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# The Taiwan Climate Change Projection Information and Adaptation Knowledge Platform: A Decade of Climate Research

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**Abstract:** Taiwan's climate change projections have always presented a challenge due to Taiwan's size and unique meteorological and geographical characteristics. The Taiwan Climate Change Projection Information and Adaptation Knowledge Platform (TCCIP), funded by the Ministry of Science and Technology, Taiwan, is a decade-long climate research project with the most predominant climate data provider and national adaptation policymaking in the country. This paper outlines the evolution of the project. It describes the project's major achievements, including climate projection arising from participation in the WCRP Coupled Model Inter-comparison Project (CMIP), dynamically and statistically downscaled data with resolutions up to 5 km grid, impact assessments of various themes, such as flooding, as well as the support of national policies through approaches including risk maps, climate data, and knowledge brokering.

**Keywords:** climate change; adaptation knowledge; climate research and projection; Taiwan

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## 1. Introduction

Taiwan is exposed to various natural hazards, such as typhoons, earthquakes, flash floods, and landslides, because Taiwan is situated in the central area of Western North Pacific typhoon pathways [1] along the western Circum-Pacific seismic belt, which is expected to be exacerbated by anthropogenic climate change with increased frequency and magnitude.

In response to the impacts of climate change, governmental institutions have introduced a series of policies. In 2010, catastrophic damage caused by Typhoon Morakot triggered nationwide awareness that focused on a more resilient adaptive approach to complement traditional disaster prevention measures. The National Adaptation Strategy [2] was formed through a series of inter-departmental and stakeholder discussions. The 1st five-year National Climate Change Adaptation Action Plan began in 2013, which considered eight adaptation themes, including disaster, water resources, land use, infrastructure, energy and industry, coastal zones, agriculture and biodiversity, and health, and ultimately proposed 399 action plans [3]. By 2015, Taiwan promulgated the Greenhouse Gas Reduction and Management Act with a legally binding emission reduction target and made adaptation policies and actions compulsory for all relevant departments and institutions [4]. Abiding by the Act and the subsequent National Climate Change Action Guidelines, the 2nd phase of the National Adaptation Plan started in 2018 (Figure 1), building upon available data, knowledge, and outcomes achieved in the 1st phase. It proposed a total of 125 action plans [5–10].

To support national adaptation actions, the TCCIP created an indicative map of climate-related actions for climate-related actions in Taiwan (as shown in Figure 2). The National Science Council (now Ministry of Science and Technology) began to fund a series of climate research projects to develop practical climate projections for purpose of enhancing decision-making. Since 2009, the NSC initiated three pilot research projects aimed at different purposes, including the Consortium for Climate Change Study (CCliCS), the TCCIP, and the Taiwan integrated research program on Climate Change Adaptation Technology (TaiCCAT), which continued for two phases within nine years, and were merged into the current and third phase of the TCCIP project (Figures 3 and 4). The following context will outline significant outcomes achieved during a decade of adaptation research, discuss the project's current status, and address existing and potential gaps from a practical perspective.

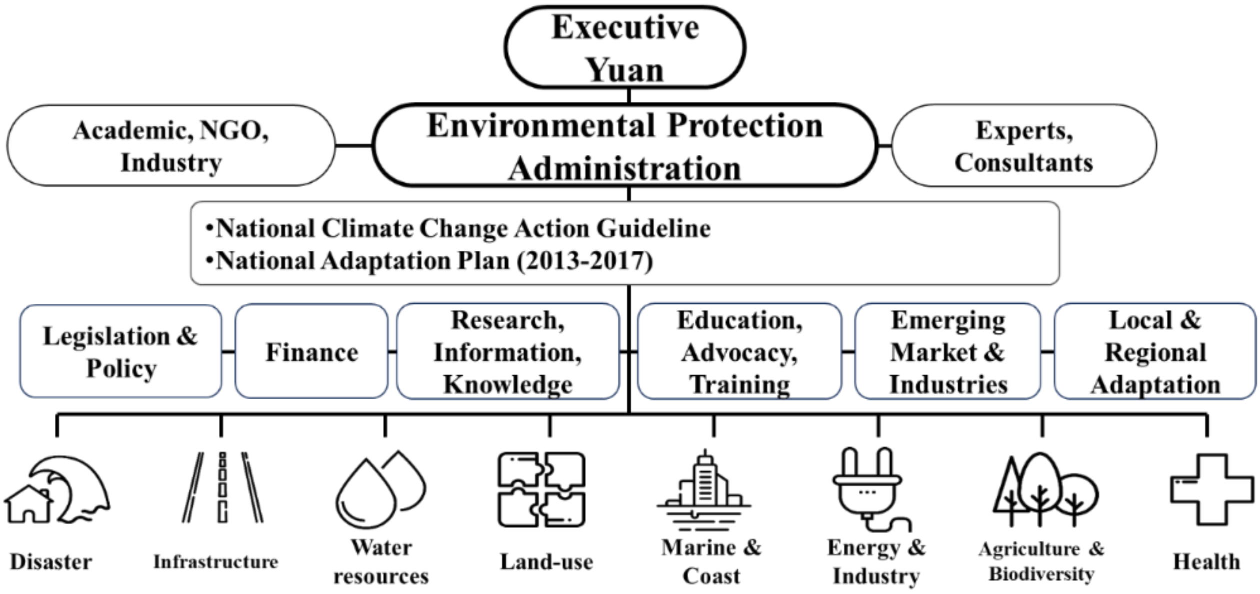


**Figure 1.** Framework of Taiwan's 2nd National Adaptation Plan (2018–2022). The "Yuan" is the same as the "Department of State" in the United States.

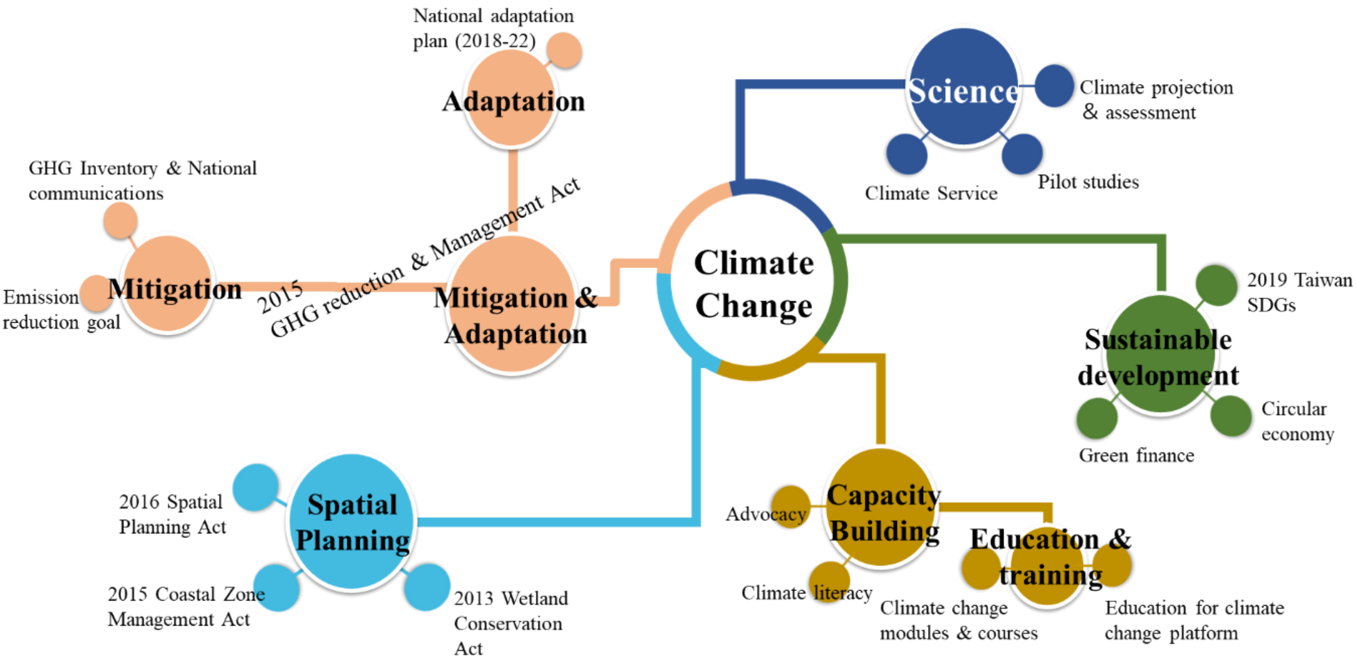


**Figure 2.** An indicative map of climate-related actions in Taiwan.

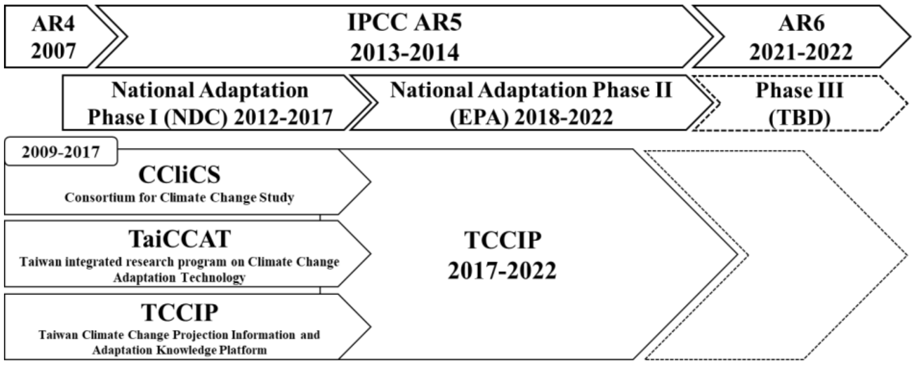


**Figure 3.** Evolution of the TCCIP project.

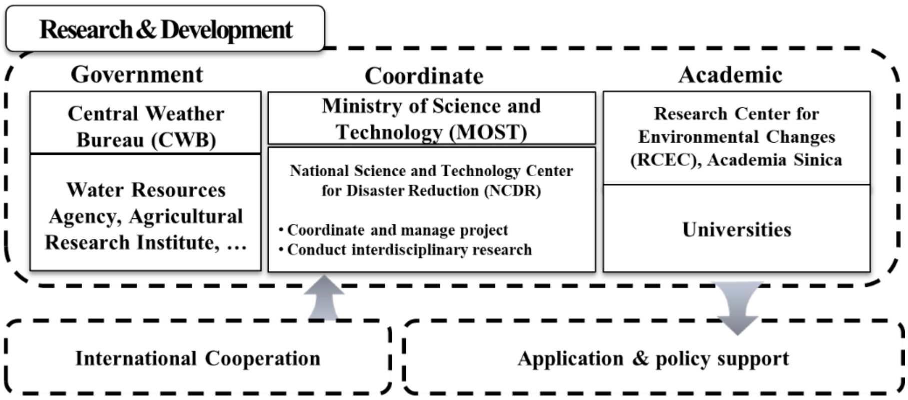


**Figure 4.** Framework of the TCCIP project.

## 2. Integration and Development of Climate Data

### *2.1. Integration of Observation Data*

The characteristics of rainfalls, such as their extremes, variations across different time scales, and spatial differences, are common problems for relevant studies during data processing. Taiwan has approximately 1500 observation stations within its 36,000 km$^2$ area. However, selecting appropriate time and spatial data from a wide range of observation records for analysis can be challenging for non-meteorologists, and these issues are further amplified in Taiwan due to its diverse climate system. Therefore, the TCCIP project assembled data from 51 institutions and established the Taiwan Rainfall Index (TRI), which comprises daily rainfall data from 1900 to 2010, processed from 1187 stations selected through stringent evaluation processes. In addition, over 7.2 million paper records from the Central Weather Bureau were also converted into an electronic dataset with 23 variables, covering parameters including air and water pressure, temperature, humidity, wind, precipitation, and sunshine. In addition, regarding previous studies [11,12], temperature and rainfall grid data were also generated with a resolution of 1 $\times$ 1 km from 1960 to 2009. These valuable data became the foundation of climate analysis in the country in the context of addressing historical weather and climate anomalies, planning infrastructure standards, or comparisons with climate projections.

### *2.2. Development of Climate Projection*

Downscaling methodology is an essential element of climate projections in Taiwan due to the fact that the resolution of international general circulation models (GCMs) used by the Intergovernmental Panel on Climate Change (IPCC) usually ranges from 150 to 300 km, which is not sufficient for practical evaluation of future climate change impacts in the country. The TCCIP project currently provides the most comprehensive climate projection data in Taiwan, with two separate methodologies aimed at different purposes, namely statistical downscaling and dynamical downscaling, and continues to evolve following the most recent international developments.

The TCCIP project team adopted bias correction and spatial disaggregation methods for statistical downscaling using the empirical cumulative distribution functions method (ECDF) [13–16], selecting three IPCC AR4 scenarios of A1B, A2, and B1 [17], using 24 atmosphere–ocean coupled general circulation models (AOGCM) for two time periods, 2020–2039 and 2080–2099, with output resolutions of 25 km and 5 km. As for dynamical downscaling, the team utilized two high-resolution atmospheric circulation models, one was developed by the Meteorological Research Institute (MRI) [18] under the Japan Meteorological Agency (JMA), another is an ECHAM5 GCM developed by the Max Planck Institute for Meteorology, which is affiliated with the Max Planck Society and the University of Hamburg.

These models were used to determine the initial field and boundary conditions, while the weather research and forecasting modeling system (WRF) developed by the National Center for Atmospheric Research in the U.S. [19] was used for downscaling and regional climate modeling. A data performance test showed that MRI performed better than ECHAM5 at a lower troposphere, whereas ECHAM5 exiled at a mid-higher troposphere. This was likely due to the terrain data used by ECHAM5 only managing to simulate 100–200 m topography, whereas the topography differences simulated by MRI can be as much as 2500 m and is thus able to project atmospheric circulation and precipitation in Taiwan more accurately.

During the 5th phase (CMIP5), a total of 33 GCMs, four warming scenarios of RCP2.6, 4.5, 6.0, and 8.5 were selected [20]. The time period between 1960–2005 was used as a historical baseline, and data between 2006–2100 underwent statistical downscaling, which was carried using spatial interpolation and bias correction using the ECDF methods utilized in the previous project phase. For dynamical downscaling, in addition to the MRI model, a high-resolution atmospheric model (HiRAM C384) [21–31] developed by the Geophysical Fluid Dynamics Laboratory (GFDL) was also used for cross-comparison, with a resolution of 25 km, baseline period of 1979–2003, simulating projections during 2039–2065 and 2075–2099 using the RCP8.5 scenario. These models were coupled with WRF to assess the impact of extreme and typhoon events in the context of topics such as flooding and landslides. Downscaled data have unique characteristics (Table 1) and were selected for subsequent analysis and assessment according to different research needs.

**Table 1.** Comparison between statistical and dynamical downscaling.

| | **Statistical Downscaling** | **WRF Dynamical Downscaling** |
|---|---|---|
| GCM (resolution) | 33 CMIP5 ocean-atmosphere coupled model (~250 km) | MRI·HiRAM AMIP (25~60 km) |
| Scenario | IPCC AR5 RCP2.6, RCP4.5, RCP6.0, RCP8.5 | IPCC AR5 RCP8.5 (Specific scenario only) |
| Time period | continual | Specific time periods only |
| Time resolution | daily average | hourly |
| Method | Statistics (ECDF) | Atmospheric physics (thermodynamic equations) |
| Time efficiency | Simple method with relatively rapid data generation | Requires ample computing resources, data generation is time-consuming |
| Parameter | Temperature, precipitation | Typhoon precipitation, wind field, pressure, radiation, relative humidity |
| Application | Overall analysis of climate based on temperature and precipitation trends | Analysis of extreme events and subsequent impacts |

## 3. The Evolution of TCCIP Projects

The first phase of the Taiwan Climate Change Projection and Information Platform Project (TCCIP) consisted of three teams who were responsible for three different core research topics: the analysis of regional observation and projections, the establishment of viable downscaling methodologies, and the application of climate data. The second phase (2013–2016) built upon the achievements of the previous phase, with improvements and updates carried out by four separate teams, each with specialized functions. To further enhance the quality of climate service, the TCCIP team digitized over 7.2 million historical climate data acquired from the Central Weather Bureau, which is affiliated with the Ministry of Transportation and Communications, Taiwan. In addition, tide stations for seal level observations were corrected into a unified dataset, while the grid dataset was updated for more accurate performance than the actual spatial distribution of observation data. These datasets received a total of 164 applications for various research purposes. The third phase (2017–2022) has emphasized the essence of a testbed platform, where new climate data is generated a more transparent and replicable way, while investigating practical approaches to close the gaps between research and practice, including plausible impact assessments, case studies, and tools. In addition, the TCCIP website has undergone its third renovation and now provides interactive information, adaptation knowledge, and climate projection data. A summary of the critical actions carried out during the different TCCIP project stages is outlined in Figure 5.

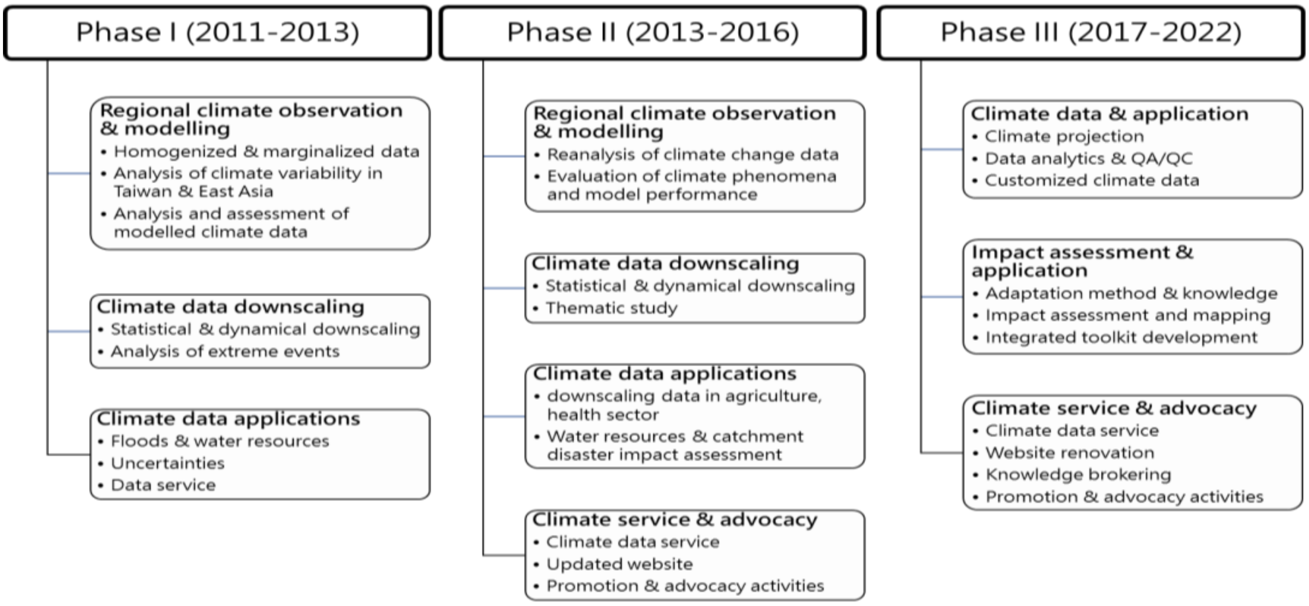


**Figure 5.** An overview on the evolution of TCCIP project.

Due to its natural spatial limitations, downscaled climate data is key to Taiwan's risk assessments and subsequent adaptation decisions. In terms of the data adopted, GCMs from CMIP5 were adopted. The statistically downscaled data were updated, providing more variables and time periods (Table 2), and were used for the preliminary assessment of rice crop production using DSSAT [32,33], as well as the distribution of dengue fever and risk of death under different climate scenarios. In addition, data generated using CMIP3 during the previous project phase were compared with the CMIP5 data, allowing the user to better understand the differences and characteristics between these two sets of data. For dynamical downscaling, the HiRAM GCM was used in addition to four sets of MRI simulations, which allowed for multi-model comparison and the evaluation of the performances of different applications.

**Table 2.** Comparison of statistical downscaled data from two project phases.

| TCCIP 1st Phase | TCCIP 2nd Phase |
|---|---|
| ▪ CMIP3 precipitation (monthly data)<br>▪ CMIP3 daily mean temperature (monthly)<br>▪ CMIP3 extreme indicators for precipitation (annual) | ▪ CMIP3 daily max. temperature (monthly)<br>▪ CMIP3 daily min. temperature (monthly)<br>▪ CMIP5 precipitation (monthly)<br>▪ CMIP5 daily mean temperature (monthly)<br>▪ CMIP5 daily max. temperature (monthly)<br>▪ CMIP5 daily min. temperature (monthly)<br>▪ CMIP5 extreme indicators for precipitation (annual)<br>▪ CMIP5 extreme indicators for temperature (annual)<br>▪ CMIP5 daily precipitation (daily) |
| ▪ Baseline: 1980–1999<br>▪ Near-future: 2020–2039<br>▪ 21st end of century: 2080–2099 | ▪ Baseline: 1986–2005<br>▪ Near future: 2021–2030<br>2041–2060<br>2061–2080<br>▪ end of 21st century: 2081–2100 |
| ▪ Southeast Asia: 25 km grid data<br>▪ Taiwan: 5 km and 25 km grid data | Taiwan: 5 km and 25 km grid data |
| CMIP3 scenarios: B1, A1B, and A2 | ▪ CMIP3 scenarios: B1, A1B, and A2<br>▪ CMIP5 scenarios: RCP2.6, 4.5, 6.0, and 8.5 |

In addition, the TCCIP website was re-designed to accommodate the increasing variety of research outcomes through an interactive interface of historical and project data, adaptation knowledge, publications, and data service. An updated version of the climate science report was also published, which addressed up-to-date climate projection and the understanding of climate impacts in Taiwan.

## 4. Application and Promotion of Climate Data

### *4.1. Adaptation Research, Policy Support and Advocacy*

To perform climate change risk assessment in Taiwan was highly challenging due to the country's complex geography and weather system. As a result, the generation of high-resolution downscaled climate data was an essential investment by the TCCIP project so that it could foster further research into critical themes such as flooding and landslides. The physical mechanisms of natural systems were investigated using different approaches in an attempt to achieve a more accurate climate projection. Precipitation is one of the critical parameters that climate change will influence and that will induce risk, hence the following were studied in great detail in Taiwan: the land–sea breeze system that that facilitates the formation of diurnal rainfall events [34–36], and seasonal monsoon events, including Madden–Julian oscillation impacts on winter rainfalls, and the East Asian summer monsoon (aka Meiyu), under different climate scenarios [37,38]. The preliminary study of watershed typhoon rainfalls and extreme precipitation under climate change found that the 24-h duration precipitation depth for 20-year and 100-year extreme events are likely to increase, suggesting concerns about the current hydrologic designs of critical infrastructures [39–42]. The secondary effects of precipitation on several factors, such as landslides, where critical precipitation is a characteristic that triggers large-scale landslide events, were studied and considered in conjunction in order to understand the cause/effect relationships; they were also impact assessed using climate projection [43–47]. Other parameters such as solar activities [1], typhoon-induced storm wave [48], tidal energy [49], and storm tides during typhoon events [50–52] were also studied.

The TCCIP project has also utilized climate data and downscale technologies in several different contexts, in particular with regard to rainfall-related topics. Simulations of summer monsoons and mei-yu seasons using statistical and dynamical downscaling methodologies have all indicated a more extreme trend of precipitation in the future under climate change scenarios [53,54]. The effect of extreme precipitation on rivers is prominent, resulting in very high annual sediment discharge [55], and studies have focused on several key catchments in Taiwan, as listed below:

- Flood disasters at the Choshui River catchment may occur in a shorter time duration, and river catchment will face more severe degradation [56].
- The risk from overbank and pier scour disasters in the Kaoping River catchment will increase in the future [57,58], where over 80% of the affected facilities related to the public and industry [59].
- In the Shihmen Reservoir and Xindian River catchment, the severity and frequency of landslide events will increase due to climate change [60,61]; a preliminary estimate suggests a total economic loss of USD 358.25 million from the cascading impacts of slope land disasters [62].
- The overflow risk of the Tsengwen River under extreme events was initially studied [63]. This was extended into a more comprehensive impact assessment of the surrounding regions [64] and coupled with assessment tools to conclude that approximately 7 billion NTD of loss may be reduced by implementing adaptation measures [65].

Furthermore, themes such as hydrological design [40,66] and water resources vulnerability were also investigated, where adaptation options were explored [67,68], and a cost-benefit analysis was performed to demonstrate the advantage of adaptation actions [69].

During various stages of adaptation strategy in Taiwan, the TCCIP project has always provided scientific insights by publishing dedicated scientific reports that consider the most recent IPCC reports while extracting the most recent literature and studies available in Taiwan. The first report, An Introduction to Climate Change in Taiwan: Scientific Report 2011, described climate change and its potential influence on existing hazards and emerging impacts, targeting academic researchers and adaptation policymakers. In addition, the SPM of reports was also translated as a potential reference for local policymakers. The "Climate Change in Taiwan 2017: Scientific Reports" was published by adopting methodologies published in the IPCC fifth assessment report and consisted of two reports: the Physical Scientific Basis and Impact and Adaptation. These reports have all become an integral part of Taiwan's adaptation policy-making process, and both stages of the National Adaptation Plan [3,5] have included scientific evidence stated by the reports.

Research outcomes, reports, and knowledge extracted at different stages of the TCCIP project were demonstrated on an integrated website [70]. As the variety and volume of climate projection grew, the concept of climate service was adopted, and data were made available to academics and other sectors for further study and analysis. The website has undergone various modifications, and the current and third version is an interactive site that consists of a dataset of 1.5 billion climate data available for various applications, as well as over 180 publications and 150 media materials. The most recent update involves a beta demonstration of climate change hazards and the impact on thematic sectors, including flooding, landslides, water resources, agriculture, coasts, fishing, and health. The website has also filed attempts to put academic climate research into practice in the form of storylines.

### 4.2. Application of Climate Data: The Risk Maps

An example for the application of climate data generated by the project is the disaster risk maps under climate change which were established by the National Science and Technology Center for Disaster Reduction (NCDR) and adopted in various policies, such as the local adaptation plan and local spatial plan, acting as fundamental materials for the identification and scoping of risk hotspots for corresponding action plans. The risk maps have undergone various transitions and are currently updated to the third version.

The first version utilized 5 km hi-resolution data from the 1st TCCIP project phase, adopting the MRI GCM coupled with WRF to assess the occurrence of extreme precipitations above 350 mm and 600 mm per day, respectively, storm surges caused by typhoons, and the characteristics of droughts, and to establish indicators for different disasters. Vulnerability is estimated using environmental (inundation, drought characteristics, average tidal differences) and socio-economic (population density, human development index, productivity) indexes. The calculated risk is then mapped using GIS during three time periods, the historical baseline, the near future, and end of the 21st century, for four specific disasters, including flooding, storm surges, drought, and landslides. These maps attempt to assess disaster risks under future climate change scenarios instead of relying on historical observations, even though only one model was used for the analysis. The second version of the risk maps demonstrates flooding and landslide disaster risks under the influence of climate change. The risk maps were generated by adopting IPCC AR5 RCP scenario projections and updating other parameters such as elevation and subsidence observational data for vulnerability calculations. The segregation of calculated risk was analyzed using statistical Z-Score methods into five different levels. The evolution of the third version includes adopting statistical downscaling methodologies [71], multiple GCMs for climate projections, and updates on parameters such as the current and projected 2036 demographic data. In addition, the risk maps were demonstrated in spatial scales of national, county, township, and essential statistical areas. A comparison of the three versions of risk maps is shown in Figure 6.

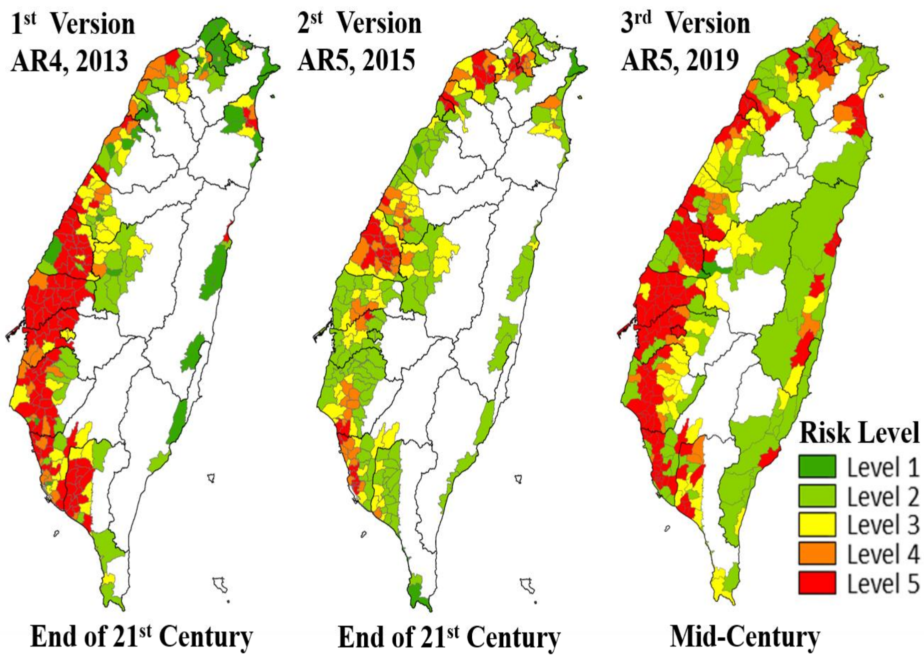


**Figure 6.** Evolution of the flooding disaster risk map.

### 4.3. Comparison with Existing Studies

The main task of the TCCIP was to develop useable climate projection data for the nation, and was latter evolved to address impacts in sectors of major concern, such as flooding, landslides and water resources, whilst establishing knowledge brokering approaches, as mentioned in the previous sections. The TCCIP share similarities to projects, such as the SOUSEI in Japan [72] and SWECLIM in Sweden [73], that developed regional models and downscaled projection data for hi-resolution analyses on potential climate hazards at national and local scales. However, the TCCIP attempted thematic studies based on existing impact models without an effective integrative approach, so the project's current capacity to address multidisciplinary analyses is limited to preliminary pilot or case studies. Compared to studies that target cross-sector and socio-economic issues, such as the CLIMSAVE platform, which adopted a meta-modelling approach [74], or the RESCCUE project, which was able to execute systematically thorough eight work packages of specific functions [75], there are some key gaps that the TCCIP should consider in the future.

## 5. Conclusions

The TCCIP project has played a vital role in the climate adaptation research of Taiwan, simulating projections under different climate scenarios according to the most recent CMIP phases and providing high-resolution 5 km grid data that are downscaled statistically or dynamically for various research needs, including impact analysis for crucial topics. In addition, the project has supported national adaptation policies by publishing scientific reports, which have formed the scientific basis for two phases of five-year national adaptation plans, and through the provision of climate services, knowledge brokering, and promoted adaptation case studies by providing stakeholders with climate and counseling expertise.

However, gaps, especially weakness when it comes to integrating socio-economic factors, should also be addressed for more comprehensive support while linking science and practice. In Taiwan, most resources emphasize short-term disaster risk reduction; these actions have successfully enhanced resilience, mainly from natural disasters and current extreme events, though only in the shorter term. Previous studies by the TCCIP have addressed vital topics, but addressing the national climate change risk in the long term still requires a more integrated effort from both public and private sectors, including interdisciplinary resource scaling, the mobilization of resources and funding, and stakeholder collaboration in the socio-economic sector. The immediate actions that are required to address the gap between science and policymaking include establishing a national scenario to accelerate policymaking amongst governmental institutions, establishing multidisciplinary meta-modeling that systematically projects future impacts, and exploring viable solutions through collaboration with practitioners, industries, and local indigenous communities, with linkage to the nation's Sustainable Development Goals.

The TCCIP project aims to engage various stakeholders in promoting user-oriented practical research that enhances capacity building and encourages learning towards an adaptation community with a consensus towards the country's sustainable development.

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