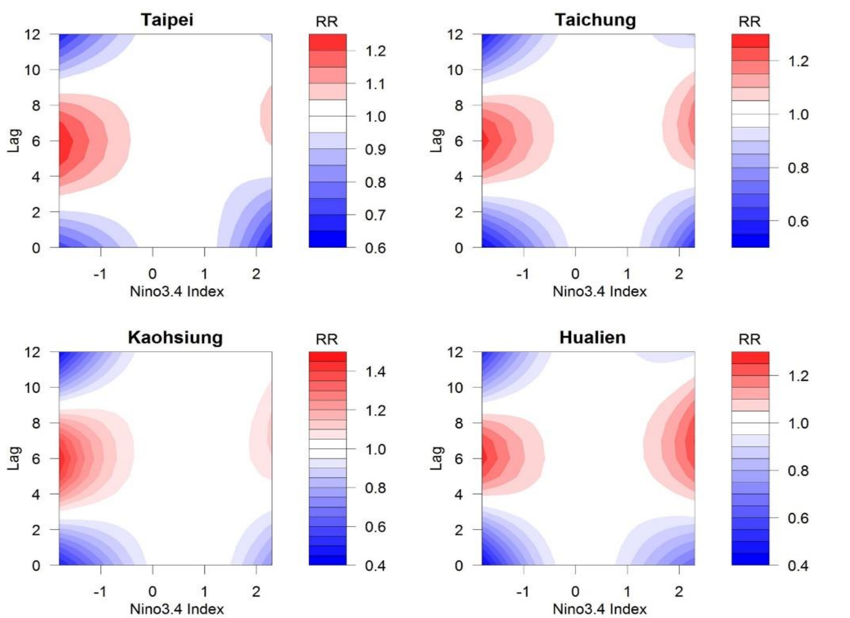
Short-term prediction of extremely hot days due to climate change & ENSO

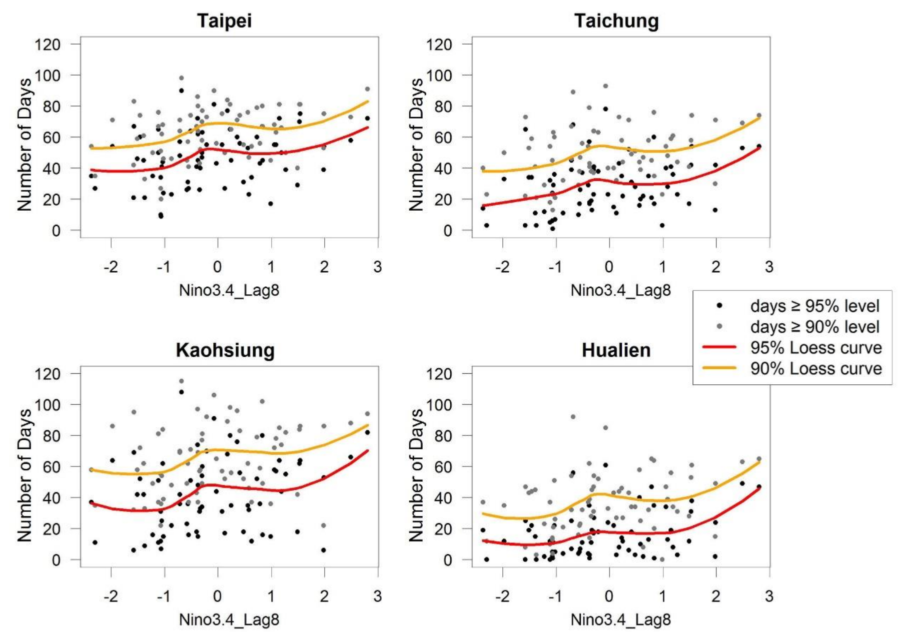
Geological location of Taiwan & Nino3.4

Taiwan

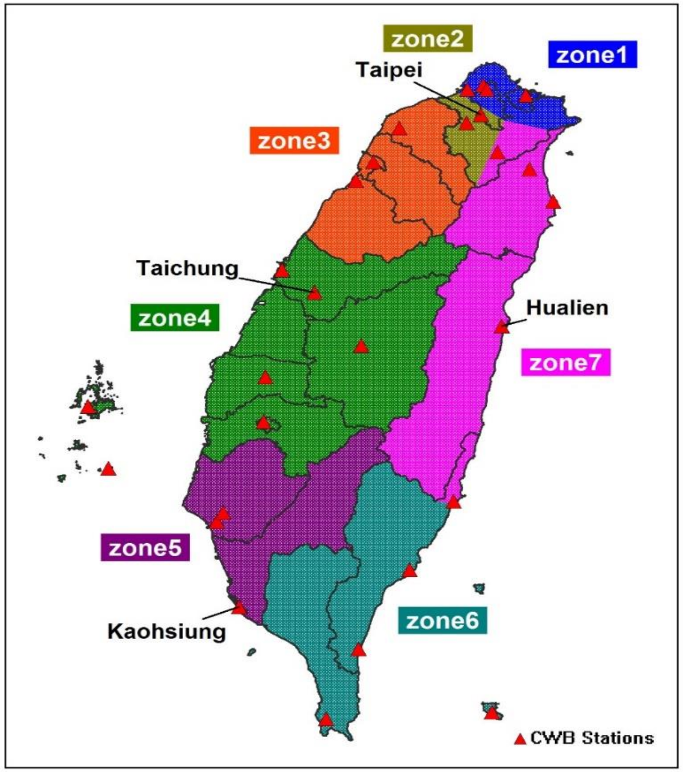


Association between lagged Nino3.4 index & hot days in June-Sept.





Division of Nino-impacted zones in Taiwan



We divided Taiwan into 7 ENSO-impacted zones based on geographical homogeneity of neighboring counties.

A single ENSO effect function f$(Nino3.4, l; T, k)$ was shared for cities/counties fall within the same zone.

State-space prediction model for number of hot days in June-September

Let the days of exceeding the daily average temperature T of year k be

$$Y_{T,k} = \mu_{T,k} + f(Nino3.4, l; T, k) + X_{T,k} + \nu_{T,k}$$

where

$\mu_{T,k}$: trend due to climate change

f$(Nino3.4, l; T, k)$: mean-adjusted nonlinear function of Nino3.4 index of lagged month *l*

$X_{T,k}$: stationary time series variation not explained by the first two factors

$\nu_{T,k}$: observational error ~ $N\left(0, \sigma_{obs}^2\right)$

Approximation for climate change trend & process error

Taylor's expansion:

$$\mu_{T,k} = g_T(k) + e^*_{T,k} \cong g_T(k-1) + g'_T(k-1) * [k - (k-1)] + e^*_{T,k}$$

$$\cong 2\mu_{T,k-1} - \mu_{T,k-2} + e_{T,k}$$

where $e_{T,k}$ is the process error, which is assumed to be normally distributed with a mean 0 and variance σ^2_{proc} .

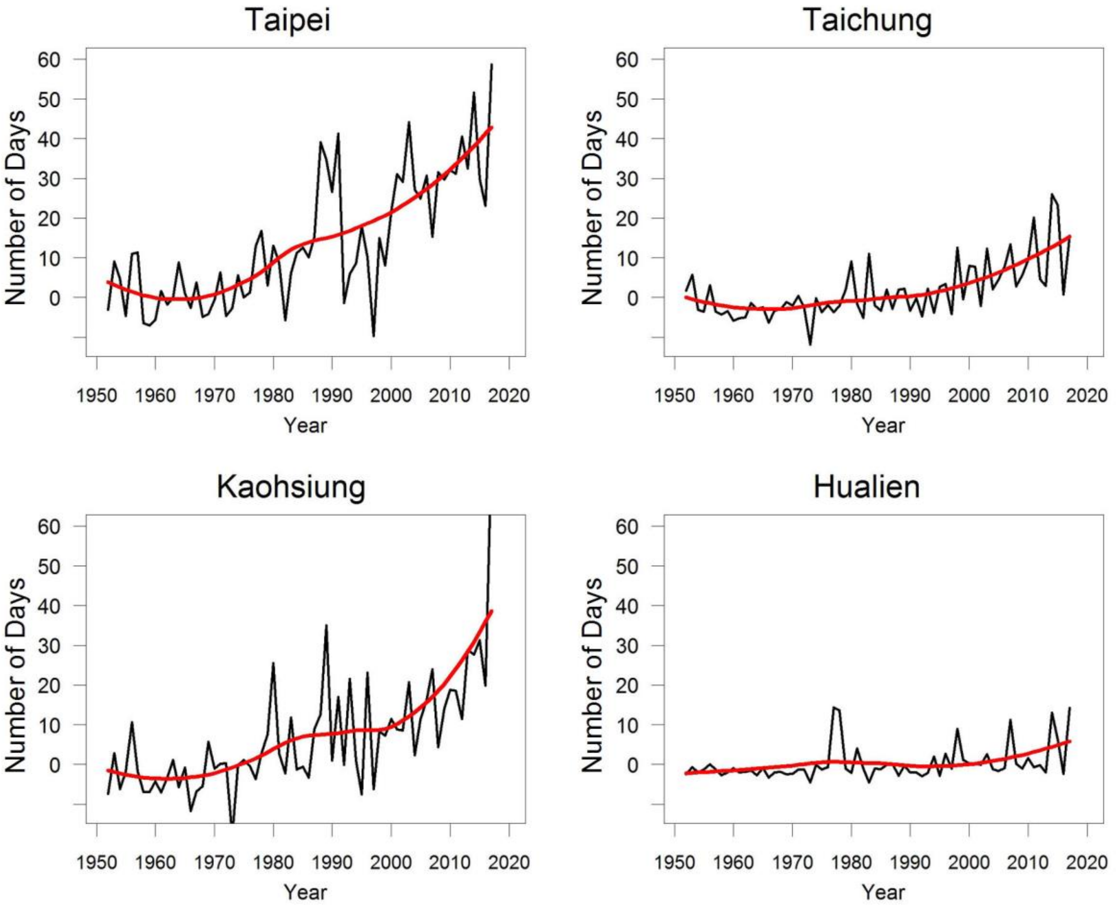
Estimation methods

- A locally weighted scatter plot smoothing (LOESS) regression was applied to estimate $\mathrm{f}(Nino3.4, l; T, k)$

- Similarly, the initial values of $\mu_{T,k}$ were obtained from LOESS estimates.
- The variation $X_{T,k}$ is assumed to follow an AR(2) model

- OpenBUGS 3.2-3.1 software using Bayesian MCMC simulations was employed for the estimation.

Estimated trend of the number of days with mean temperature >30°C after adjusting for the effect of lagged Nino3.4 index at 8 months



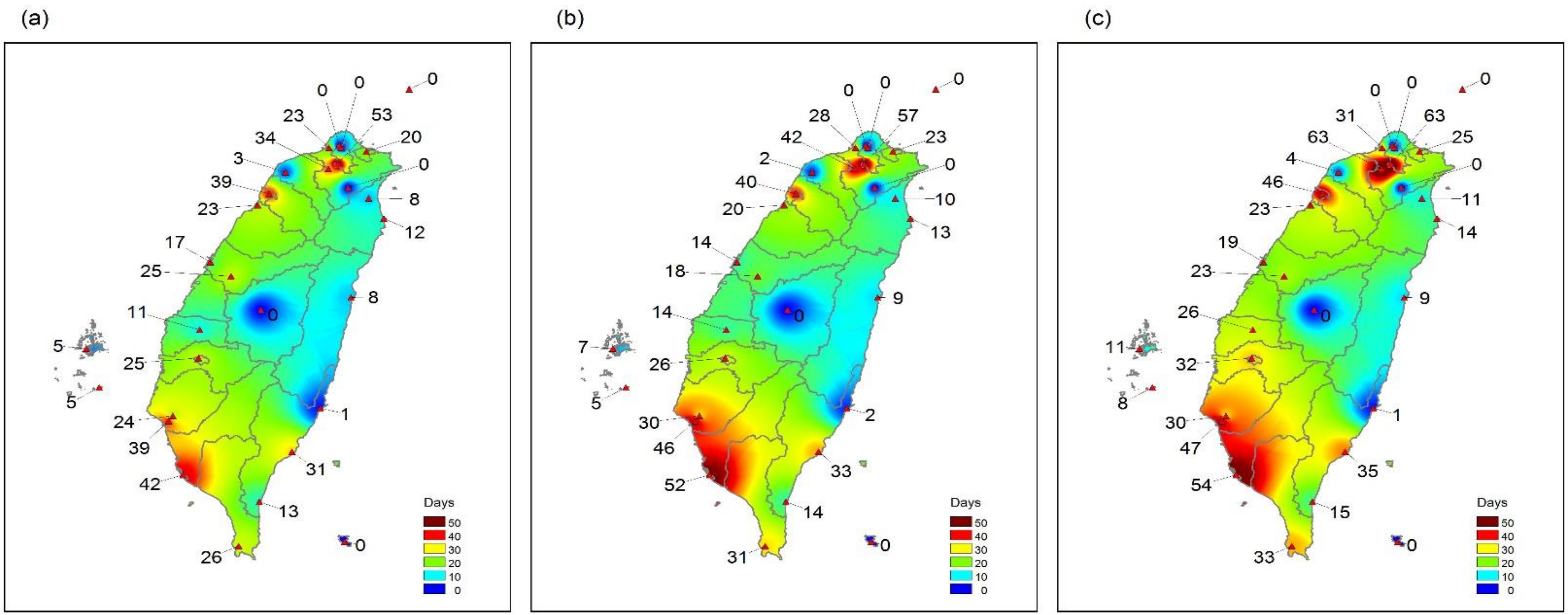
Average differences between predicted vs. observed hot days 2015-2017

Station / Year / Temperature	Tonghou	Xinwu	Zhunan	Huwei	Banqiao	Tamsui	**Taipei**	Keelung	**Hualien**	Suao	Yilan	Dongjidao	Penghu	Tainan	Yongkang	**Kaohsiung**	Chiayi	**Taichung**	Dawu	Hsinchu	Hengchun	Chengkung	Taitung	Wuqi
≥ 26 °C	4	0	0	3	2	4	1	0	-1	1	2	0	-1	2	-2	1	1	2	-1	1	0	0	-1	1
≥ 27 °C	2	0	-1	7	1	4	4	1	0	3	2	0	0	3	-1	1	5	3	-1	5	-2	3	1	4
≥ 28 °C	3	-3	1	13	0	5	3	1	-1	5	5	-2	2	3	-2	-1	4	1	1	7	-2	5	-1	5
≥ 29 °C	5	-3	0	11	4	6	3	2	-1	5	2	1	-3	4	-2	-2	1	2	-1	7	-6	8	0	3
≥ 30 °C	NA	1	1	9	11	2	4	0	-1	0	0	0	1	0	-3	-8	-3	1	4	2	-8	2	-2	1
≥ 31 °C	NA	1	-1	2	2	0	-1	-2	NA	0	0	NA	0	0	-1	-3	-1	1	0	-2	-1	NA	2	NA
≥ 32 °C	NA	NA	NA	NA	0	1	-2	-1	NA	NA	NA	NA	NA	NA	NA	0	NA	NA	0	0	NA	NA	NA	NA

-8 ~ -6   -5 ~ -3   -2 ~ +2   +3 ~ +7   +8 ~ +13   NA

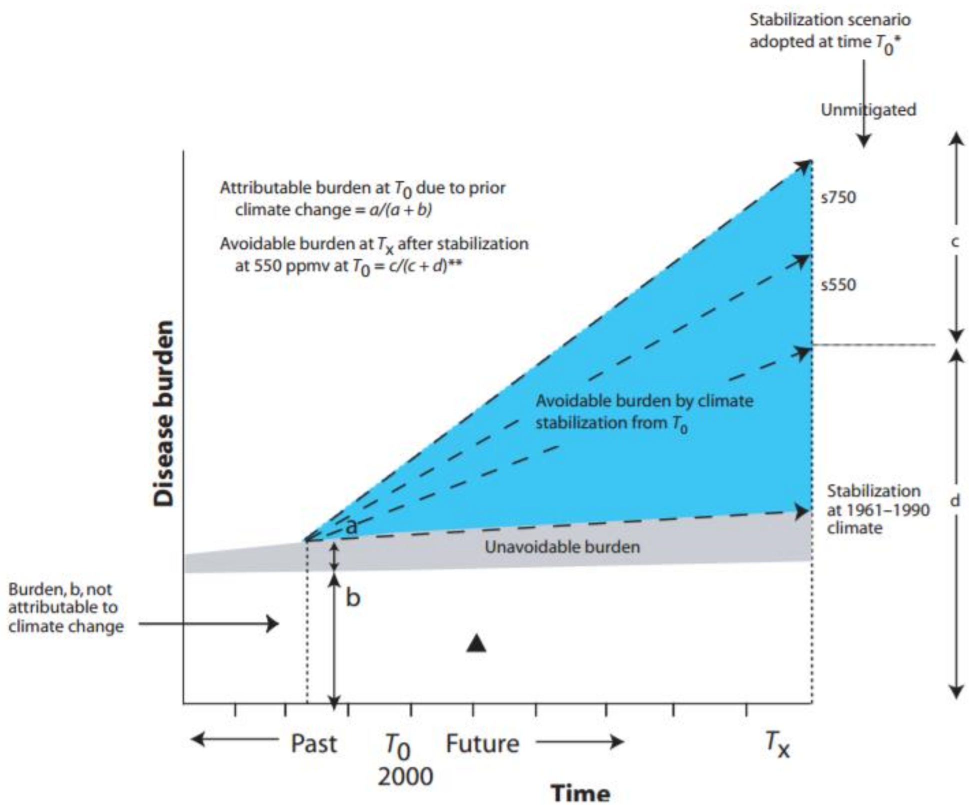
$\cong 70\%$ cells were within prediction errors $-2 \sim +2$ days

Predicted number of days with ave. temperature >30 ^{o}C (June-Sept.) in (a) 2018; (b) 2019; and (c) 2020.



Health risk assessment due to climate change

WHO的比較風險評估(comparative risk assessment, CRA)的做法，探討全球疾病負荷(Global burden of disease)中有關氣候變遷的各項危險因子的可歸因風險，計算在不同暴露情境如每日均溫的改變下，所導致的可歸因全死因，以及呼吸道疾病、心血管疾病死亡，以及急診、住院人數，與壽命損失年(Years of Life Lost, YLLs)，以及急診、住院等的失能調整生命年(Disability-adjusted Life-years, DALYs)。



Patz et al. (2008) Ann Rev Public Health

Attributable mortality (AM) 計算方法

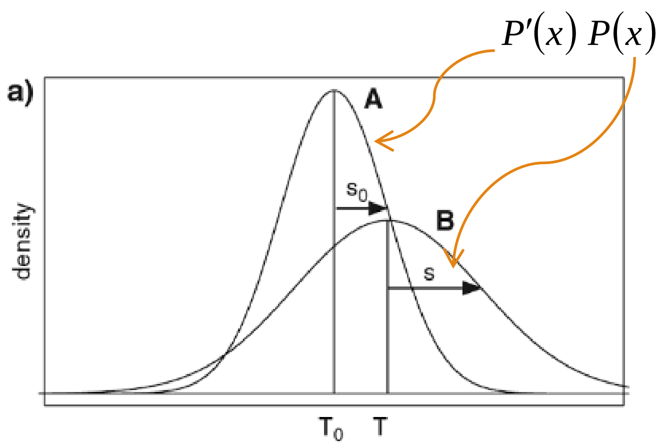
可歸因死亡(attributable mortality, AM) (或morbidity 急診、住院)人數的計算

$$AM_{ij}(T;y,\mathbf{z})=PAF_{M_{ij}}(T;\mathbf{z})\times M_{ij}(\mathbf{z})\times Pop(y,\mathbf{z})$$

可歸因人口比例 (population attributable fraction) PAF

$$PAF_{M_{ij}}(T;\mathbf{z})=\frac{\int_T^m RR_{M_{ij}}(x;\mathbf{z})P(x)dx-\int_T^m RR_{M_{ij}}(x;\mathbf{z})P'(x)dx}{\int_T^m RR_{M_{ij}}(x;\mathbf{z})P(x)dx}$$

其中 $P(x)$, $P'(x)$ 分別為未來預估 (短期: 2018~2020; 中長期: 2021~2060) 與相對基期 (2001~2010)的機率分布， RR 為 relative risk, T 為 threshold， Pop 為預估未來(65歲以上老年)人口數，M 為 mortality rate



可歸因人口比例 PAF 計算

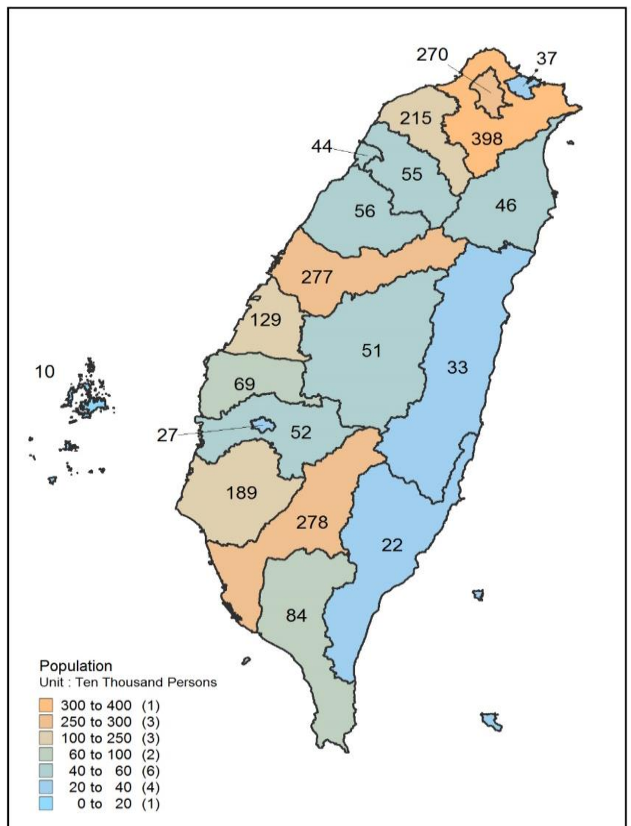
$$PAF=\frac{\int_T^m RR(x)P(x)dx-\int_T^m RR(x)P'(x)dx}{\int_T^m RR(x)P(x)dx}=1-\frac{\int_T^m RR(x)P'(x)dx}{\int_T^m RR(x)P(x)dx}$$

$$\int_T^m RR(x)P(x)dx \cong \sum_{l=27}^{32} RR(l)[P(Tmpt \geq l-1)-P(Tmpt \geq l)]$$

$$\cong \sum_{l=27}^{32} RR(l)\left(\hat{y}_{l-1,k}-\hat{y}_{l,k}\right)$$

此處 $T=26$°C, $m=32$°C, RR(k), 全台19個縣市的全死因、心血管、呼吸道疾病死因每度變化的RR

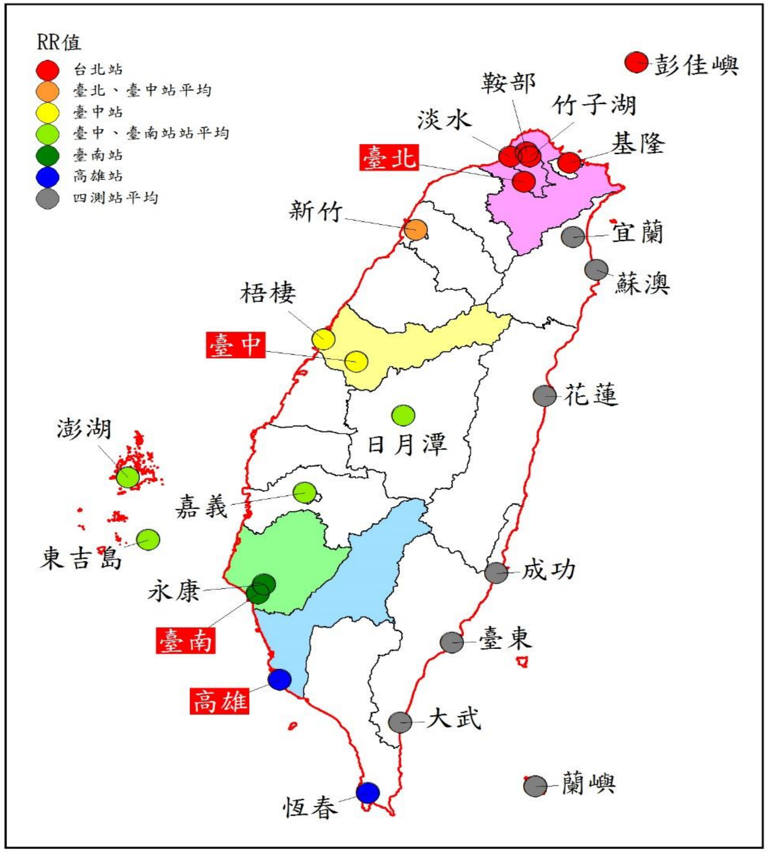
台灣地區人口分布現況（$\times 10^4$）



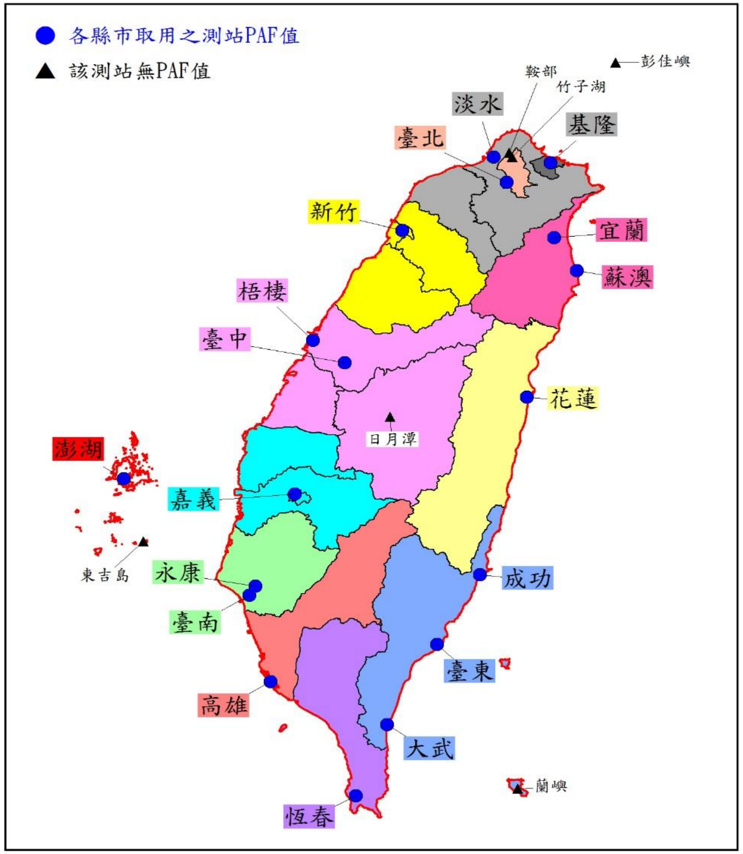
Population of administrative divisions, end of 2016

RR & PAF計算行政區域劃分

各測站RR值



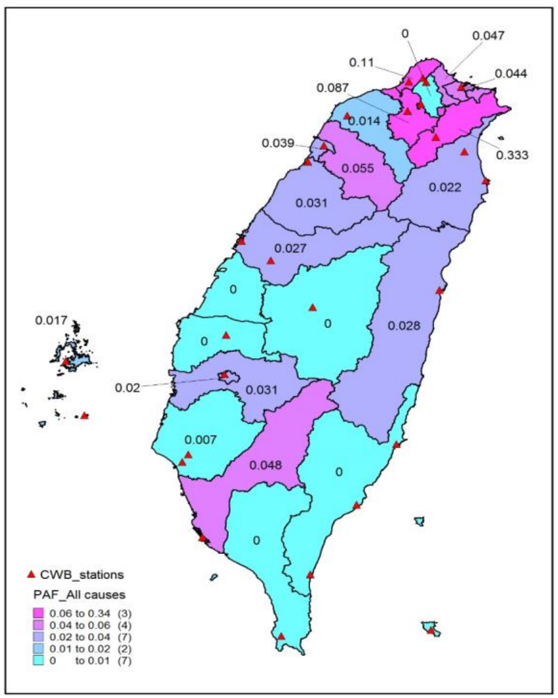
各縣市PAF值



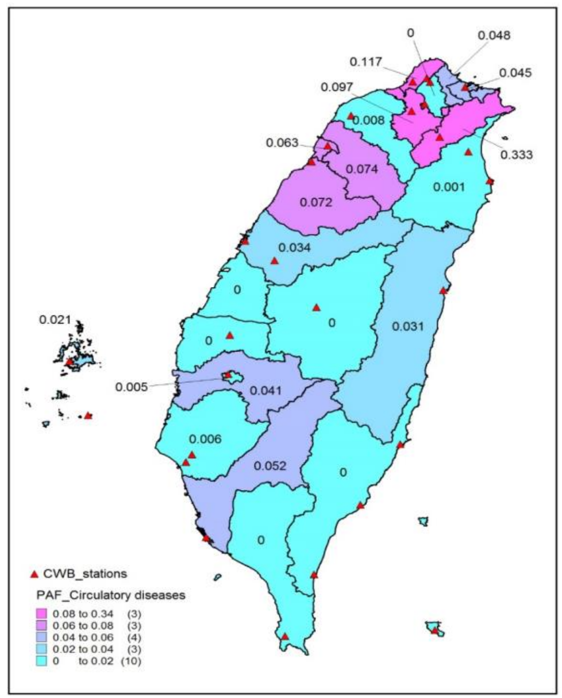
2018年各縣市預測高溫可歸因死亡人口比例 (PAF) (全死因、心血管、呼吸道疾病)

(reference period 2001-2010)

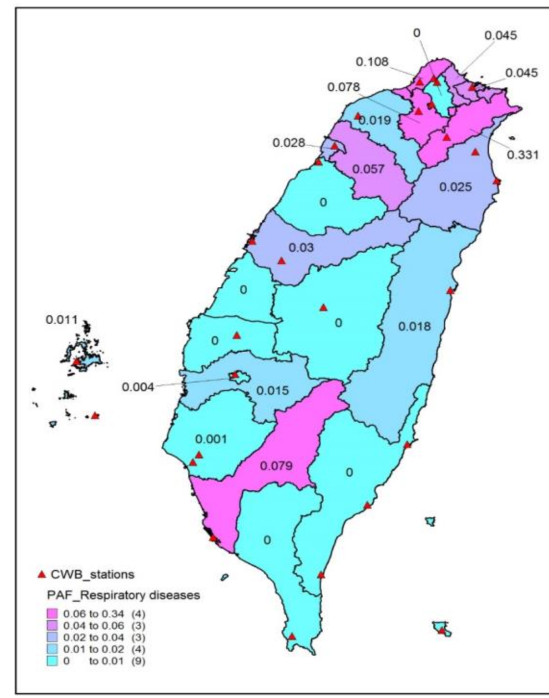
PAF of Deaths from All-Causes, 2018



PAF of Deaths from Circulatory diseases, 2018



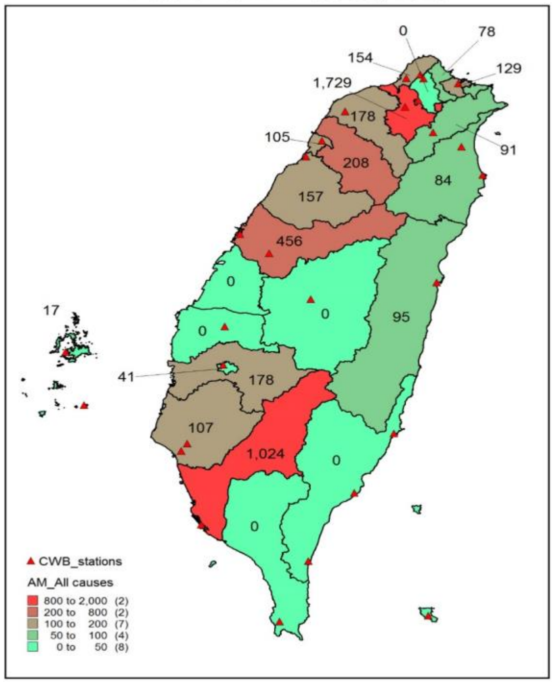
PAF of Deaths from Respiratory diseases, 2018



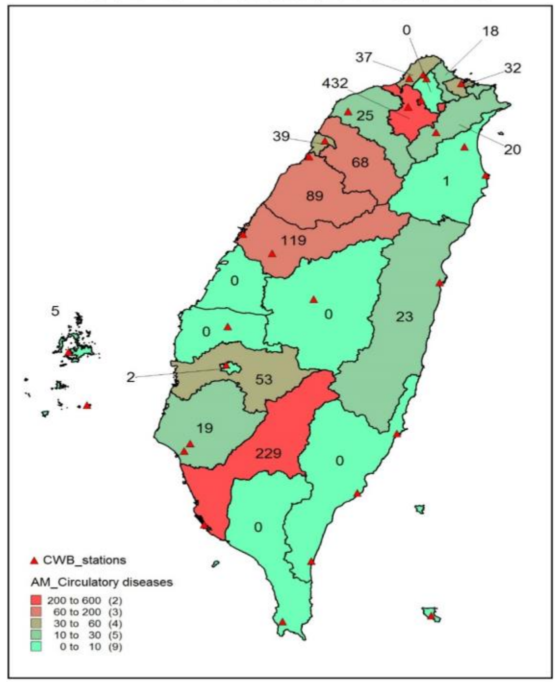
2018年各縣市預測高溫可歸因死亡人數高溫可歸因死亡人數(全死因、心血管、呼吸道疾病)

(reference period 2001-2010)

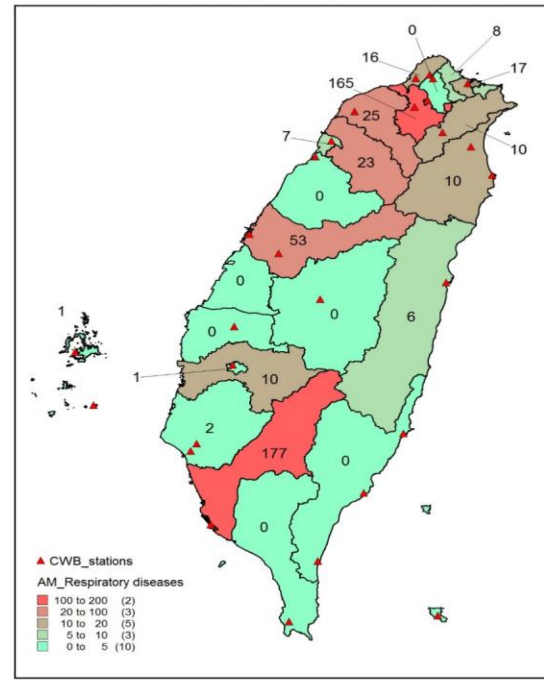
Attributable mortality (AM) of
Deaths from All-Causes, 2018



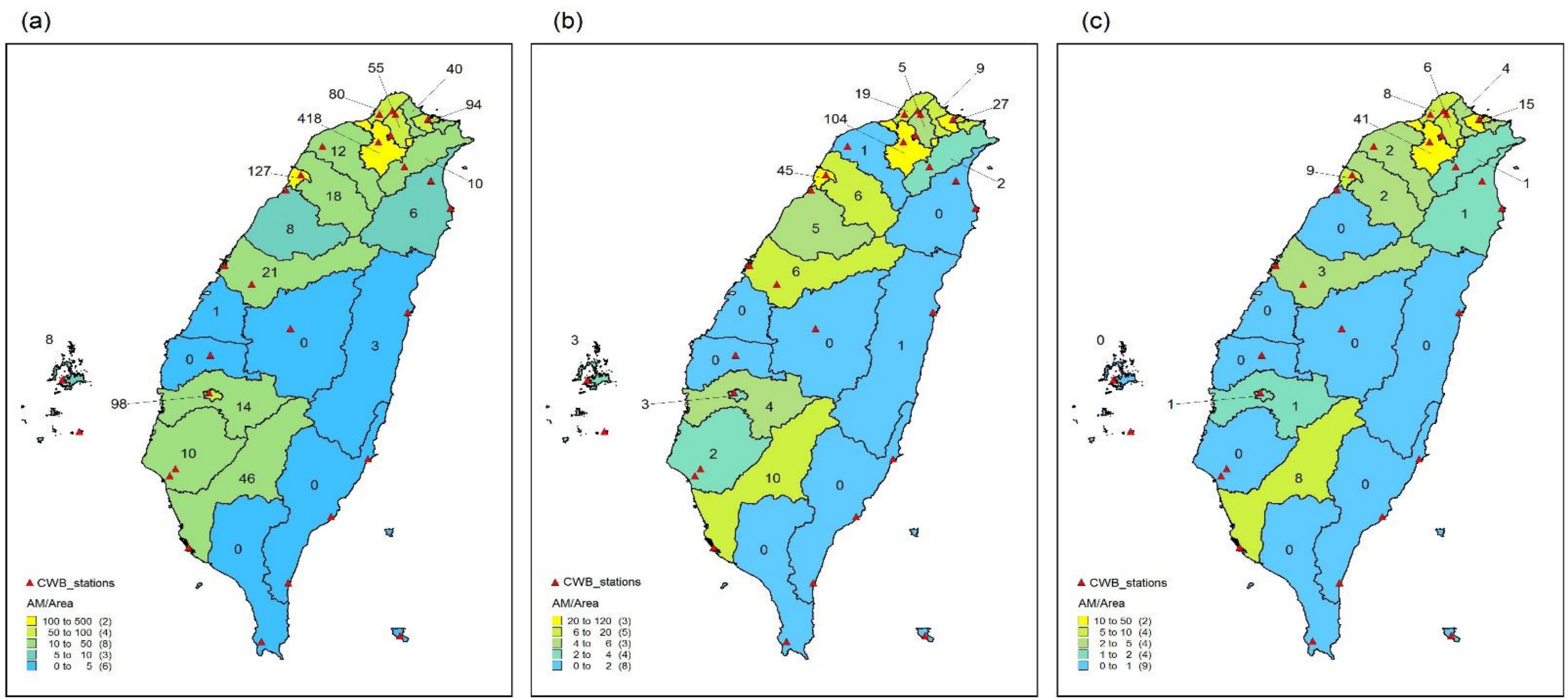
Attributable mortality (AM) of
Deaths from Circulatory diseases, 2018



Attributable mortality (AM) of
Deaths from Respiratory diseases, 2018



Mean projected numbers of attributable mortality of (a) overall; (b) circulatory diseases; (c) respiratory diseases in 2018-2020 (reference period 2001-2010) (Per 100 Km^2)



Mean projected heat-related attributable mortalities for Taipei/New Taipei, Taichung, Kaohsiung, and Hualien in 2018-2020

City/County	Area (km^2)		Population	Attributable mortality		
				All causes	Circulatory	Respiratory
Taipei/New Taipei	2324.4		6,674,912	3,107 (133-7,859)	741 (24-2,077)	311 (10-1,122)
Taichung	2214.9		2,767,239	473 (6-1,256)	130 (2-386)	58 (3-223)
Kaohsiung	2951.9		2,779,371	1,344 (426-2,169)	295 (39-576)	226 (50-426)
Hualien	4628.6		330,911	145 (89-270)	35 (15-80)	9 (3-34)

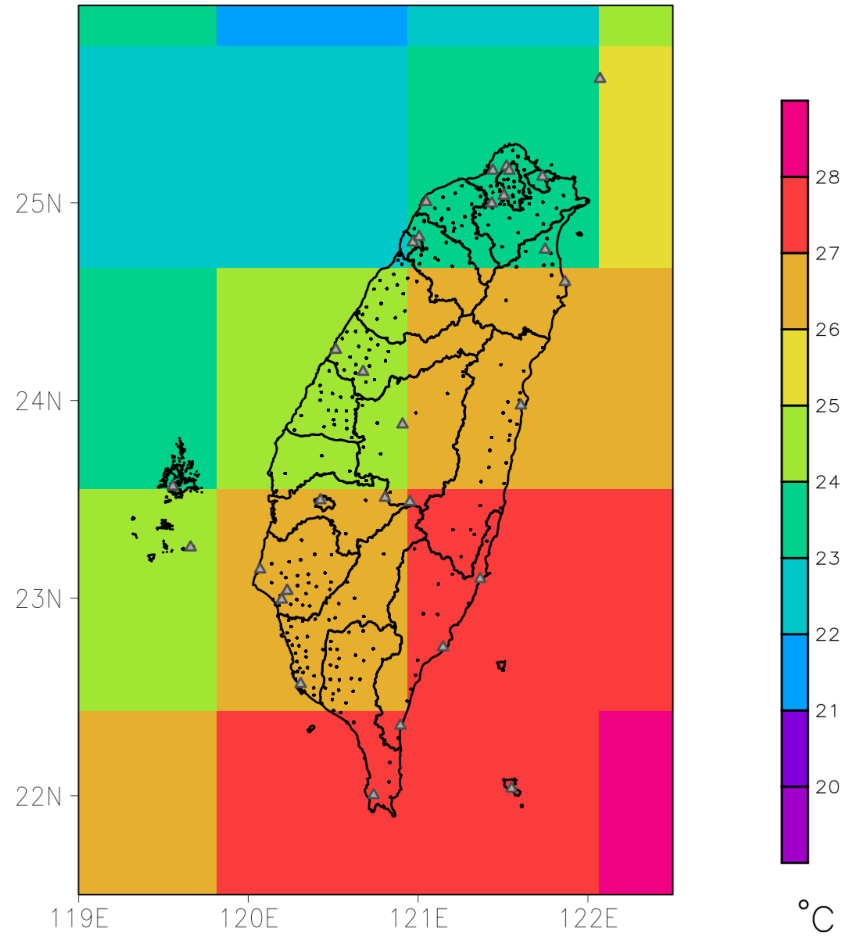
Mid (1921-1940) & long-term (1941-1960) prediction of extremely hot days due to climate change

CMIP5	Daily	Atmosphere						
Model	Institute	RES.	格點大小	historical	rcp26	rcp45	rcp60	rcp85
ACCESS1-0	CSIRO-BOM	192x145	1.875x1.241	○		○		○
ACCESS1-3		192x145	1.875x1.241	○		○		○
bcc-csm1-1	BCC	128x64	2.813x2.813	○	○	○	○	○
bcc-csm1-1m		320x160	1.125x1.125	○	○	○	○	○
BNU-ESM	BNU	128x64	2.813x2.813	○	○	○		○
CanESM2	CCCMA	128x64	2.813x2.813	○	○	○		○
CCSM4	NCAR	288x192	1.25x0.938	○	○	○	○	○
CESM1-BGC	NCAR	288x192	1.25x0.938	○		○		○
CESM1-CAM5		288x192	1.25x0.938	○	○	○	○	○
CMCC-CESM	CMCC	96x48	3.75x3.75	○				○
CMCC-CM		480x240	0.75x0.75	○		○		○
CMCC-CMS		192x96	1.875x1.875	○		○		
CNRM-CM5	CNRM-CERFACS	256x128	1.406x1.406	○	○	○		○
CSIRO-Mk3-6-0	CSIRO-QCCCE	192x96	1.875x1.875	○	○	○	○	○
EC-EARTH	ICHEC	320x160	1.125x1.125	○		△		○
FGOALS-g2	LASG-CESS	128x60	2.813x3	○	○	○		○
GFDL-CM3	NOAA-GFDL	144x90	2.5x2	○	○	△	○	○
GFDL-ESM2G		144x90	2.5x2	○	○	○	○	○
GFDL-ESM2M		144x90	2.5x2	○		○	○	○
HadGEM2-AO	MOHC	192x145	1.875x1.241	○	○	○	○	○
HadGEM2-CC		192x145	1.875x1.241	○		○		○
HadGEM2_ES		192x145	1.875x1.241	○	○	○	○	○
inmcm4	INM	180x120	2x1.5	○		○		○
IPSL-CM5A-LR	IPSL	96x96	3.75x1.875	○	○	○	○	○
IPSL-CM5A-MR		144x143	2.5x1.259	○	○	○	○	○
IPSL-CM5B-LR		96x96	3.75x1.875	○		○		○
MIROC5	MIROC	256x128	1.406x1.406	○	○	○	○	○
MIROC-ESM		128x64	2.813x2.813	○	○	○	○	○
MIROC-ESM-CHEM		128x64	2.813x2.813	○	○	○	○	○
MPI-ESM-LR	MPI-M	192x96	1.875x1.875	○	○	○		○
MPI-ESM-MR		192x96	1.875x1.875	○	○	○		○
MRI-CGCM3	MRI	320x160	1.125x1.125	○	○	○	○	○
MRI-ESM1		320x160	1.125x1.125	○				○
NorESM1-M	NCC	144x96	2.5x1.875	○	○	○	○	○
			Total：	34(30)	22(21)	32(28)	17(16)	33(30)

- 8種模式列表

CMIP5	Daily	Atmosphere						
Model	Institute	RES.	calendar	historical	rcp26	rcp45	rcp60	rcp85
bcc-csm1-1m	BCC	320x160	365	○	○	○	○	○
CCSM4	NCAR	288x192	365	○	○	○	○	○
CESM1-BGC	NCAR	288x192	365	○		○		○
CESM1-CAM5		288x192	365	○	○	○	○	○
CMCC-CM	CMCC	480x240	standard	○		○		○
EC-EARTH	ICHEC	320x160	standard	○				○
MRI-CGCM3	MRI	320x160	standard	○	○	○	○	○
MRI-ESM1		320x160	standard	○				○
			Total :	8	4	6	4	8

- 氣候模式bcc-csm1-1-m、RCP8.5情境、2006~2060年最高溫平均分布圖



- 假設存在一轉換式T[0,1] → [0,1]使得測站歷史資料CDF分布可轉換至月平均CDF分布。

轉換式T使得：

$$T\left(F_{Xc}(X)\right) = F_{Yc}(X) \text{❶} \quad \text{且}$$

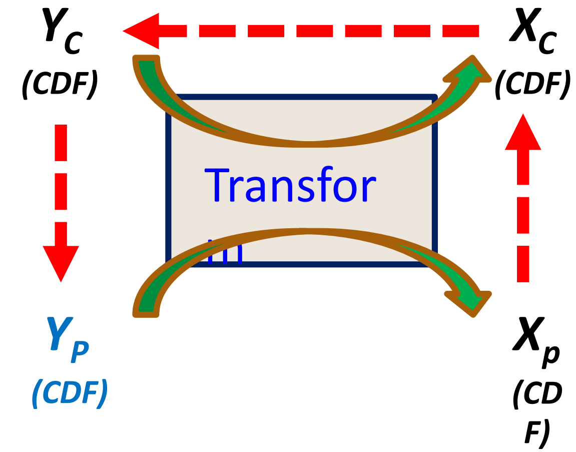
$$T\left(F_{Xp}(X)\right) = F_{Yp}(X) \text{❷}$$

令❶式中 $F_{Xc}(X) = u \rightarrow X = F_{Xc}^{-1}(u)$ 代入❷

$$T(u) = F_{Yc}\left(F_{Xc}^{-1}(u)\right) \quad \text{❸}$$

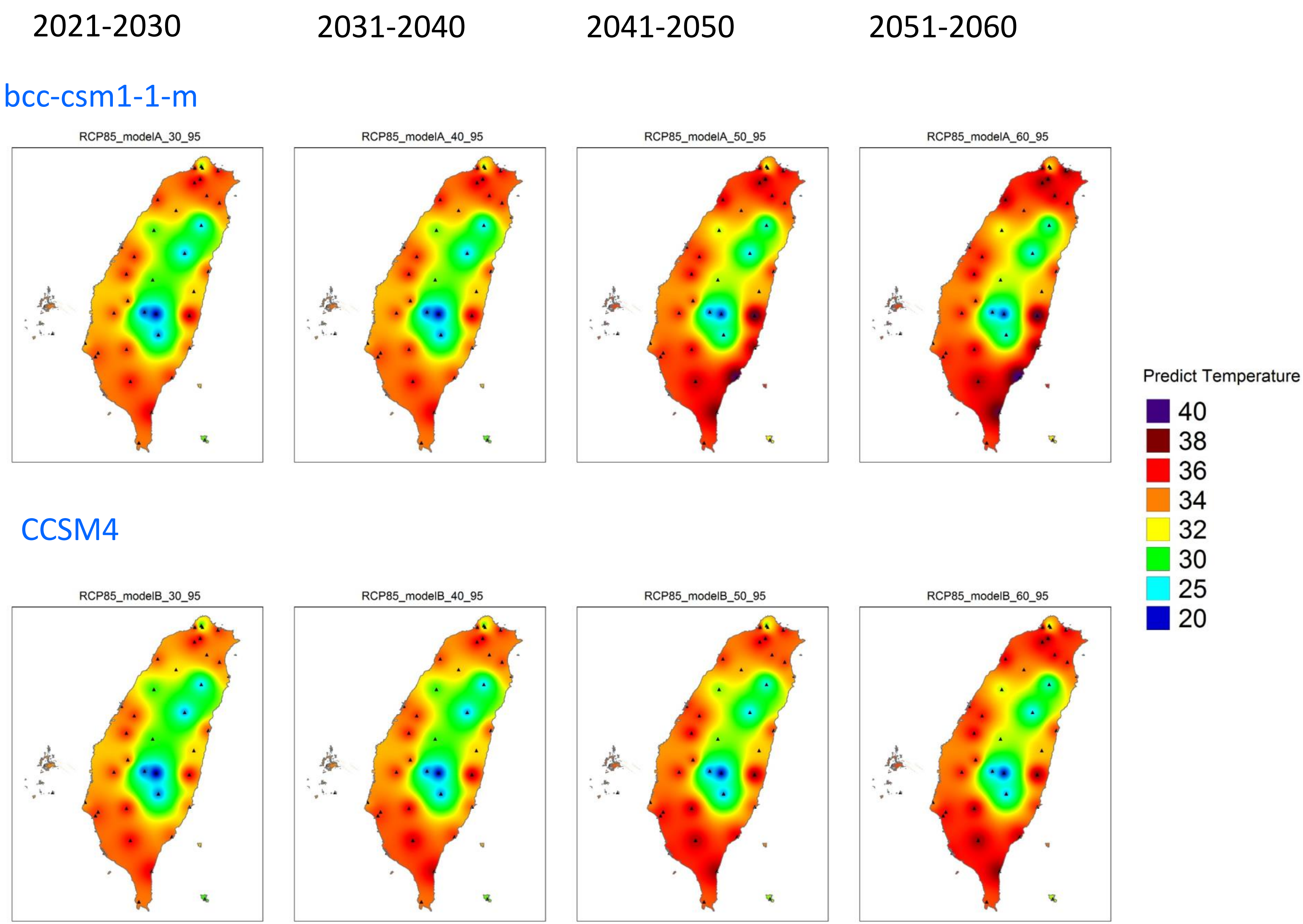
$$F_{Y_P}(X) = T\left(F_{X_P}(X)\right) = F_{Y_C}\left(F_{X_C}^{-1}\left(F_{X_P}(X)\right)\right)$$

❷代入❸



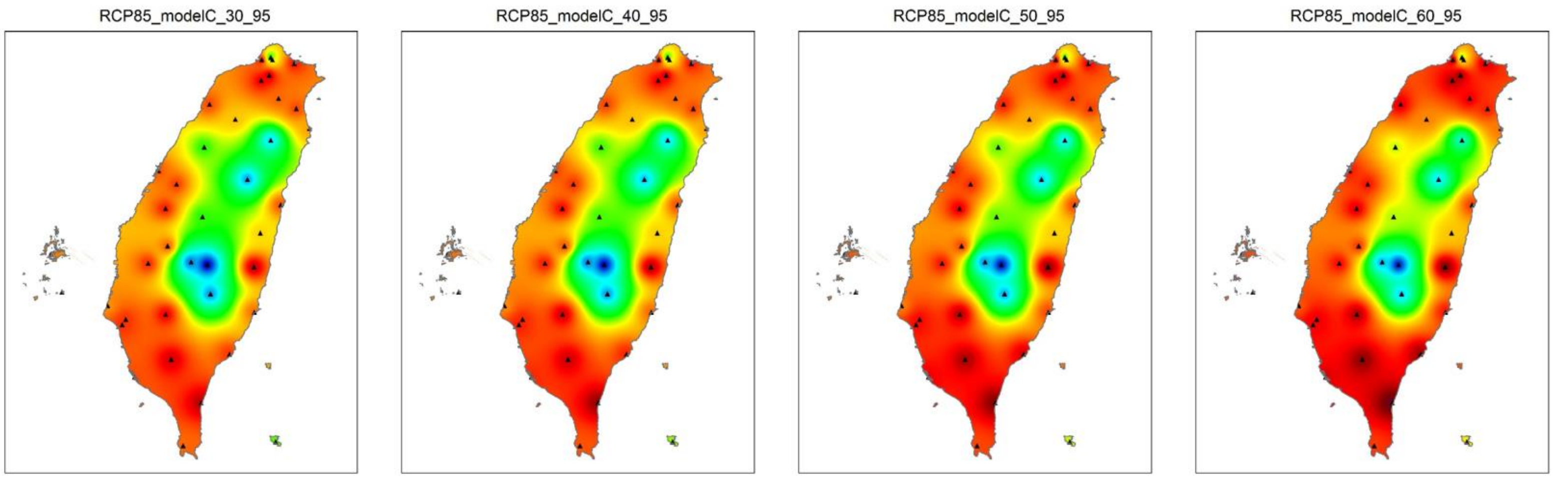
- X_C：氣候模式過去(1961-2005)的輸出值(Model輸出之歷史每日最高溫度CDF)
  X_P：氣候模式未來(2006-2100)的預測值(Model輸出之未來每日最高溫度CDF)
  Y_C：當地測站過去(1961-2005)資料(CWB逐日CDF)
  Y_P：當地測站未來氣溫(2005-2100)推估值(逐日CDF)

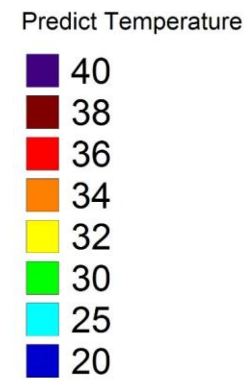
Michelangeli et al. (2009) 機率降尺度法
(Probabilistic Downscaling) CDF-t


2021-2030
2031-2040
2041-2050
2051-2060
bcc-csm1-1-m
RCP85_modelA_30_95
RCP85_modelA_40_95
RCP85_modelA_50_95
RCP85_modelA_60_95
CCSM4
RCP85_modelB_30_95
RCP85_modelB_40_95
RCP85_modelB_50_95
RCP85_modelB_60_95
Predict Temperature
40
38
36
34
32
30
25
20

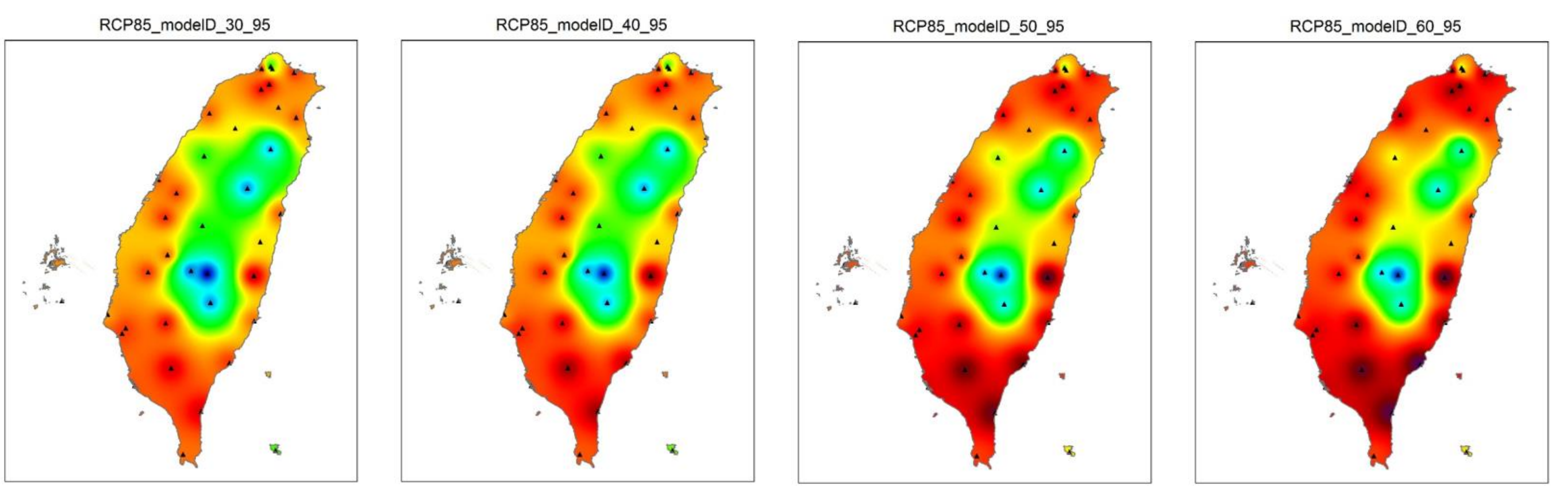
2021-2030 | 2031-2040 | 2041-2050 | 2051-2060

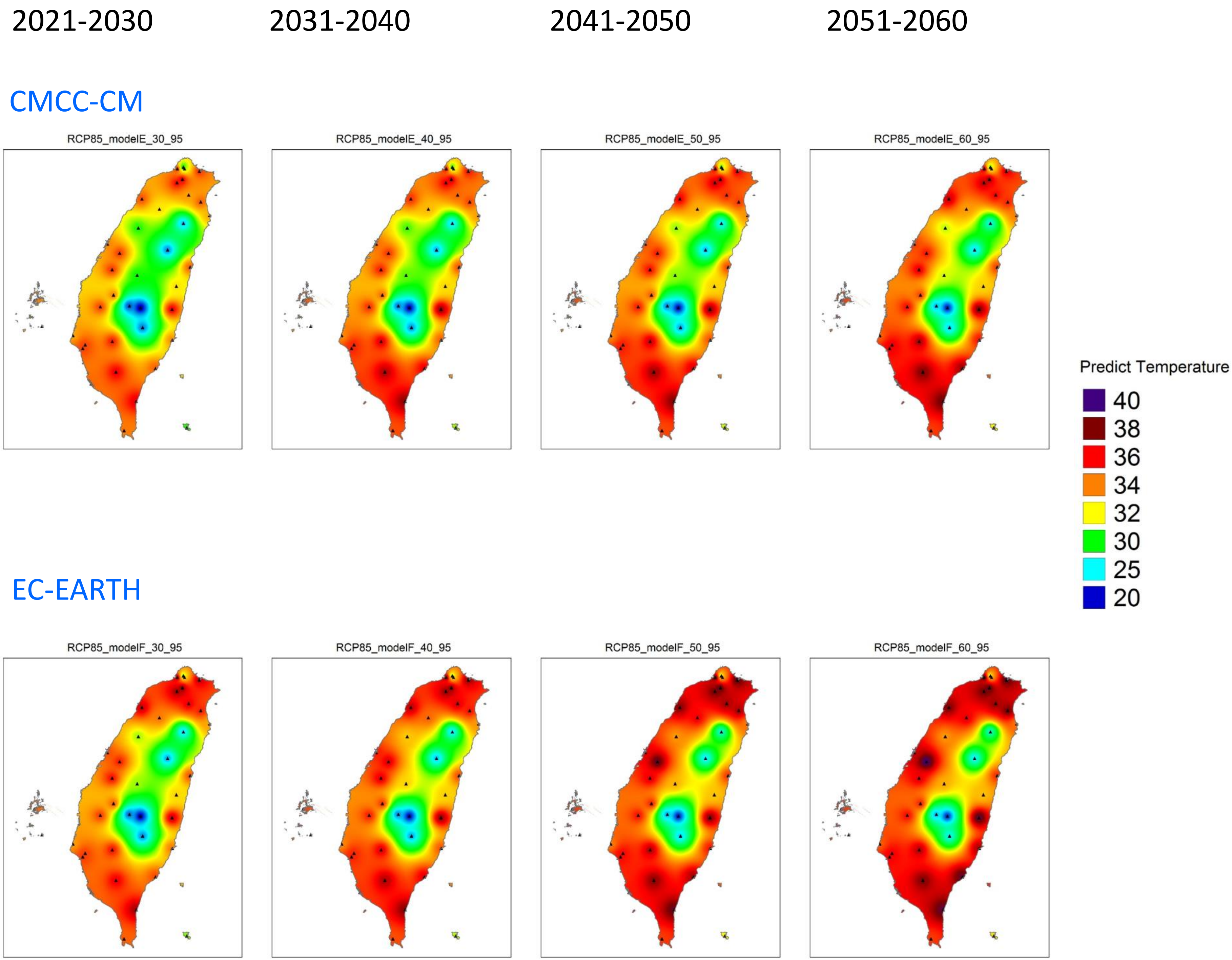
CESM1-BGC





CESM1-CAM5




2021-2030
2031-2040
2041-2050
2051-2060
CMCC-CM
RCP85_modelE_30_95
RCP85_modelE_40_95
RCP85_modelE_50_95
RCP85_modelE_60_95
EC-EARTH
RCP85_modelF_30_95
RCP85_modelF_40_95
RCP85_modelF_50_95
RCP85_modelF_60_95
Predict Temperature
40
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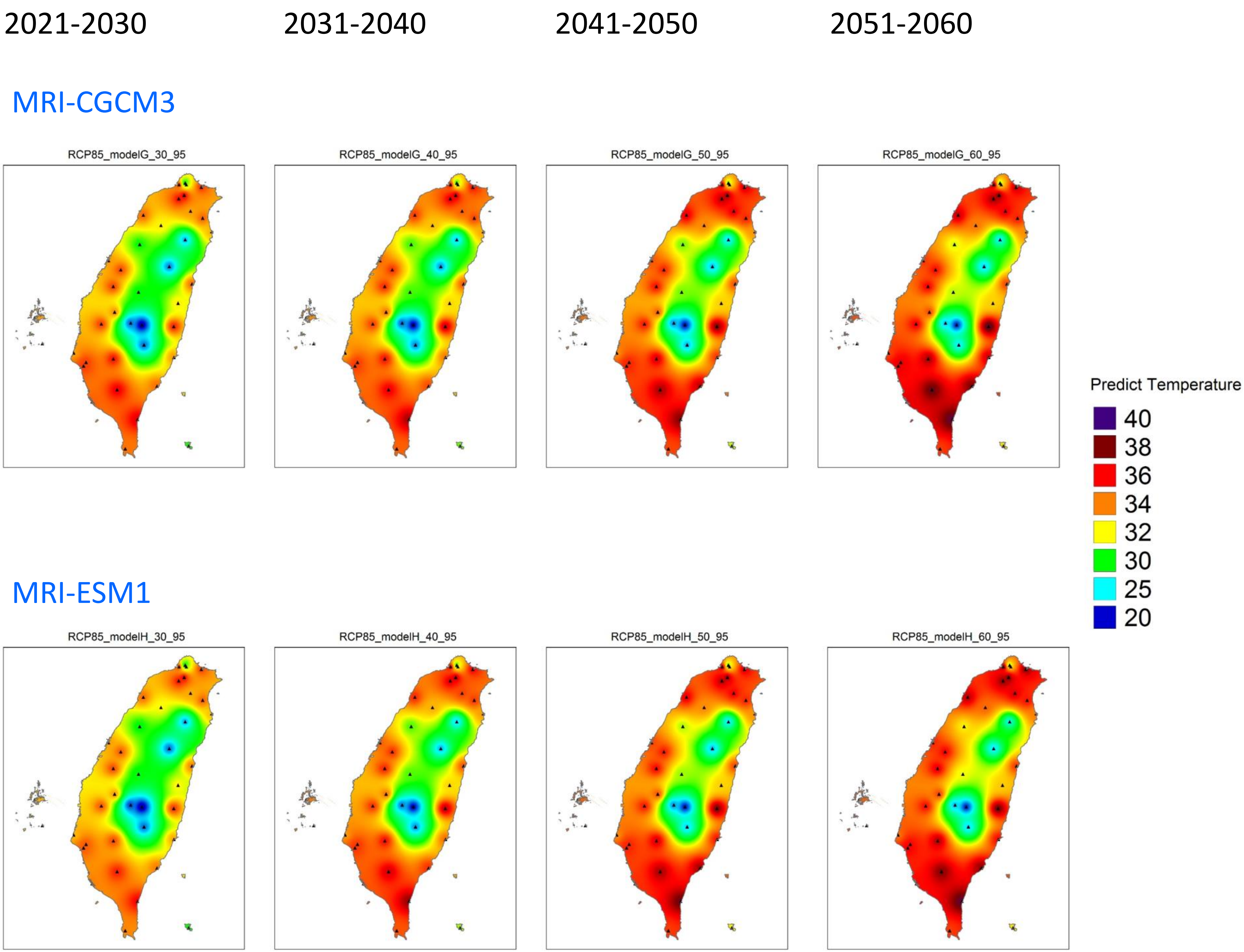

2021-2030
2031-2040
2041-2050
2051-2060
MRI-CGCM3
RCP85_modelG_30_95
RCP85_modelG_40_95
RCP85_modelG_50_95
RCP85_modelG_60_95
MRI-ESM1
RCP85_modelH_30_95
RCP85_modelH_40_95
RCP85_modelH_50_95
RCP85_modelH_60_95
Predict Temperature
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Future work

- Model ensemble for the simulation outcomes of 8 GCM models
- Other data sources, e.g., population projection for 2021-2060
- Further epidemiological study outcomes for health impacts due to extreme heat

Summary

- Climate change is ongoing.
- Short-term predictions of extremely hot days in June-Sept. 2018-2020 are already substantially higher than those in 2001-2010. New Taipei & Kaohsiung are the most impacted area for attributable mortality
- The established statistical model for short-term predictions had well performance.
- Lots uncertainties exist for future climate change projection
- Integration of various sources of data are required for future projection.

Thank you for your attention!