Climate Change Impact Assessment in Taiwan

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ABSTRACT

Climatic warming is discernible in Taiwan, as evidenced by a warming rate of 1.1-1.6°C/century, a clear trend of a continuous increase in days without rain and a steady increase in the yearly contribution of heavy rainfall to the annual precipitation total. Devastating disasters associated with record-breaking rainfalls have put Taiwan in a vulnerable position and now Taiwan faces the challenges of intensified typhoon intrusions and steady sea level rise. Ecological systems can detect such changes and are expected to be widely affected by such changes. Fisheries have been suffering because valuable cold-water fish stocks have retreated northward. Therefore, fishers are adapting to profit, using species that come from the southern warm oceans. Agricultural practices have also been changing, but the harvest is disturbed by droughts and typhoon damages. The future of water resource management will rely on a successful transition from the current water-dependent industry to a less water-dependent society. In recent years, adaptation strategies and action plans have been proposed, but Taiwan is still far from strengthening its resilience to climate change and lowering its vulnerability.

Keywords: climate change, impact assessment, vulnerability, Taiwan

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1. Introduction

Global warming over the past 100 years has been accompanied by changes in physical and biological systems (IPCC, 2007). Mountain glaciers and ice caps have been estimated to be melting at approximately 0.50 mm yr^{-1} (Lemke et al., 2007), sea level has risen by an average rate of 1.8 mm yr^{-1} (Bindoff et al., 2007), fish species with southern biogeographical affinities have moved northward (Grebmeier et al., 2006), plants have flowered one to three days earlier per decade in most of the northern hemisphere (Rosenzweig et al., 2007) and animal and plant species have shifted toward the poles or to higher altitudes (Root et al., 2002). To understand global changes, climate change impact assessments have been conducted by parties of the UNFCCC (United Framework on Climate Change Convention) under Article 4.1.

In Taiwan, research was initiated in the 1990s that focused on research programs organized by projects under IGBP (International Geosphere-Biosphere Programme), such as International Global Atmospheric Chemistry (IGAC), Past Global Changes (PAGES) and the Earth System Science Partnership. In the 2000s, the funding shifted toward local impact studies on water resources, climate, ecology and agriculture (Liu and Hwa et al., 2009).

Island-wide warming of 1-1.4^{o}C/century was first reported by Hsu and Chen (2002). They projected a temperature increase of 0.9-2.74^{o}C with minor precipitation changes if the level of global CO_2 increased by 1.9 times the 1961-1990 level. Yu et al. (2002) attempted to generate future warming climates from the past local temperature and precipitation trends in a studied catchment region statistically. They concluded that there was an increase of available water in the wet season and a decrease in the dry season in the future. Chang (2002) adopted yield response regression models for 60 crops and a price-endogenous mathematical model to estimate the potential impact of climate change on Taiwan's agricultural sector. She suggested that warming and climate variations should have a significant but non-monotonic impact on crop yields. Because various adaptive approaches were considered, society as a whole was not expected to suffer from warming unless precipitation increased considerably.

Recently, Li et al. (2009) projected more extreme precipitation and surface runoff with a persistent increase of evapotranspiration in both wet and dry seasons during the 21st century due to a projected consistently higher temperature. A weather generation model was applied to generate daily temperature and precipitation estimates from AOGCM outputs under different climate scenarios. A physically-based water balance model was used to simulate the land hydrology. A decision support system for assessing water shortage and allocation with climate change was thereafter proposed by Liu and Tung et al. (2009). Additionally, a stochastic simulation approach was developed to assess the future annual typhoon rainfall over watershed areas (Cheng et al., 2009). The addition of heavier sediments into water reservoirs could be a serious threat to a stable supply of fresh water in Taiwan.

Downscaling climate data from the AOGCM to Taiwan is apparently the most challenging task in dealing with local climate impact studies (Liu et al., 2010; Lin et al., 2010). Meanwhile, ecological changes due to climate warming are difficult to determine because of limited monitoring data from the past.

In this study, we grouped findings from different disciplines to identify the major physical and biological changes in Taiwan that are linked to the warming over the last century. Additionally, we attempted to evaluate possible future changes in the land and marine ecological systems and their impacts on water resources, disaster management, agriculture and fisheries.

2. Climate change in Taiwan

2.1 1900-2009

From 1900 to 2009, temperatures recorded at eight lowland meteorology stations in Taiwan (marked in Fig. 1) have been increasing at a rate of approximately 1.1-1.6°C/century (Fig. 2a). This rate is higher than the global rate of 0.74°C/century, but it is comparable to the warming conditions in other Eastern Asia regions (Wang and Gaffen, 2001; Chung et al., 2004; Trenberth et al., 2007). In the last 30 years, the warming rate has doubled and reached 0.23-0.40°C/decade. The possible influence of urbanization has been suggested as the cause of this increase (Lin et al., 2005; Fujibe, 2009).

Additionally, the daily maximum temperature increased at half the speed of the increase in the daily minimum temperature, even though both increased over the last 30 years. Following Zhai and Pan (2003), we took the number of days with daily maximum temperatures higher than or equal to 35°C in the major metropolitan city, Taipei (marked in Fig. 1), as an indicator of hot days in Taiwan. The decadal mean number of days was between 5-22 days/year, but increased to 37 days/year in the 2000s.

Precipitation before 1960 seemed to be increasing gradually, but it fluctuated with no significant trend after 1960 (Fig. 2b). The frequency of days with relative humidity higher than 90% decreased after 1960, and the frequency of mist, drizzle (precipitation less than 1 mm/hr) and light rains also showed a decreasing trend. This trend is likely associated with a higher saturation level with the increase of temperature (Dai, 2006). Days with precipitation less than 0.1 mm (i.e., rainless days) increased significantly to a rate of 1.7-11 days/decade at the lowland stations. The highest increase was observed over southern Taiwan, where the decadal mean of rainless days used to be 145-229 days/year before 1960 and became 232-272 days/year in the 2000s.

With no significant change in annual rainfall and an increase of rainless days, strong rainfalls are contributing more and more to the total annual precipitation. Groisman et al. (2005) classified days with rainfall exceeding the 95th percentile of each year as the heavy rainfall events. Figure 2c illustrates the yearly averaged contribution of those events to the annual precipitation. An increasing trend occurred after 1954, although the trend is not yet statistically meaningful. The average yearly contribution of heavy rainfall events was measured to be approximately 28% and varied with respect to different regions. Over northern Taiwan, the decadal mean contribution during the 2000s was approximately 19%-23%, whereas it was 31%-34% over the southern area.

In the analysis above, only data from eight lowland stations were used, since they kept the longest measurement record. Still, the general trend after 1950 is similar with the inclusion of data from 20 additional climate stations.

It is worth noting that stations in the mountainous area have continued to document record-breaking rainfalls. For instance, on July 31, 1996, a record of 1094.5 mm of rainfall was set by Typhoon Herb at Alishan (marked in Fig. 1). However, this record was soon replaced by a new record of 1161.5 mm and then 1165.5 mm on August 8 and 9 of 2009 by Typhoon Morakot. Additionally, typhoons, which are the main source of precipitation and natural disasters, struck Taiwan at a decadal average rate of 2.2-3.5 times per year in the 1960s-1990s, but increased to 4.3 times per year in the 2000s. However, there was actually a decreasing trend of typhoons formed in the northwest Pacific, with a change from the decadal mean of 26-29 typhoons per year in the 1960s-1990s to 23 typhoons per year in the 2000s. Warm sea surface temperature anomalies over the equatorial western and central Pacific appear to have caused such changes (Tu et al., 2009).

Furthermore, in an effort to link extreme rainfall with temperature increases, Liu and Fu et al. (2009) concluded that with each one-degree increase in atmospheric temperature, the probability of strong rainfall (hourly rainfall greater than 13 mm) increased by 110%. However, the probability of weak rainfall (hourly rainfall less than 1 mm) declined by 70%.

2.2 Climate projection

Lin et al. (2010) outlined a statistical downscaling approach to predict the climate change in Taiwan based on the outputs of 21 global circulation models (GCMs) released from the IPCC data center. The procedure adjusted the monthly mean AOGCM outputs near Taiwan with respect to the NCEP reanalysis data (Kistler et al., 2001) in order to remove any systematic bias in the model outputs. Additionally, a transfer function (i.e., a multiple variant linear regression) was established to link NCEP reanalysis variants (i.e., predictors such as temperature, sea-level pressure and precipitation) with local climatic observations (i.e., predictors such as temperature or precipitation). Finally, the GCM outputs were adjusted and transferred to establish the future projected temperature and precipitation data at each climate station for the 21st century.

Figure 3 shows that under the SRES A1B scenario, the ensemble projection of the average temperature will increase in 2080-2099 compared to the 1980-1999 values by approximately 2.3^{o}C, while it will increase by 2.5^{o}C and 1.5^{o}C, under scenarios A2 and B1, respectively. Higher increases are expected over the western lowland region, as compared to the mountainous and eastern coastal regions. Additionally, a net rainfall increase of 5.2-5.6% is expected, with major increases over the eastern and northern regions but decreases over the central and southern areas (Fig. 3). Consistency between models of the future projection is quite high.

The disadvantage of the monthly mean projection is the lack of data to foretell changes in extreme values. In order to do so, a dynamic downscaling dataset simulated by a regional climate model (RCM), NCEP-RSM (Lee et al., 2005), after driving by the high-resolution AOGCM ECHAM4/OPYC3 (Roeckner et al., 1996) under SRES A2 and B2, was used. The NCEP-RSM was selected because of its ability to closely match the circulation of the driver after a careful comparison of the model performance against two other RCMs for the East Asia region (Liu et al., 2010). However, due to limited resources, there is no continuous projection for the entire 21st century by the NCEP-RSM except for the two transient periods of the 2040s and 2090s.

We considered Taipei, Taichung, Hengchun and Taitung (marked in Fig. 1) to represent the northern, central, southern and eastern regions of Taiwan, respectively. Under the A2 scenario, NCEP-RSM forecasted the summer daily maximum temperature in the 2090s to be an average of 3.2°C, 3.0°C, 2°C and 2°C higher than the 1990s for the northern, central, southern and eastern regions, respectively. Clearly, extremely high temperatures will continue to set new records. Additionally, the model predicted a relatively significant change for the dry season (from September to April). It is expected that the number of rainless days in the southern region will increase by 50 days or more in the 2090s relative to the 1990s, representing a change of approximately 60%. Concerning the projection of the number of days with heavy rainfall and changes in rainfall intensity, there was no clear result due to limits of the model's resolution, although record-breaking rainfalls are highly likely.

3. Impact on the ecological system

3.1 Forest

Taiwan is a mountainous island, and the forest ecosystems are highly diverse due to various topography and geology. Therefore, there are many forest types along altitudinal gradients, such as subtropical rain forests, evergreen broad-leaved forests, coniferous and broad-leaved mixed forests and sub-alpine coniferous forests in high mountain regions. The dominant coniferous forest types of high mountain regions in Taiwan are *Abies kawakamii* forests, *Tsuga chinensis* var. *formosana* forests and *Chamaecyparis* forests (including *Chamaecyparis obtusa* var. *formosana* and *Chamaecyparis formosensis* forests). The distribution of forest vegetation is not homogeneous because the habitat varies along altitudinal gradients. Hence, there are ecotones among forest communities. The distribution of high mountain coniferous forests and ecotones can be distinguished by using species distribution modeling, such as the classification and regression tree (CART) (Yen et al., 2008). The species data was extracted from the vegetation database of the National Vegetation Diversity Inventory and Mapping Project (Chiou et al., 2009). The results show that the threshold value of the occurring probability to define suitable habitats is 0.067 for *Abies kawakamii* forests (1021 km^2), 0.146 for *Tsuga chinensis* var. *formosana* forests (3028 km^2) and 0.108 for *Chamaecyparis* forests (2872 km^2).

The forest margin or ecotone is sensitive and affected by climate change (Brubaker, 1986), especially in the treeline of the high mountain region. By using the high resolution data downscaled from global climate models (Hijmans et al., 2005), the decreasing rates of suitable habitats for *Abies kawakamii* forests, A-T ecotone, *Tsuga chinensis* var. *formosana* forests, T-C ecotone and *Chamaecyparis* forests in Taiwan under IPCC SRES-A2 and B2 scenarios with respect to the recent inventory was projected (Sun, 2010). The climate parameters used were the warmth index (WI), minimal temperature of the coldest month (TMC), accumulated summer precipitation (PRS) and accumulated winter precipitation (PRW).

The results in Fig. 4 demonstrate that by 2080, the habitat areas of both the *Abies kawakamii* forests and the *Tsuga chinensis* var. *formosana* forests will decrease by approximately 58%-90%, while the *Chamaecyparis* forest will decrease by 20%. The suitable habitat of the A-T ecotone will no longer exist under the A2 scenario. Moreover, the area of the T-C ecotone will decrease from 1581 km^2 to 28-46 km^2, with a rate of decrease larger than 97%. It can be concluded that the rate of upward shift of *Abies kawkamii* is higher than that of *Tsuga chinensis* var. *formosana,* while *Tsuga chinensis* var. *formosana* is higher than *Chamaecyparis* forest. In addition, when the suitable habitat of a single dominant species forest is compressed, the distribution of the ecotones will be also compressed considerably.

3.2 Birds

Birds have long been used as environmental indicators of the state of the world's ecosystems, because they live in almost every type of environment, they are at the top of the food chain, they represent a range of diets, and they can be easily observed and monitored with the complete classification. Since individual metabolism and food resources are affected by temperature, bird species are highly sensitive to weather and are already responding to increased global temperatures (Walther et al., 2002; Parmesan and Yohe, 2003; Root et al., 2003; Crick, 2004).

In Taiwan, a change in the number of a total of 13 species of breeding birds at locations above 3100 m a.s.l. in the Yushan National Park (marked in Fig. 1) was been monitored in 1992, 2006 and 2009 (Ding, 1993; Tung et al., 2007; Lin and Lee, 2009). These monitoring sites have limited outside access. Within 14-17 years, more species moved to areas >3600 m a.s.l. (Fig. 5), which matches a decreasing trend of winter snow days from 40 days to 11 days. Of the 13 species monitored, three mid-elevation species, i.e. species with major distribution ranges of 2000-3000 m in elevation, increased in population density (number of individuals/ha). Five high-elevation species, i.e. occurring at >3000 m in elevation, decreased in density. An additional five high-elevation species showed no clear variation trend.

Ko (2010) applied a maximum-entropy approach (i.e., Maxent) (Phillips et al., 2006) of a species distribution model to simulate the spatial changes in bird species under projected climates from different scenarios. She also concluded that species richness would be apparent at higher elevation regions in Taiwan. For instance, the endemic Taiwan Yuhina (*Yuhina brunneiceps*) would gradually move toward higher elevations, but would experience a narrowing spatial distribution under the A2 scenario with climate projection by the Climate Modeling and Analysis (CCCma) Coupled Global Climate Model from

Canadian Centre (Flato et al., 2000) (Fig. 6). Similar patterns are also projected for a summer visiting species, the Fairy Pitta (*Pitta nympha*), which is listed as vulnerable by the IUCN (BirdLife International, 2001) with a total global population of less than 10,000. The Fairy Pitta winters in Borneo, located north of Australia, and visits Taiwan every late April and stays until late September. The bird inhabits secondary lowland forests. The model projects that prior to 2050, the habitat of the Fairy Pitta will experience relatively few changes, but between 2050 and 2100, they will have to move to the mid-elevations when their overall suitable areas are reduced.

In general, the shift in bird species' elevation ranges affects species richness. Current species richness of breeding birds will decrease in low and mid-elevation areas, while the richness in higher elevation regions (exceeding 2,500 m a.s.l.) is expected to increase in the future. Furthermore, the current distributional hotspots will gradually disappear, and no particular hotspots will be formed using the current standard value (species richness >72 in a grid of 1 km x 1 km).

In the coastal regions, many habitats for winter migrants are predicted to be destroyed due to sea level rise. Many of the coastal wetlands will be affected, especially along the southwest coast, at the Danshui River mouth in the north and at the Lanyang River mouth in the east (marked in Fig. 1), where the elevations are low. This will result in a significant reduction in habitats for the winter migrant species and probably the reduction of the global number of migrating birds. For instance, the black-faced spoonbill (*Platalea minor*) has a world population of approximately 2000 in 2008 and 50% of the population winters along the southwest coast of Taiwan and is expected to be affected inevitably.

3.3 The Formosan landlocked salmon

The endemic Formosan landlocked salmon (*Oncorhynchus masou* *formosanus*) is an Ice Age relic organism in Taiwan, and it is one of the most precious natural and cultural assets. Although it belongs to the land-based cold zone salmon and trout family, it survives in the tropical and subtropical regions of Taiwan in habitats that are among the southernmost in the global distribution of natural salmon populations (Oshima, 1955). It represents a major biogeography discovery. The Formosan landlocked salmon has been listed as a critically endangered species by the International Union for Conservation of Nature (IUCN) (Kottelat, 1996). The Chichiawan Stream and its tributaries in the Wuling Basin (marked in Fig. 1) are the last refuge of the landlocked salmon. Data collected in the habitat region from 2005-2008 were carefully analyzed by Lin et al. (2009). They concluded that the optimal reproductive water temperature for salmon is approximately 12^{o}C. If the summer temperature exceeds 16^{o}C in any stream segment, there will be no survival of salmon there. Moreover, if typhoons occur in Taiwan in the fall or winter, the torrential rains will wash away yearling and new autumn hatchling salmon, causing a huge decline in the number of salmon in the following year. It is predicted that each flooding is accompanied with a 30% decrease in the population.

In the future, if the water temperatures increase by 1^{o}C, the habitat of the Formosan landlocked salmon is likely to be reduced by 50%, in alliance with a serious habitat fragmentation problem. If the water temperatures increase by 3^{o}C, then no salmon will survive (Lin et al., 2008). In addition, as typhoon-induced record-breaking rainfalls continue to cause the stream velocity to exceed 100 cm s^{-1}, fewer salmon are expected to endure the harsh environment (Chung et al., 2008).

3.4 Coral reefs

Taiwan's adjacent coral reefs were subject to the influences of anomalous high sea surface temperatures (SSTs) in the western Pacific in 1998 and 2007, with varying degrees of coral bleaching and mortality. For example, serious coral bleaching and mortality was reported in 1998 from southern Japan, extending southward to the Penghu Islands and the southeastern waters of Taiwan, during an El Niño - La Niña climate change event (Dai et al., 2002). In addition, a cold-water intrusion around the Penghu Islands (marked in Fig. 1) in February 2008 caused SSTs to drop below 16°C. This lasted for 20 days and led to a large-scale coral bleaching and the death of 172 species of reef fishes and invertebrates in the northern Penghu Islands (Hsieh et al., 2008).

Genetic programming based on data collected during 1986-2004 was previously used to develop a niche model of the coral reef distribution surrounding Taiwan (Tsai et al. 2004). With the projected increase of coastal SST by the second version of the Canadian Centre for Climate Modeling and Analysis (CCCma) Coupled Global Climate Model (CGCM2) (Flato and Hibler, 1992) under the SRES A2 scenario, the ecological model projected that by 2025 an increase in the SST by 0.5-0.75°C will not lead to an exceedance of the maximum temperature tolerance for corals (30°C). Rather, many regions will become even more suitable for coral growth (Fig. 7), so coral species may have increased diversity and an expanded distribution range, while some waters may increase their number of marine species. By 2055, SSTs are expected to increase by 1.2-1.3°C and richness in the northern sea species may continue to expand. However, sensitive coral species in southern and eastern waters will disappear, and the number of species will show a significant drop throughout, resulting in significant changes in species composition. By 2085, the SST surrounding Taiwan is projected to increase by 2.0-2.5°C and cause severe reductions in the number of coral species and even coral extinction, except for corals along the north and northeast coast. In addition, the normal distribution of coral communities will be greatly affected due to the changes in species composition, which is likely to develop toward a stress-tolerant community. Marine species surrounding Taiwan are likely to fluctuate with the changing coral reefs.

3.5 Marine ecosystems

Marine ecosystems are influenced by water temperature, water acidification, rising sea levels, changes of ocean currents and patterns, climate anomalies, and other factors (Fischlin, et al., 2007). For example, Typhoon Wyne shifted the reef fish community structure around the southern tip of Taiwan in 1984 (Jan et al., 2001), the El Nino–Southern Oscillation was associated with fluctuations in the abundance of larval anchovy in coastal waters off southwestern Taiwan (Tsai et al., 1997), and the intrusion of cold waters caused fish kills at the southern tip of Taiwan in 1988 and 2008 (Shao et al., 2008). These factors and their related interactions have a significant impact on marine productivity, biodiversity, community distribution, and marine bio-physiological functions (e.g., growth, metabolism, reproduction, and behavior).

Unfortunately, anthropogenic factors such as overfishing, habitat destruction, pollution and thermal discharge, and alien species invasion have been causing direct and obvious damages to marine biological diversity. For example, overfishing and eutrophication were the causes of the decline of coral reef ecosystems in areas around the southern tip of Taiwan (Liu and Shao et al., 2009; Liu and Lin et al., 2009). Artificial concrete coastlines now cover 55% of the total length of the coastline in Taiwan and have destroyed many natural habitats of intertidal marine organisms. Meanwhile, despite gradual improvement in the quality of coastal waters in the past decades, illegal discharges still exist which cause eutrophication problems (Lin et al., 2007). Thermal discharges created malformed juvenile or young thornfish and mullet at the nuclear power plant near Keelung in northern Taiwan (Hung et al., 1998; Shao, 1995). *Sciaenops ocellatus*, a marine fish introduced for cage-culture purposes, was found to be invasive along the western coastal Taiwan (Liao et al., 2009).

Finally, after considering the factors above, we conclude that the damages to the marine biological diversity surrounding Taiwan caused by human influences are likely to be faster and more intense than those associated with climate change.

4. Impacts on the society

4.1 Water resources

Taiwan has abundant rainfall of approximately 2510 mm per year, which is three times the average global rainfall (Wurbs and James, 2002). However, the average annual per capita of available rainfall is only 3000 cubic meters, or 43.5% of the global average. Therefore, Taiwan can be classified as a water scarce country. Furthermore, with steep slopes and short river lengths, rainfall rapidly discharges into the sea and its capture for use is quite difficult. In addition, the wet and dry seasons are distinct, regional rainfall is uneven, water storage is not easy, and redistribution of water resources is difficult. Only about 22% of the annual precipitation is available for use. Therefore, Taiwan can be classified as in a moderate water stress country (Alcamo et al., 2003).

Unfortunately, due to historical manipulation by the government in maintaining a fairly low water price, the average daily per capita water consumption was 271 liters in 2009, 13% higher than the global average. The consumption by the agriculture and industry sectors remained around 72% and 9% of the total water usage, respectively. However, the household water usage grew at a rate of 3% per decade. Since 1960, serious shortage of rainfall occurred in 1963, 1971, 1976, 1980, 1993, 1995, 2002 and 2003 (as indicated in Fig. 2b). However, according the official record of fallow farmlands caused by irrigation-stopped events of water shortage, drought events actually occurred in 1963, 1964, 1971, 1980, 1984, 1985, 1987, 1988, 1991, 1993, 1994, 1996, 1998, 2002, 2003, 2004, 2006 and 2009. Clearly, excessive waste of water frequently put Taiwan in a demand-oriented drought.

The annual total water demands in the 1990s were 16.6 billion tons. The Taiwan Water Resources Administration estimated that under a projected decrease in the total population after the 2010s and a transition of the current water dependent industry to a water-smart society, the net demands will reach at most 18.5 billion tons in 2020, and then reach a constant level afterward. To assess the balance between water supply and demand in the future, Lin et al. (2010) defined a yearly water resource index, F, as:

$$\frac{D_c}{Q_c} \times 1 = \frac{D_t}{Q_t} \times F \qquad (1).$$

This equation can be rearranged to give:

$$F = {}^{(D_c / Q_c)} \Big/ {}_{(D_t / Q_t)} \qquad (2),$$

where D stands for demand, Q stands for river run-off, sub-index c stands for the past mean control period (1990s) and t stands for a certain future time. It is assumed here that the condition between supply and demand, on average, was balanced for the past period, with F = 1.0. Therefore, after 1990, if F is equal to or larger than 1.0, it indicates that the water management condition is similar or better than that in the past. However, when F is lower than 1.0, the condition can be shown to be worsening. Five water resource index categories can be distinguished: unbalanced toward a wet climate ($F > 1.25$), slightly unbalanced toward a wet climate ($1.25 \geqq F > 1.05$), balanced ($1.05 \geqq F \geqq 0.95$), slightly unbalanced toward a dry climate ($0.95 > F \geqq 0.75$), and unbalanced toward a dry climate ($0.75 > F$).

Based on the projected temperature and precipitation for the 21st century from a statistical downscaling of GCM outputs and a feed forward neural network (FFNN) method to estimate regional river runoff (Lin et al., 2010), the probability of F occurring in five different categories in each decade under the SRES A2 scenario can be projected and plotted as shown in Fig. 8. The decadal mean F index is also plotted. The mean value in the 1990s was 1.0, and this was taken as the base condition for comparison. In general, the occurring frequencies of the last two categories (i.e., slightly unbalanced toward a dry climate ($0.95 > F \geqq 0.75$) and unbalanced toward a dry climate ($0.75 > F$)) will be around 78%-94% with a mean F value of 0.8, i.e., a slightly unbalanced condition toward a dry climate. Clearly, to avoid more frequent droughts in the future, efforts are needed to considerably cut down water demands.

4.2 Extreme rainfall disasters

Extreme rainfall disasters in Taiwan are mainly associated with typhoons. Heavy rainfall after frequent earthquakes, i.e., at least two earthquakes of magnitude 6 or higher on the Richter scale annually, shatters the stability of the mountain slope, where the worst damages have occurred. Official records indicate that there has been an annual average of three typhoon disasters before 1980, then 3.8 disasters between 1981-1999 and 5.2 disasters in the 2000s. Economic losses are increasing (NFA, 2010). The worst economic loss was in 2009, with a total loss of $500 million USD.

Typhoon Morakot, a Category 2 storm that hit Taiwan in August of 2009 with an unprecedented and record-breaking rainfall far beyond the local coping range over the southern Taiwan, altered the local vulnerability abruptly from a status of neutrally safe to a complete breakdown. The net amount of rain during the typhoon intrusion period was more than the yearly average of 2510 mm at most stations, while the return period estimated at most mountain stations was more than 2000 years (NDPPC, 2009).

Though flooding was expected in the lowlands, the devastating landslides in the mountains were a surprise. Images shot by the Formosat-2 satellite before and after the Morakot event suggests that 2.6-7.2% of the watershed area of three major rivers was disrupted. This is similar to the effects of a major earthquake. Following the typhoon, sediment yield in these rivers was 13-22 times the annual mean yield (Liu, 2009). Additionally, 2.5-8.3% of the forest areas in these watershed areas were flushed down by landslides. Logs weighing up to 718 kilotons floated quickly with the strong river current, along with mudflow and rocks, and destroyed at least 51 bridges. Meanwhile, up to 5000 houses collapsed, and nearly 700 people were either dead or missing due to overbanking of the water. Rivers were widened 1.75-6 times their original width. One ill-fated village was destroyed by a combination of river overbanking, landslide and the breakdown of an upslope debris dam. The most unexpected consequence was due to the turbidity of water reaching downstream dams. The turbidity registered up to 100,000 nephelometric turbidity units (NTU), thus causing at least one million people to be without access to fresh water for nearly two weeks (NDPPC, 2009).

Typhoons and earthquakes are common nightmares for people living along the western Pacific Rim. The most vulnerable areas are constantly monitored and evacuated. Disaster warning, prevention measures and relief procedures are practiced constantly. Sea walls, river banks, flood discharge trenches, bridges and even dams are required by law to be constructed and operated to endure extreme rainfall events that happen every 200 years, but not 2000 years.

By organizing the data from 25 climate stations in Taiwan with at least 50 years of accumulated data each, we identified each station's five highest daily rainfalls and then calculated the frequency of these high rainfall days falling within each decade. From this, we determined that the occurrences in the 2000s were the highest (Fig. 9), followed by the 1960s and 1990s. This is in agreement with the conclusion by the Intergovernmental Panel on Climate Change (Meehl et al., 2007) that the frequencies of extreme events are very likely to increase in the future. However, the serious damages associated with typhoon Morakot were not caused only by the unprecedented rainfall, but also by the insufficient weather forecast, unforeseen large-scale landslides and debris flows, unsuccessful evacuation plans, and slow-responding relief measures.

In the future, adapting to unpredictable record-breaking rainfall events will not only be a sustainability issue in Taiwan, but also a survival challenge. Disaster management has to be adapted to face the unavoidable future.

4.3 Food security

Taiwan's food needs generally include the staple food category and the livestock feed. Staple food consists primarily of rice and wheat. The rapid economic growth since the late 1970s has significantly changed the dietary pattern in Taiwan by decreasing the consumption of rice and increasing the consumption of meat and wheat flour (Shen and Yao, 2009). In 2009, there was an approximate annual need of 1.3 million tons of rice with a self-sufficiency rate of more than 90%. Demand for wheat is about one million tons a year, but all wheat products are imported. Sorghum has a self-sufficiency rate of about 6%, whereas 6 million tons of corn, soybean and barley are imported annually with a self-sufficiency rate between 0 to 1.5%. In all, Taiwan's self-sufficiency rate of total cereal consumption is only about 33%. Accordingly, the impact of climate change on Taiwan's food security will not only affect the regional production but will also affect the foreign grain production unless local production can compensate any deficiencies in imports.

Rice yield and quality are sensitive to the increase of averaged and nighttime temperatures on enhancing the plant respiration (Huang and Lur, 2000). Change in cultivated varieties for warmer climate is being considered. Meanwhile, farmers are learning to adjust the planting operation to cope with the warming climate. For instance, the central and southern farmers have advanced the transplanting period of the first crop of rice, which is usually between January and July, and have delayed planting and harvesting the second-crop rice, which is usually between June to December (Lur et al., 2009). Unfortunately, frequent autumn typhoons have caused losses of the second crop and have consequently caused a rise in the price of rice. The threat of typhoon disasters to grain production and food security cannot be ignored.

In addition, irrigation water is likely to be limited, pests and diseases under warmer climate are likely to increase their effects (Shen and Yao, 2009), and arable land area could decrease because of sea level rise, land subsidence, soil salinization, pollution, agricultural land use changes and other factors. Meanwhile, international climate variability and the development of biomass plants may affect the international wheat, corn and soybean prices, leading to an increase in the use of flour products, feed and animal product prices, and even adversely affecting average consumer prices. A number of developing trends may affect the food security, and the vulnerability of Taiwan is not likely to be lowered.

4.4 Fisheries

Taiwan's coastal fisheries have been affected by climate warming. The sea surface temperature (SST) of the four square zones of waters surrounding Taiwan (marked in Fig. 1) has increased dramatically after the mid-1990s. The differences between 1996-2009 and 1982-1995 are about 0.29-0.54^{o}C (Table 1). The southeastern corner has experienced the lowest temperature increase. Consequently, commercial fish stocks that normally migrate southward with the China Coastal Current (marked in Fig. 1) to Taiwan’s waters for spawning and wintering have been retreating northward, while warm-water species are being carried northward by the Kuroshio Current and the South China Sea Current (marked in Fig. 1) (Hsieh et al., 2009). In the last 30 years, catches of grey mullet (*Mugil cephalus* L.) and black pomfret (*Parastromateus niger*) have dropped by more than 90%. Table 2 summarizes the impacts that have occurred on various marine fisheries (including shallow water culture). In contrast, the proportion of the summer catch to the annual catch has been climbing from about 5% in the early 1990s to nearly 40% in the 2000s, but with fish species of much lesser economic value.

In addition, occurrences of El Niño/La Niña usually result in warmer/colder surrounding seawater and hence unfavorable/favorable impacts on fisheries, as summarized in Table 3. However, the exceptional intrusion of China's coastal waters in early 2008 (a La Niña year) resulted in a drop of 12^{o}C in the surface waters surrounding the Penghu Islands (marked in Fig. 1) and caused the death of fish (172 species in 58 families) in cage culture fisheries as well as in the sea, with a financial loss of more than $30 million USD.

Since fish movements are very sensitive to changes of SST, the projection of the ECHAM4/OPYC3 model (Roeckner et al., 1996) under the SRES A2 scenario (Fig. 10) estimated that catches of the China Coastal Current species near Taiwan, such as spotted mackerel (*Scomber australasicus*), hairtail (*Trichiurus lepturus*), Grey mullet (*Mugil cephalus L.*) and black pomfret (*Parastromateus niger*), will be reduced to very low levels or eventually to zero by the end of this century (Lee, 2009). In the meantime, catches of Kuroshio Current and South China Sea species, such as anchovy (*Encrasicholina punctifer*), bullet tuna (*Auxis rocheii)*, yellowfin tuna (*Thunuus albacares*) and skipjack (*Katsuwonus pelamis*) will increase. For instance, bullet tuna will increase by 4% by 2030 and 19% by 2100. However, the majority of these species with increasing abundance have lower economic value in the present fish market.

In the future, higher seawater acidification due to increasing atmospheric carbon levels may affect the calcification of hard coral reefs and bony fishes (Daw et al., 2007). In addition, the rise of sea level due to global warming may influence aquaculture in the tidal zone. Furthermore, frequent typhoons and exceptional cold-water intrusions can easily cause devastating effects on coastal marine ecosystems. These impacts on fisheries should not be neglected.

6. Summary and conclusions

Warming in Taiwan has been occurring at a rate of approximately 1.1-1.6°C/century and 0.23-0.40°C/decade over the last 30 years. Although there has been no significant long-term trend of rainfall increase or decrease detected, rainless days have increased significantly at a rate of 1.7-11 days/decade. The highest increase of rainless days occurred in southern Taiwan, where the decadal mean of rainless days was 145-229 days/year before 1960, but became 232-272 days/year in the 2000s. Additionally, the yearly contribution of heavy rainfalls to the annual precipitation increased after 1954 by a rate 0.4%/decade. Over northern Taiwan, the decadal mean contribution in the 2000s was about 19%-23%, whereas it was 31%-34% over the southern area. The most note-worthy phenomenon is a continuous occurrence of record-breaking rainfall events (Fig. 9), which usually accompany typhoon intrusions and serious disasters. Economic losses due to weather disasters are becoming greater. The worst loss so far was in 2009, with a total loss of $500 million USD (NFA, 2010).

At the highest meterorological station, Yushan (marked in Fig. 1), the 1st day of snow was 143-144 days after July 1st in the 1970s and 1980s, but was delayed by approximately 20-22 days in the 1990s and 2000s and by approximately 55 days in an extremely warm year (Fig. 11). The yearly total length of snow days was on average about 148-160 days in the 1970s and 1980s, but was shortened to 139 days in the 1990s, and then 116 days in the 2000s. The decadal mean of yearly accumulated snow changed slightly, but the variaiton was largest in the 2000s. The decadal change of the mean daily snowfall (Fig. 11d) clearly illustrates the phenomenon that although there were shorter snow days in 2000s, a larger daily snowfall happened when the yearly accumulated snow was the largest. Clearly, warming has caused the delay of snowfall and the shortening of snow days, but record-breaking daily snow could still happen in the 2000s, similar to the occurrence of record-breaking rainfall at mid- and lower-elevation stations.

The effect of warming on the mountain ecological system was revealed after monitoring 13 species of breeding birds in the Yushan National Park in 1992, 2006 and 2009. Within this period, more species moved to >3600 m areas, with three mid-elevation species expanding in population density, five high-elevation species decreasing and five other species showing no clear trend. These findings suggest that the richness of bird species will be apparent at higher elevation regions in Taiwan in the future, but with a lower number of hotspots. This is also supported by the projection of decreased suitable habitat of dominant species forests and ecotones in the high-mountain ranges.

Furthermore, the vulnerability of land-based freshwater ecosystems to global warming and frequent extreme rainfall events can be identified after a careful study of the endemic Formosan landlocked salmon. For every $1^{o}C$ increase of the water temperature, the habitat is of salmon is likely to be reduced by 50%. If the water temperature increases by $3^{o}C$, then no salmon will survive. Additionally, with each typhoon-induced flooding in the fall or winter, a decrease of the population by 30% is expected, although yearling salmons are currently raised and released under a conservation plan.

A dramatic increase or decrease of seawater temperature caused by climate variation has already resulted in coral breaching and dramatic fish kills. Additionally, warmer waters associated with the advancement of the Kuroshio Current and the retreat of the China Coast Current since the mid-1990s has significantly affected the southward migration of valuable fish stocks and has increased South China Sea fish species. Therefore, the projection under a global warming trend suggests a significant reduction in the number of coral species and marine species in the coral community and a substantial change of fishery with more stocks of fishes from southern waters with less economic value. The other devastating factor not to be ignored is the human influence on the marine biological diversity surrounding Taiwan, which is projected to be more efficient at causing damage than climatic change.

The stability of an isolated island society is very sensitive to a stable supply of water. With an occasionally shortage of rainfall and an excessive waste of water, Taiwan has been frequently in a demand-oriented drought for the past 20 years. Under a projected decrease in the total population after the 2010s, this study suggests that frequent occurrences of conditions of a dry climate are expected in the 21st century, unless a transition of the current water-dependent industry to a less water-dependent society occurred.

With the expectation of warmer climate in the future, changes in managing the water consumption and the development of new rice breeds to endure with higher plant transpiration rates are currently being developed (Shen and Yao, 2009). In the meantime, farmers are advancing the transplanting period of the first crop of rice and delaying the planting and harvesting of the second crop of rice to fit with the earlier arrival of spring and the later retreat of autumn in the recent decade. Unfortunately, frequent autumn typhoons have caused huge losses of the second crop and have raised the price of rice. Furthermore, with a self-sufficiency rate of only 33% of the total cereal consumption, Taiwan's food security is quite vulnerable to the turbulence of the global food market. Chang (2002) and Shen and Yao (2009) proposed various adaptive approaches. This study stressed that there are a number of developing trends affecting the food security in Taiwan and the vulnerability is not likely to be lowered.

In recent years, epidemics of dengue hemorrhagic fever (DHF), mainly from dengue-endemic areas, have triggered frequent alarms in society (Chen et al., 1996; Shang et al., 2010). In southern Taiwan, *Aedes aegypti* mosquitoes (the indoor vector) are abundant and epidemics of dengue involving clinically severe cases of DHF occur nearly every autumn (Pai and Lu, 2009). The possibility of increasing imported cases and the northward extension of the distribution of *Aedes aegypti* due to global warming in the future increase the risk to the public exposing under the threat of dengue/DHF. Closer monitoring through mosquito and environmental surveillance are exercised intensively by the government.

Finally, the devastating disaster associated with Typhoon Morakot in August 2009 triggered a serious debate among local policy makers on how to strengthen the resilience to tackle the challenge of an increasing frequency of record-breaking rainfalls. To persuade people to move out of most vulnerable areas, such as subsiding coasts, landslide-prone mountain slopes, and frequently flooding riverbanks, is a reasonable but difficult task. Long-term investments and historical family bindings are often the reason behind the reluctance to move. Even if the government intervenes, the problem of finding safer places in this small island is not a trivial issue. Therefore, establishing a quick response system to warn and rescue people in a weather disaster event is currently on the highest priority. On May 21, 2010, a military exercise has assumed that a super typhoon X poses as the major rival challenging the national security and simulated response from the military to local governments on a large-scale retreat and rescuing. In the meantime, the national emergency response standard operating procedure has been reviewed and modified.

The expected warming in this current century will definitely damage the habitats of birds, land-locked fishes and coastal corals and affect the migration of valuable fishes in the surrounding waters. Damage to the fishery industry is clearly happening already, while the stability of the food and water supply are also in question. However, the most troubling challenge is the expected occurrence of more frequent record-breaking rainfall events. Such events are projected but are not foreseeable. Although they are usually associated with typhoon intrusions, the forecasting of these events has never been easy and the response has hardly been satisfactory in the past. Currently, adaptation strategies and action plans of comprehensive extent are proposed (Chen et al., 2010), but Taiwan is still far from strengthening its resilience and lowering its vulnerability.

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References

Alcamo, J., P. Döll, T. Henrichs, F. Kaspar, B. Lehner, T. Rösch, and S. Siebert, 2003: Global estimates of water withdrawals and availability under current and future “business-as-usual” conditions”. *Hydrological Sciences Journal* , 48, 339-348.

Bindoff, N.L., J. Willebrand, V. Artale, A, Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Quere, S. Levitus, Y. Nojiri, C.K. Shum, L.D. Talley and A. Unnikrishnan, 2007: Observations: Oceanic Climate Change and Sea Level. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

BirdLife International, 2001: *Threatened birds of Asia: the BirdLife International Red Data Book*. Cambridge, UK: BirdLife International.

Brubaker, L. B., 1986: Responses of tree populations to climatic change. *Vegetatio,* 67, 119–130.

Chang, C.-C., 2002: The potential impact of climate change on Taiwan’s agriculture. *Agricultural Economics*, 27, 51–64.

Chang, Y., K. T. Lee, M. A. Lee, K.W. Lan, 2009: Satellite Observation on the Exceptional Intrusion of Cold Water in the Taiwan Strait. *Terr. Atmos. Ocean. Sci.*, 20(4), 661-669.

Chen, C.-F., M.-L. Liou, C.-M. Liu, C.-I Hua, L.-Y. Su and Y.-C. Lee, 2010: Key Elements on Designing a Climate Change Adaptation Framework. (submitted to *Climatic Change*)

Chen, K. Y., 2005: *Population Fluctuation of the Spotted Mackerel (Scomber australasicus) in the Northeastern Waters off Taiwan*. Ms. Thesis, National Taiwan Ocean University. 54pp. (in Chinese)

Chen, W. J., S. L. Chen, L. J. Chien, C. C. Chen, C. C. King, M. R. Harn, K. P. Hwang and J. H. Fang, 1996: Silent transmission of the dengue virus in southern Taiwan. *Am. J. Trop. Med. Hyg.*, 55,12-6.

Cheng, K.-S., J.-C. Hou, Y.-C. Wu and J.-J. Liou, 2009: Assessing the impact of climate change on annual typhoon rainfall—a stochastic simulation approach. *Paddy Water Environ.*, 7, 333–340.

Chiou, C.-R., Hsieh, C.-F., Wang, J.-C., Chen, M.-Y., Liu, H.-Y., Yeh, C.-L., Yang, S.-Z., Chen, T.-Y., Hsia, Y.-J. and Song, G.-Z. M., 2009: The first national vegetation inventory in Taiwan. *Taiwan Journal of Forestry Science,* 24, 295-302. (in Chinese)

Chiu, H. Y., 2006: *A study on the fluctuation in catch of Japanese eel (Anguilla japonica) elvers immigrating into the waters off Kungliao*. Ms. Thesis, National Taiwan Ocean University. 59pp. (in Chinese)

Chung, L.-C., H.-J. Lin, S.-P. Yo, C.-S. Tzeng, C.-H. Yeh and C. H. Yang, 2008: Relationship between the Formosan landlocked salmon *Oncorhynchus masou formosanus* population and the physical substrate of its habitat after partial dam removal from Kaoshan Stream, Taiwan. *Zoological Studies*, 47, 25-36.

Chung, Y.-S., M.-B. Yoon and H.-S. Kim, 2004: On climate variations and changes observed in South Korea. *Climatic Change* 66: 151–161.

Crick, H. Q. P., 2004: The impact of climate change on birds. *Ibis*, 146, 48-56.

Daw, T., W. N. Adger, K. Brown and M. C. Badjeck, 2009: Climate change and capture fisheries: potential impacts, adaptation and mitigation. In Cochrane, K., C. De Young, D. Solo, and T. Bahri (eds). *Climate change implications for fisheries and aquaculture: overview of current scientific knowledge*. FAO Fisheries and Aquaculture Technical Paper, No. 530, Rime, FAO, pp.107-150.

Dai, A., 2006: Recent climatology, variability, and trends in global surface humidity. *J. Climate*, 19, 3589-3606.

Dai, C.F., G. Chen, M. Inaba, K. Iwao, F. Iwase, Y. Kakuma, K. Kajiwara, T. Kimura, K. Nomura, K. Oki, K. Sakai, T. Shibuno, H. Yamano, M. Yoshida, 2002: Status of coral reefs in East Asia: China, Japan, Korea and Taiwan. In: Wilkinson C (ed) *Status of Coral Reefs of the World: 2002*, p. 153-162, Australian Institute of Marine Science, Townsville, Queensland, Australia.

Ding, T. S., 1993: *Avian community ecology of mature forest in Mt. Yushan.* M.S. Thesis, National Taiwan University, Taipei, 80pp. (In Chinese, English abstract)

Fischlin, A., G.F. Midgley, J.T. Price, R. Leemans, B. Gopal, C. Turley, M.D.A. Rounsevell, O.P. Dube, J. Tarazona, A.A. Velichko, 2007: Ecosystems, their properties, goods, and services. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, 211-272.

Flato, G. M., Boer, G. J., Lee, W. G., McFarlane, N. A., Ramsden, D., Reader, M. C., and Weaver, A. J. 2000: The Canadian Centre for Climate Modelling and Analysis Global Coupled Model and its Climate. *Climate Dynamics*, **16**, 451-467.

Flato, G. M. and Hibler, W. D. III, 1992: Modelling Pack Ice as a Cavitating *Fluid. J. Phys. Oceanogr.*, **22**, 626-651.

Fujibe, F., 2009: Detection of urban warming in recent temperature trends in Japan. *Int. J. Climatol.*, 29, 1811–1822.

Grebmeier, J.M., J.E. Overland, S.E. Moore, E.V. Farley, E.C. Carmack, L.W. Cooper, K.E. Frey, J.H. Helle, F.A.McLaughlin and S.L.McNutt, 2006: A major ecosystem shift in the northern Bering Sea. *Science*, **311**, 1461-1464.

Groisman, P. Y., R. W. Knight, D. R. Easterling, T. R. Karl, G. C. Hegerl, V. N. Razuvaev, 2005: Trends in intense precipitation in the climate record. *J. Climate*, 18, 1326-1350.

Hijmans, R.J., S.E. Cameron, J.L. Parra, P.G. Jones and A. Jarvis, 2005: Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology,* 25, 1965-1978.

Hsieh, C. H., C. S. Chen, T. S. Chiu, K. T. Lee, F. J. Shieh, J. Y. Pan and M. A. Lee, 2009: Time series analyses reveal transient relationships between abundance of larval anchovy and environmental variables in the coastal waters southwest of Taiwan. *Fisheries Oceanography*, 18(2), 102-117.

Hsieh, H. J., Y. L. Hsieh, M. S. Jeng, W. S. Tsai, W. C. Su, and C. A. Chen, 2008: Tropical fishes killed by the cold. *Coral Reefs,* 27.599.

Hsu, H-H, and C-T Chen, 2002: Observed and projected climate change in Taiwan. *Meteorology and Atmospheric Physics*, **79**, 87-104.

Huang, J. J. and H. S. Lur, 2000: Influences of temperature during grain filling stages on grain quality in rice (*Oryza sativa* L.) 1. Effects of temperature on yield components, milling quality, and grain physico-chemical properties. *J. Agric. Assoc. China,* 1, 370-389.

Hung, T. C., C. C. Huang and K. T. Shao., 1998: Ecological survey of coastal water adjacent to nuclear power plants in Taiwan. *Chemistry and Ecology*, 15: 129-142.

IPCC, 2007: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK.

Jan, R. Q, J. P. Chen, C. Y. Lin and K. T. Shao., 2001: Long-term monitoring of the coral reef fish communities around a nuclear power plant. *Aquatic Ecology*, 35, 233-243.

Kistler R, Kalnay E, Collins W, Saha S, White G, Woollen J, Chelliah M, Ebisuzaki W, Kanamitsu M, Kousky V, vanden Dool H, Jenne R, Viorino M, 2001: The NCEP-NCAR 50-year reanalysis: monthly means CD-ROM and documentation. *Bulletin of Amer. Meteorolo. Socie.*, 82, 247–267.

Ko, C.-Y., 2010: *Current and Future Distributions of Endemic Bird Species.* Ph.D. Thesis, National Taiwan University, 150pp.

Kottelat M., 1996. *Oncorhynchus formosanus*. 2006 IUCN Red List of Threatened Species. Ver. 2.3. Internet resource. available at http://www.iucnredlist.org (last accessed on 25 December 2006).

Lee, C. T., M. C. Wu, and S. C. Chen, 2005: Regional Spectral Model Simulation of the Summertime Regional Climate over Taiwan and Adjacent Areas. *J. Terrestrial Atmos. and Oceanic Sci. (TAO)*, 16, 487.

Lee, K. T., 2009: The impact assessment of climate change on fishery of Taiwan and adaptation strategy. *Proceeding of the Cross-Strait Fisheries Week 2009 in Fuzhou*, 88-92. (in Chinese)

Lemke, P., J. Ren, R.B. Alley, I. Allison, J. Carrasco, G. Flato, Y. Fujii, G. Kaser, P. Mote, R.H. Thomas and T. Zhang, 2007: Observations: Changes in Snow, Ice and Frozen Ground. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Liao, Y. C, L. S. Chen and K. T. Shao, 2009: Predatory Atlantic red drum fish, Sciaenops ocellatus, invades along the western Taiwanese coast of Indo-West Pacific. *Biological Invasions* (in press) DOI

10.1007/s10530-009-9642-x.

Li, M.-H., W. Tien and C.-P. Tung, 2009: Assessing the impact of climate change on the land hydrology in Taiwan. *Paddy Water Environ.*, 7, 283–292.

Lin, H.-J., C.-B. Hsu, C.-H. Yeh, W.-H. Kuan, T.-R. Peng, S.-J. Kao, S.-T. Tsai., M.-H. Kuo, J.-T. Yang, W.-B. Yeh, S.-H. Wu, C.-S. Tzeng, Y.-H. Sun and K.-T. Shao. 2009: Wuling Long-Term Ecological Research and Modeling. *J. National Taiwan Museum* 62(4):13-24, 2009. (in Chinese)

Lin, H.J., C.C. Hsu and H. R. Guo, 2007: Increased lower limb cellulitis after a typhoon followed by a flood. *Epidemiology,* 18(3), 410.

Lin, H.-J., C.-H. Yeh, W.-H. Kuan, T.-R. Peng, S.-J. Kao, S.-T. Tsai., M.-H. Kuo, J.-T. Yang, W.-B. Yeh, S.-H. Wu, C.-S. Tzeng, Y.-H. Sun and K.-T. Shao., 2008: *Wuling Long-Term Ecological Research and Modeling*. Final report to Shei-Pa National Park. (in Chinese)

Lin, H.-J., C.-Y. Wu, S.-J. Kao, W.-Y. Kao and P.-J. Meng, 2007: Mapping anthropogenic nitrogen through point sources in coral reefs using δ15N in macroalgae. *Marine Ecology Progress Series*, 335, 95-109.

Lin, L. and P. F. Lee, 2009: *The research project of building biodiversity GIS database of national parks.* Construction and Planning Agency, Taipei, 242pp. (In Chinese, English abstract)

Lin, S.-H., C.-M. Liu, W.-C. Huang, S.-S. Lin, Z.-H. Yen, H.-R. Wang, J.-T. Kuo and Y. C. Lee, 2010: Developing a yearly warning index to assess the climatic impact on the water resources of Taiwan, a complex-terrain island. (Submitted to *J. Hydrology*).

Lin, W.-Z., H.-C. Tsai, C.-H. Wang and W.-H. Teng, 2005: Urbanization-induced regional climate change on the western plain of Taiwan for the period 1964~1999. *2005 WSEAS Int. Conf. on Environment, Ecosystems and Development*, Venice, Italy, November 2-4, 2005, p.

7-13.

Liu, C. M., 2009: From draught to record-breaking flooding over southern Taiwan. *6th Annual Climate Change Research Symposium*, Sept. 8-10, 2009, Sacramento, California, USA.

Liu, C. M., C. I. Huang and P. s. Yu, 2009: *Climate Change Long-term Impact Assessment and Adaptation Strategies Project*. Council for Economic Planning and Development, No. 97022703, 583pp. (in Chinese)

Liu, C.-M., M.-C. Wu, S. Paul, C.-Y. Chen, S.-H. Lin, W.-S. Lin, Y.-C. Lee, H.-H. Hsu, R.-Y. Tzeng and C.-T. Chen, 2010: Super-ensemble of three RCMs for climate projection over East Asia and Taiwan. *Theoretical and Applied Meteorology*, DOI 10.1007/ s00704-010-0275-x (on line).

Liu, P.-J., K.-T. Shao, R.-Q. Jan, T.-Y. Fan, S.-L. Wong, J.-S. Hwang, J.-P. Chen, C.-C. Chen and H.-J. Lin, 2009: A trophic model of fringing coral reefs in Nanwan Bay, southern Taiwan suggests overfishing. *Marine Environ. Res.*, 68, 106-117.

Liu, P.-J., S.-M. Lin, T.-Y. Fan, P.-J. Meng, K.-T. Shao and H.-J. Lin, 2009: Rates of overgrowth by macroalgae and attack by sea anemones are greater for live coral than dead coral under conditions of nutrient enrichment. *Limnology and Oceanography*, 54, 1167–1175.

Liu, S. C., C. Fu, C.-J. Shiu, J.-P. Chen, and F. Wu, 2009, Temperature dependence of global precipitation extremes, *Geophys. Res. Lett.*, 36, L17702, doi:10.1029/2009GL040218.

Liu, T.-M., C. P. Tung, K. Y. Ke, L. H. Chuang and C. Y. Lin, 2009: Application and development of a decision-support system for assessing water shortage and allocation with climate change. *Paddy Water Environ.*, 7,301–311.

Lu, H. J., K. T. Lee, H. L. Lin and C. H. Liao, 2001: Spatio-temporal distribution of yellowfin tuna, *Thunnus albacares*, and bigeye tuna, *T.*

obesus, in the Tropical Pacific Ocean in relation to large-scale temperature fluctuation during ENSO episodes. *Fisheries Science*, 67, 1046-1052.

Lur, H.-S., C.-L. Hsu, C.-W. Wu, C.-Y. Lee, C.-L. Lao, Y.-C. Wu, S.-J. Chang, C.-Y. Wang and M. Kondo, 2009: Changes in Temperature, Cultivation Timing and Grain Quality of Rice in Taiwan in Recent Years. *Crop, Environment and Bioinformatics*, 6, 175-182.

Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver and Z.-C. Zhao, 2007: Global Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

National Fire Agency (NFA), Ministry of the Interior, Executive Yuan (Taiwan/ROC), 2010: Statistics of natural disasters over the years. http://www.nfa.gov.tw/Show.aspx?MID=97&UID=827&PID=97 (in Chinese).

National Disaster Prevention and Protection Commission (NDPPC), Executive Yuan (Taiwan/ROC), 2009: *Report from the Morakot Disaster Response Center on August 21, 2009*. (in Chinese)

Oshima M., 1955: *Masu Salmon* (*Oncorhynchus masu Brevoort*), *and Biwa Salmon*, *Oncorhynchus rhodurus* (*Jordan and McGregor*). Nireshobo, Tokyo, Japan. 79 pp. (in Japanese)

Pai, H. H. and Y. L. Lu, 2009: Seasonal abundance of vectors at outdoor environments in endemic and nonendemic districts of dengue in Kaohsiung, South Taiwan. *J. Environ. Health,* 71, 56-60.

Parmesan, C. and G. Yohe, 2003: A globally coherent fingerprint of climate change impacts across natural systems. *Nature,* 421, 37–42.

Phillips, S. J., R. P. Anderson and R. E. Schapire, 2006: Maximum entropy modeling of species geographic distribution. *Ecological Modelling*, 190, 231-259.

Roeckner, E., J. M. Oberhuber, A. Bacher, M. Christoph and I. Kirchner, 1996: ENSO variability and atmospheric response in a global coupled atmosphere-ocean GCM. *Clim. Dyn*., 12, 737-754.

Rosenzweig, C., G. Casassa, D.J. Karoly, A. Imeson, C. Liu, A. Menzel, S. Rawlins, T.L. Root, B. Seguin, P. Tryjanowski, 2007: Assessment of observed changes and responses in natural and managed systems. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 79-131.

Root, T.L., J. T. Price, K. R. Hall, S. H. Schneider, C. Rosenzweig and J. A. Pounds, 2002: Fingerprints of global warming on wild animals and plants. *Nature,* **421**, 57-60.

Shao, K. T., 1995: The effect of climate change to coastal fish distribution in Taiwan. In S.S. Yang (ed.) *Climate change and Agriculture production,* p.189-206, Taiwan Agricultural biochemistry Society. (in Chinese)

Shao, K. T., T. Y. Fan, P. J. Meng, Z. W. Chang, K. H. Lee, B. Z. Liu, S. Y. Huang and Z. Y. Change, 2008: Cause of death of a large amount of coral reef marine fish at Maopitou, Kenting, on July 3, 2008. (in Chinese, private communication).

Shen, Y. and M. H. Yao, 2009: *Evaluation of impact of climate change to agriculture of Taiwan and response strategies.* Project report, NSC96-2625-Z005-008, National Science Council, Republic of China (Taiwan) (in Chinese).

Shang, C.-S., C.-T. Fang, C.-M. Liu, T.-H. Wen, K.-H. Tsai and C.-C. King, 2010: The Role of Imported Cases and Favorable Meteorological Conditions in the Onset of Dengue Epidemics. (accepted by *PLoS Neglected Tropical Diseases*)

Sun, S.-T., 2010: *Applying species distribution model on the establishment of monitoring plots under climate change*. Master's thesis, School of Forestry and Resource Conservation, National Taiwan University, Taipei, Taiwan. (in Chinese)

Tsai, C. F. P. Y. Chen, C. P. Chen, M. A. Lee, G. Y. Shiah and K. T. Lee, 1997: Fluctuation in abundance of larval anchovy and environmental condition in coastal waters off south-western Taiwan as associated with the El Nino – Southern Oscillation. *Fishery Oceanography* 6, 238-249.

Tsai, W. S., C. F. Dai, I. C. Yang and C. P. Tung, 2004: Using Genetic Programming to Modeling Spatial Distribution of Corals and the Impacts of Climatic Changes: A Case Study from Taiwan. *Proceedings of the 10th International Coral Reef Symposium*, Okinawan, Japan, pp. 1441-144

Trenberth, K.E., P.D. Jones, P. Ambenje, R. Bojariu, D. Easterling, A. Klein Tank, D. Parker, F. Rahimzadeh, J.A. Renwick, M. Rusticucci, B. Soden and P. Zhai, 2007: Observations: Surface and atmospheric climate change. In: *Climate Change 2007: The Physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Tu, J. Y., C. Chou and P.-S. Chu, 2009: The abrupt shift of typhoon activity in the vicinity of Taiwan and its association with Western North Pacific–East Asian climate change. *J. Climate*, 22, 3617-3628.

Tung, C. P., P. F. Lee, and C. J. Ko, 2007: *Early warning indicators and framework of climate change to terrestrial ecosystem in Taiwan*. Environmental Protection Administration, Taipei, 46pp. (In Chinese, English abstract)

Walther, G.-R., E. Post, P. Convey, A. Menzel, C. Parmesan, T.J.C. Beebee, J.-M. Fremont, O. Hoegh-Guldberg and F. Bairlein, 2002: Ecological responses to recent climate change. *Nature,* 416, 389–395.

Wang, J. X. L., and D. J. Gaffen, 2001: Late-twentieth-century climatology and trends of surface humidity and temperature in China. *J. Climate*, 14, 2833–2845.

Wurbs, R.A. and W.P. James, 2002: *Water Resources Engineering*. Prentice Hall, NJ. 828pp.

Yen, S.-M., C.-R. Chiou and K.-T Chang, 2008: Modeling the species distribution of three dominant coniferous species in Taiwan. *Taiwan Journal of Forest Science,* 23,165-181. (in Chinese)

Yu, P.S., Yang, T.C., Wu, C.K., 2002: Impact of climate change on water resources in southern Taiwan. *J. Hydrology,* 260, 161– 175.

Zhai, P. and X. Pan, 2003: Trends in temperature extremes during 1951–1999 in China. *Geophys. Res. Lett.*, 30, 1913-1916, doi:10.1029/2003GL018004.

Table 1: Mean SST (°C differences between periods of 1982~1995 and 1996~2009 in the four square zones of waters surrounding Taiwan (as indicated in Fig. 1). Data are downloaded from IGOSS nmc Reyn_SmithOIv2 monthly SST.

Zones (marked in Fig. 1)	1982~1995		1996~2009		diff.
	mean	SD	mean	SD	
A	25.80	2.82	26.30	2.70	+0.50
B	22.13	4.53	22.67	4.39	+0.54
C	26.58	2.17	26.87	2.05	+0.29
D	24.28	3.62	24.79	3.42	+0.51

Table 2: Impact of SST increase after mid 1990s on the important commercial fishes in the surrounding waters of Taiwan.

Type of fishery	Target species	Fishing ground	Impact
offshore tuna long line fishing (1977-2008) (Lu et al., 2001)	Skipjack tuna (*Euthynnus pelamis*) Yellowfin tuna (*Thunuus albacares*)	southern, eastern, and northern waters of Taiwan	Warmer water was accompanied with an increase in recruitment and hence an increase of 10-20% in total catch.
	Albacore (*Thunnus alalunga*) Bigeye tuna(*Thunnus obesus*)		Warmer water was accompanied with a decrease in recruitment and hence a decrease of 10-20% in total catch.
paired purse seine (Lee, 2009)	Grey mullet (*Mugil cephalus L.*) (1958-2000)	western waters of Taiwan	Warm water of a branch of Kuroshio Current flew into the Yun-Chang Ridge (F1 in Fig. 1), which prevented grey mullet from migrating southward for spawning. The total number of grey mullet to migrate southward decreased from 2.73 million fish in 1980 to 200,000 fish after 2000.
	Black pomfret (*Parastromateus niger*) (1981-2008)	western waters of Taiwan	Southward migration was interfered due to a retreat of the China Coastal Current. Annual catch decreased from 11,231 tonnes in 1981 to1,182 tonnes in 2000.
large purse seine for carangid fishes (1982-2008) (Chen, 2005)	Chub mackerel (*Scomber japonicus*) Japanese Jack mackerel (*Trachurus japonicus*) Pacific red-tail scad (*Decapterus kurroides akaadsi*)	northeastern waters of Taiwan	Dominated 60-75% of the total catch before mid-1990s, but down to 25-40% after.
	Spotted mackerel (*Scomber australasicus*) Slender scad (*Decapterus lajang*)		Dominated 25-40% of the total catch before mid-1990s, but up to 60-75% after.
larval anchovy fishery (1982-2008) (Hsieh et al., 2009)	Japanese anchovy (*Engraulis japonicus*) Buccaneer anchovy (*Encrasicholina punctifer*) Shorthead anchovy (*Encrasicholina heteroloba*)	I-Lan Bay (F2 in Fig. 1) and coastal water of Fang-Liao (F3 in Fig. 1)	Before mid-1990s, 90% of the total catch in spring was Japanese anchovy, but it down to 5-20% in 2000-2004. Over the southwestern waters, genus *Encrosicholina* dominated completely after mid-1990s.
shallow seawater oyster aquaculture (1982-2008)	Pacific oyster (*Crassostrea gigas*)	coastal water of western Taiwan	Warmer water caused frequent ovulation and semination, creating difficulty in larvae settling. Total production of oyster decreased by 21.4% in the last twenty years.
inshore abalone aquaculture (1995-2007)	Small abalone (*Haliotis aqualilis*)	coastal water of Gong-Liao (F4 in Fig. 1), Taipei County	Retreat of the China Coastal Current during breeding period of abalone caused a change in the nitrate/phosphate ratio of water and resulted in the dominance of diatom in algal composition and hence a failure of larvae settling. In 1995, the annual production of abalone was 1,500 tonnes with a market value of more than US$ 30 million, but it decreased to 139 tonnes with a market value only about US$ 0.3 million total in 2007.

Table 3: Extent of impact of climate variability and extremes on the important commercial fishes of Taiwan

Types of fishery	Target species	Phenomenon	Impact
glass eels fishery (Chiu, 2006)	Japanese eel (*Anguilla japonica*)	*El Niño* years: 1994-1995, 1997-1998, and 2002-2003. Averaged December SST in zones B and D were 0.73°C higher than previous normal year.	Eastward shifting of the Indo-Pacific warm pool and a weakening Kuroshio Current caused a reduction of glass eels recruitment.
		La Niña years: 1995-1996, 1999-2000 and 2000-2001. Averaged December SST in zones B and D were 0.79°C lower than previous normal year.	Westward shifting of the Indo-Pacific warm pool and a strengthening in the China Coastal Current caused an increase in glass eels recruitment. Annual productions in three *La Niña* years were 10 times those in three *El Niño* years
paired purse seine fishery (Lee, 2009)	Grey mullet (*Mugil cephalus*)	*El Niño* years: 1977-1978, 1982-1983, and1986-1987. Averaged December SST in zone A was 0.58°C higher than previous normal year.	Strengthening of a branch of Kuroshio Current into southwestern Taiwan waters and a weakening of China Coastal Current reduced the southward spawning of mullet. A reduction of more than 30% in production of the preceding year was observed.
coastal fishery at Penghu Islands (marked in Fig. 1) (Chang et al., 2009)	wild and aquaculture fishes in the archipelagic shallow waters	*La Niña* year: 2007-2008. Averaged February SST was 8.2°C lower than previous 5-year mean.	An abnormal intrusion of China Coastal Current resulted in a significant drop of 12°C in the surface waters surrounding Penghu Islands in February. Death of huge quantities of fishes of 172 species in 58 families caused a financial loss of more than US$ 30million.

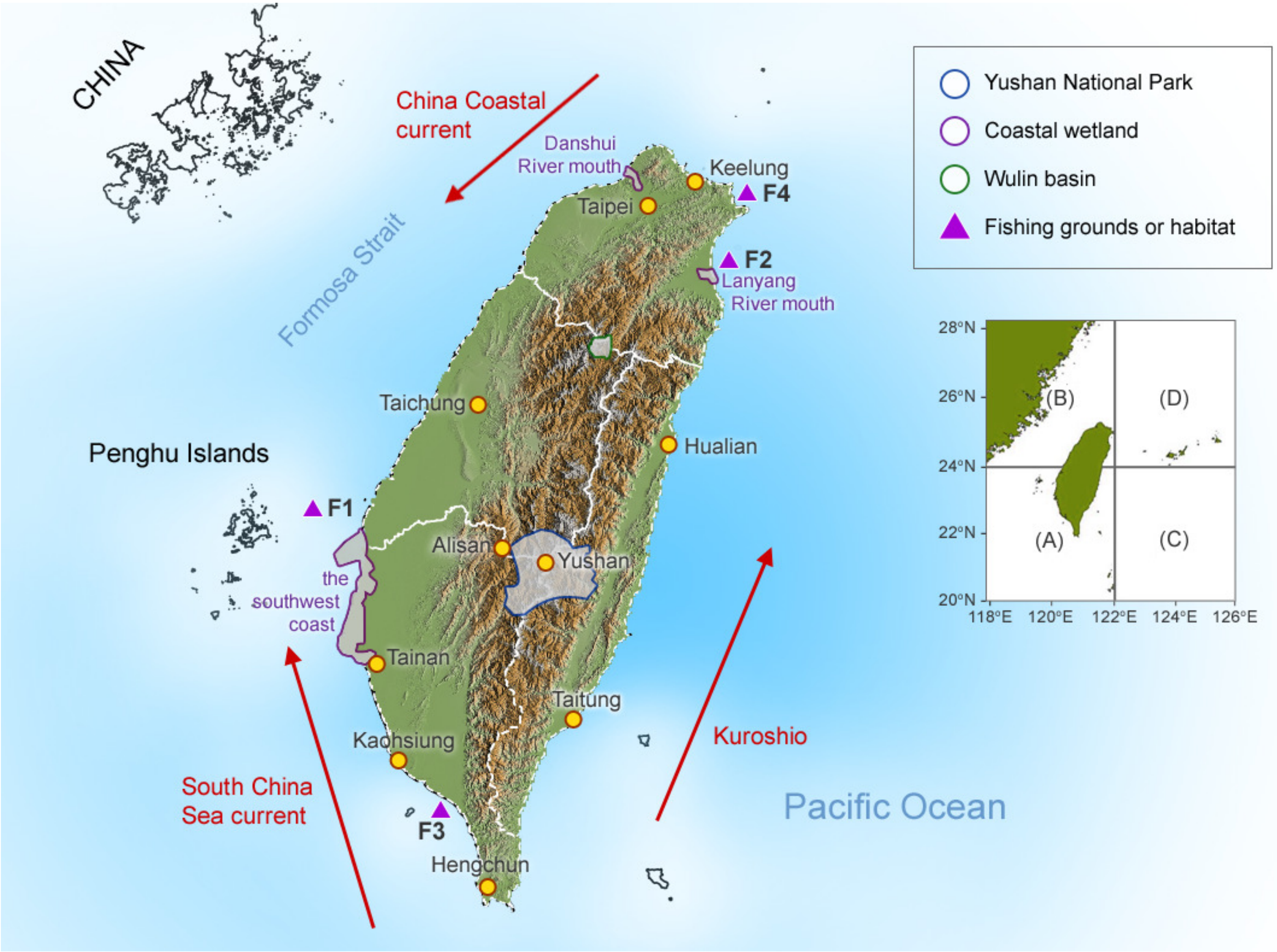
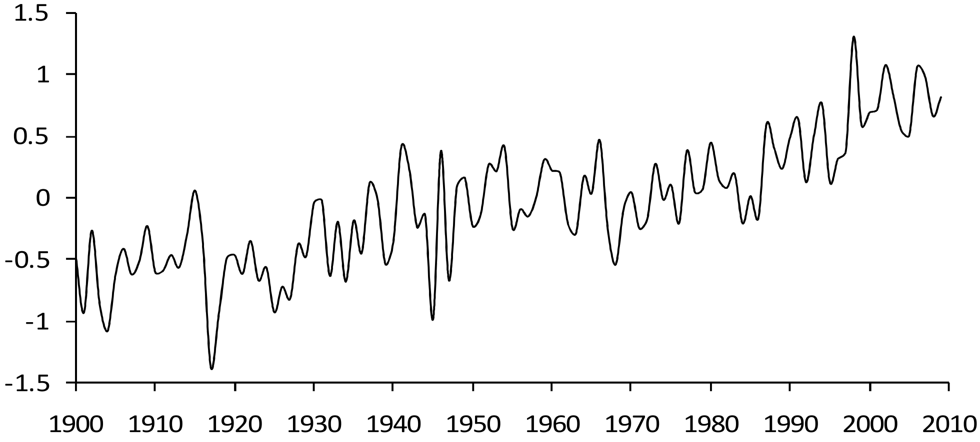
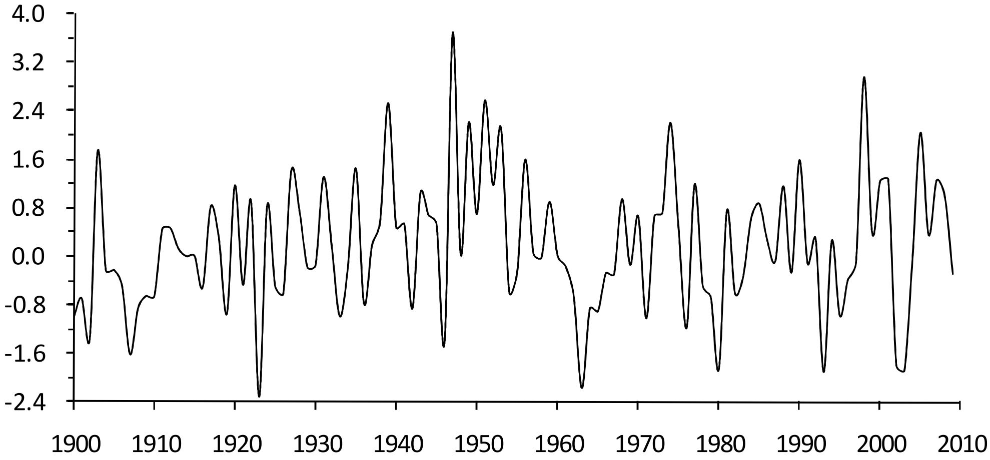


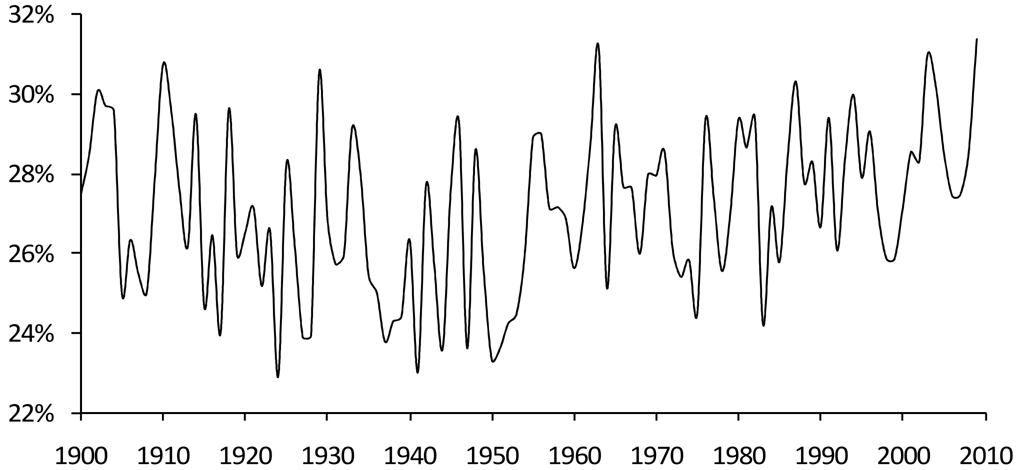
Figure 1: Taiwan topography, surrounding currents and locations of climate monitoring stations and specific marked areas discussed in this paper.



(a) temperature anomaly (°C)



(b) precipitation anomaly (mm/day)



(c) annual contribution of heavy rainfall

Figure 2: Long-term variation of the (a) temperature and (b) precipitation anomaly with respect to the 1961-1990 mean, and the (c) annual contribution of heavy rainfall, i.e. events with daily precipitation larger than the annual 95th percentile, in Taiwan.

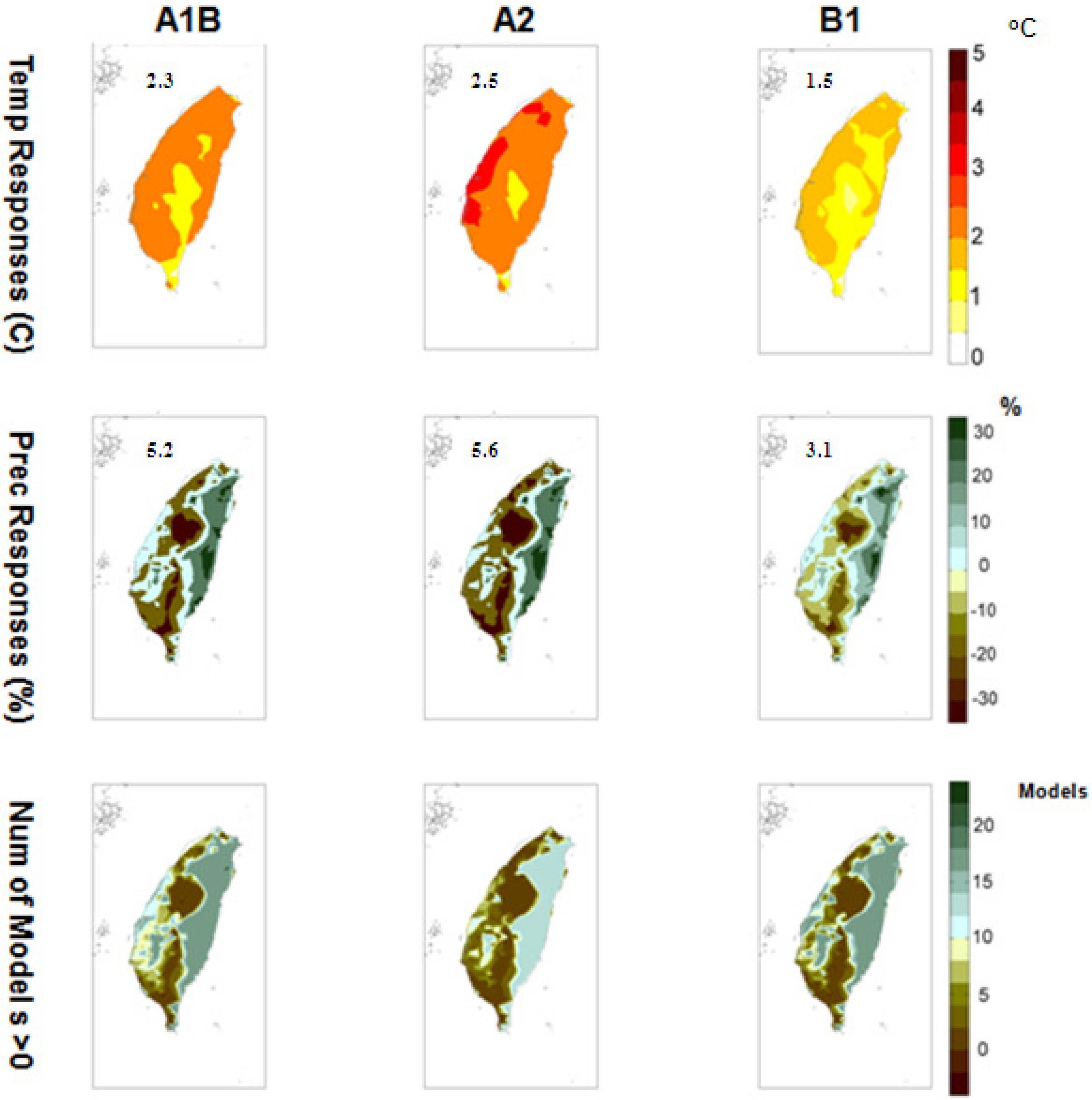


Figure 3: Ensemble projection of temperature (top row) and precipitation (central low) change over Taiwan under scenario SRES A1B, A2 and B1 in 2080-2099 with respect to 1980-1999. The value indicated in each graph is the averaged change. The number of models with the same change of sign in precipitation is shown in the bottom row.

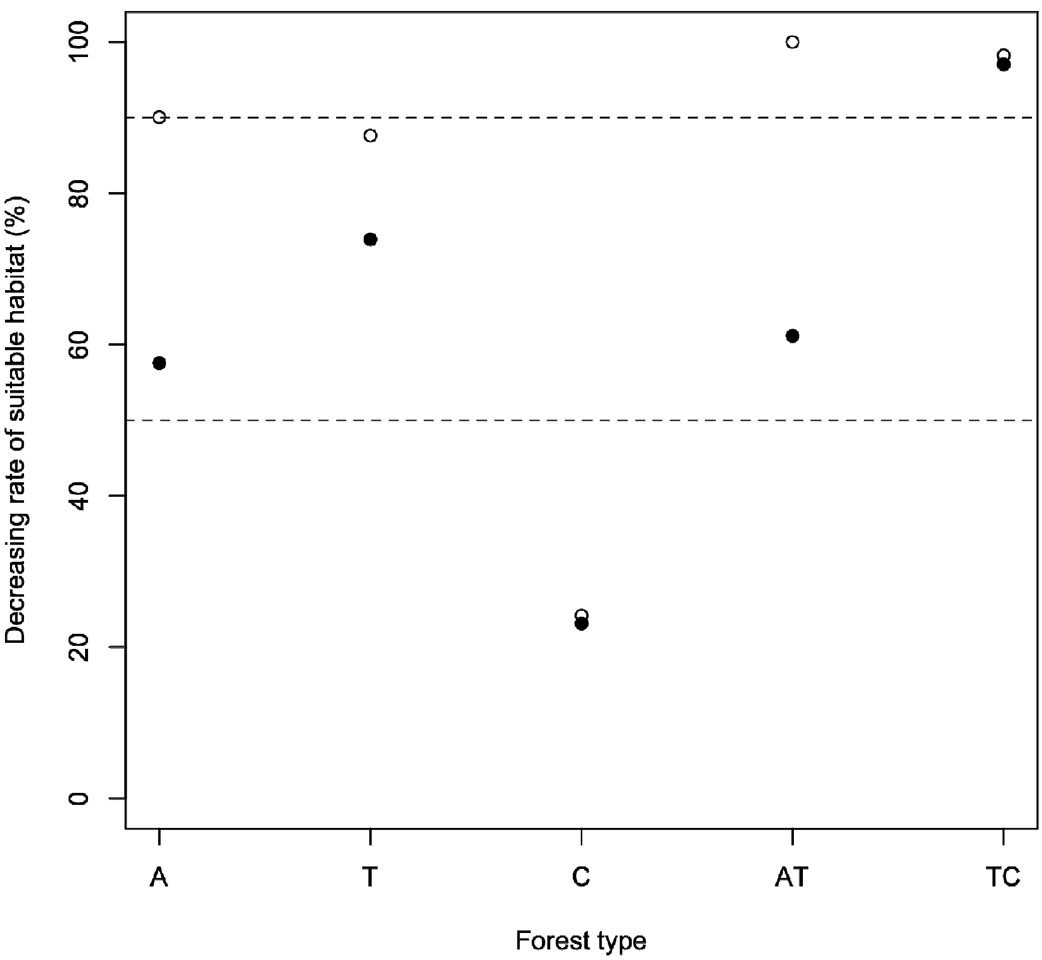


Figure 4: The projected decreasing rate of suitable habitat of different forest types and ecotone in 2080 with respect to the recent forest inventory by Chiou et al. (2009). A is *Abies kawakamii* forest; T is *Tsuga chinensis* var. *formosana*; C is *Chamaecyparis formosensis* mixed with *Chamaecyparis obtusa* var. *formosana* (*Chamaecyparis)* forest; AT is the *Abies kawakamii* and *Tsuga chinensis* var. *formosana* ecotone; TC is the *Tsuga chinensis* var. *formosana* and *Chamaecyparis* ecotone. Mark ○ indicates the A2 scenario and ● the B2 scenario.

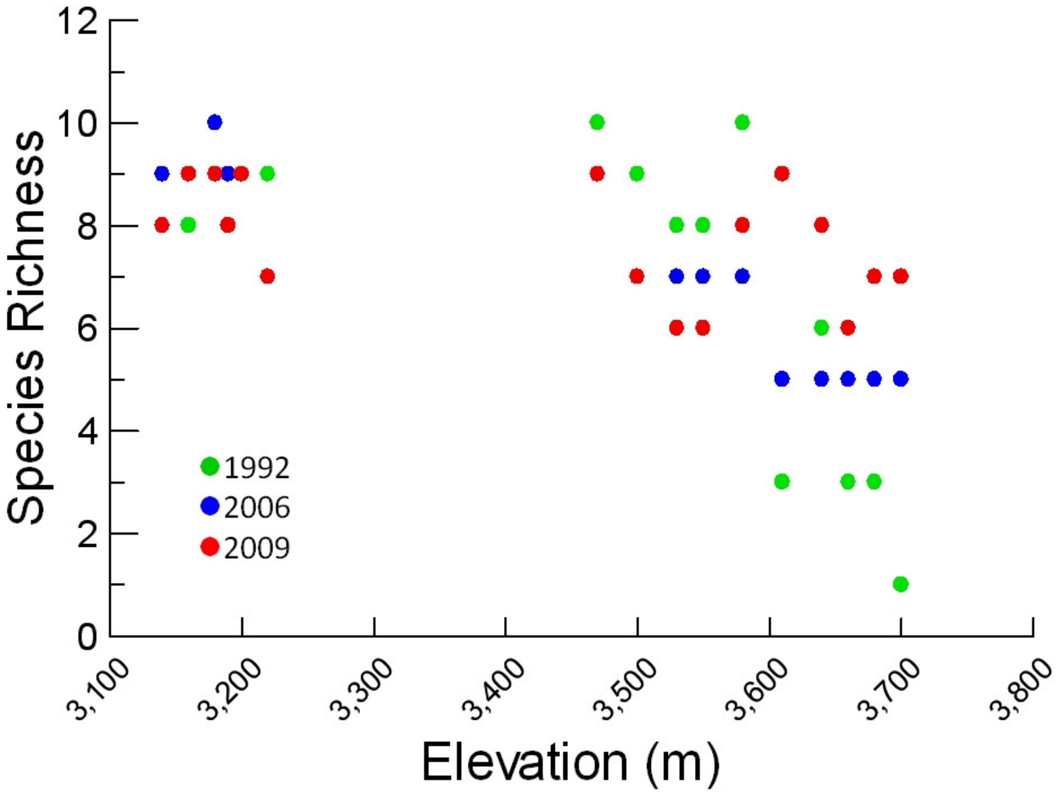


Figure 5: Change in breeding bird species richness from 1992 to 2009 in alpine mountain monitoring sites over 3100 m in Yushan National Park of Taiwan (marked in Fig. 1).

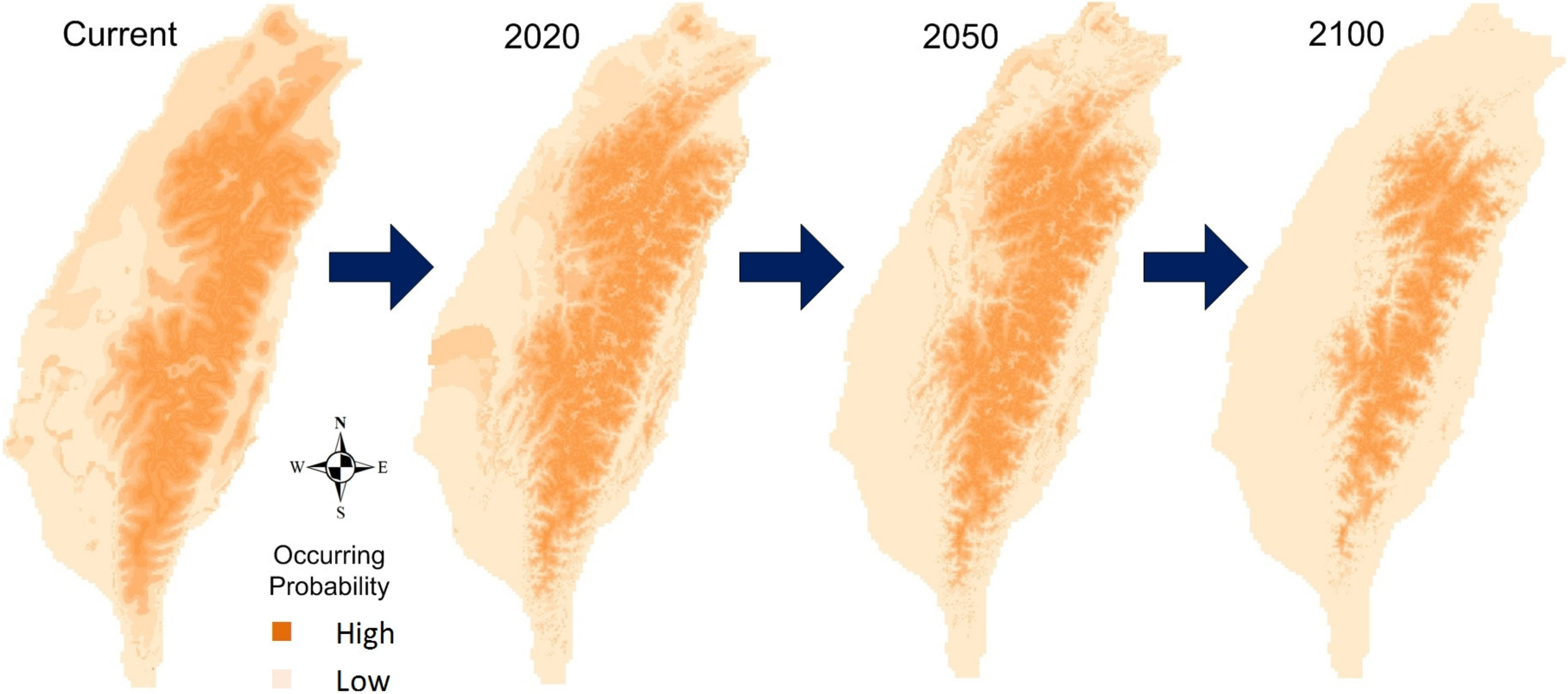


Figure 6: Projected changes in species spatial distribution of endemic Taiwan Yuhina (*Yuhina brunneiceps*) under A2 scenario in 2020, 2050 and 2100 with climate projection by the Climate Modelling and Analysis (CCCma) Coupled Global Climate Model from Canadian Centre.

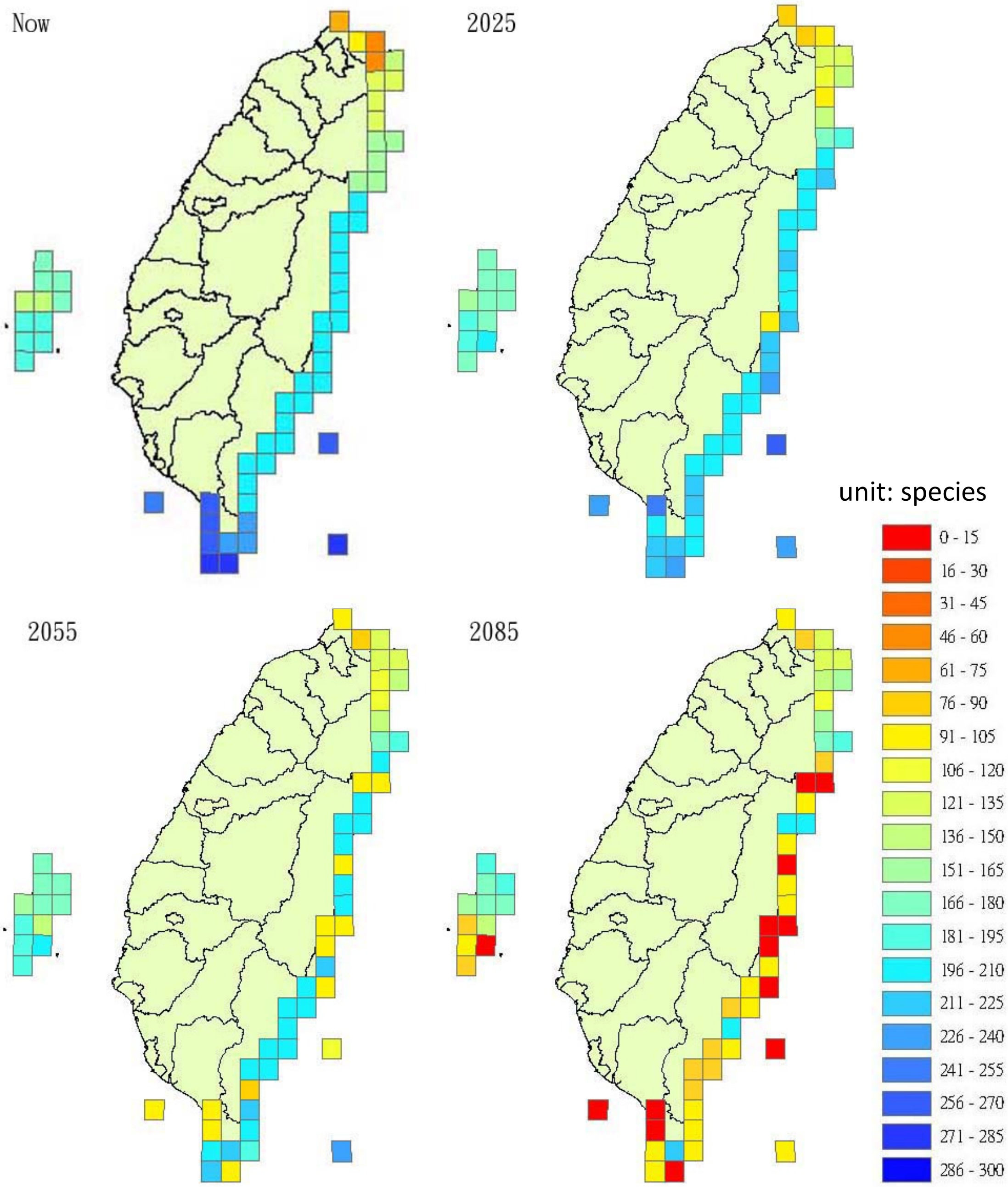


Figure 7: Summarized distribution patterns of coral species richness in reef areas of Taiwan in the present, and projected in 2025, 2055, and 2085.

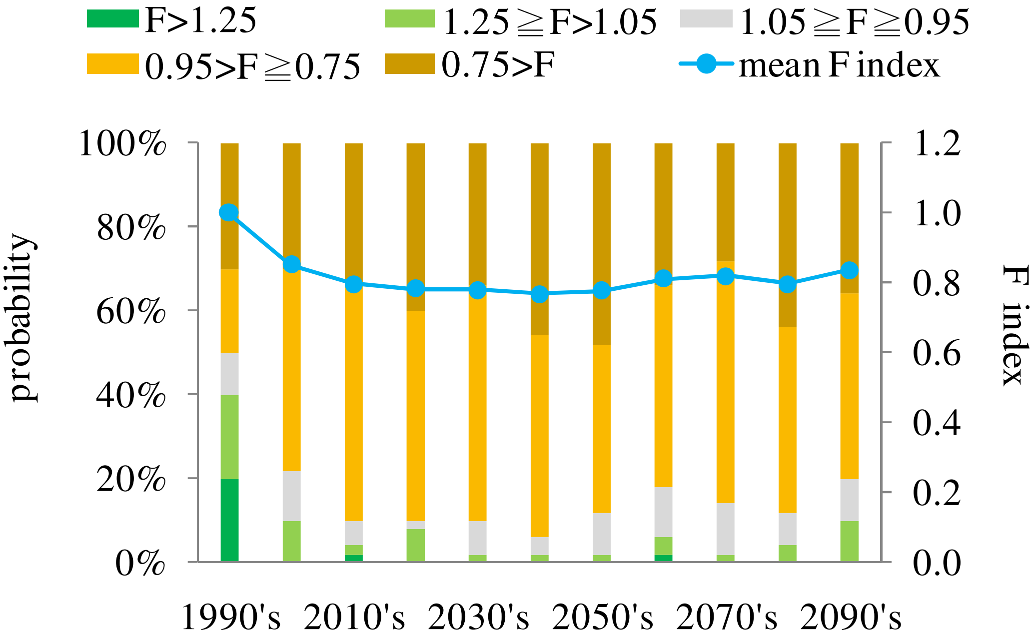


Figure 8: The occurring frequency of F index in the 1990s and the projected probability of F index under scenario SRES A2 in every decades of the 21th century. Within each figure, the decadal-mean F index is also plotted.

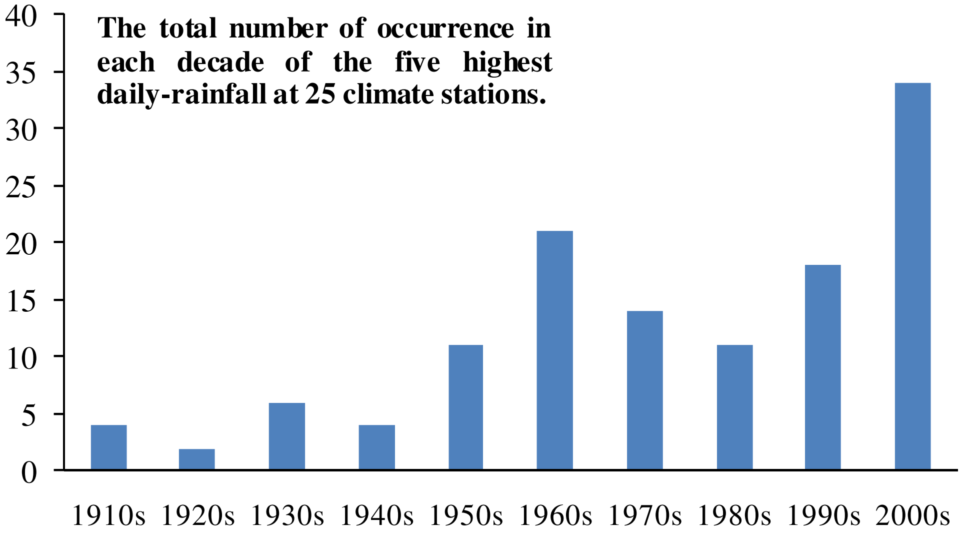


Figure 9: The total number of occurrence in each decade of the five highest daily rainfall at 25 climate stations in Taiwan.

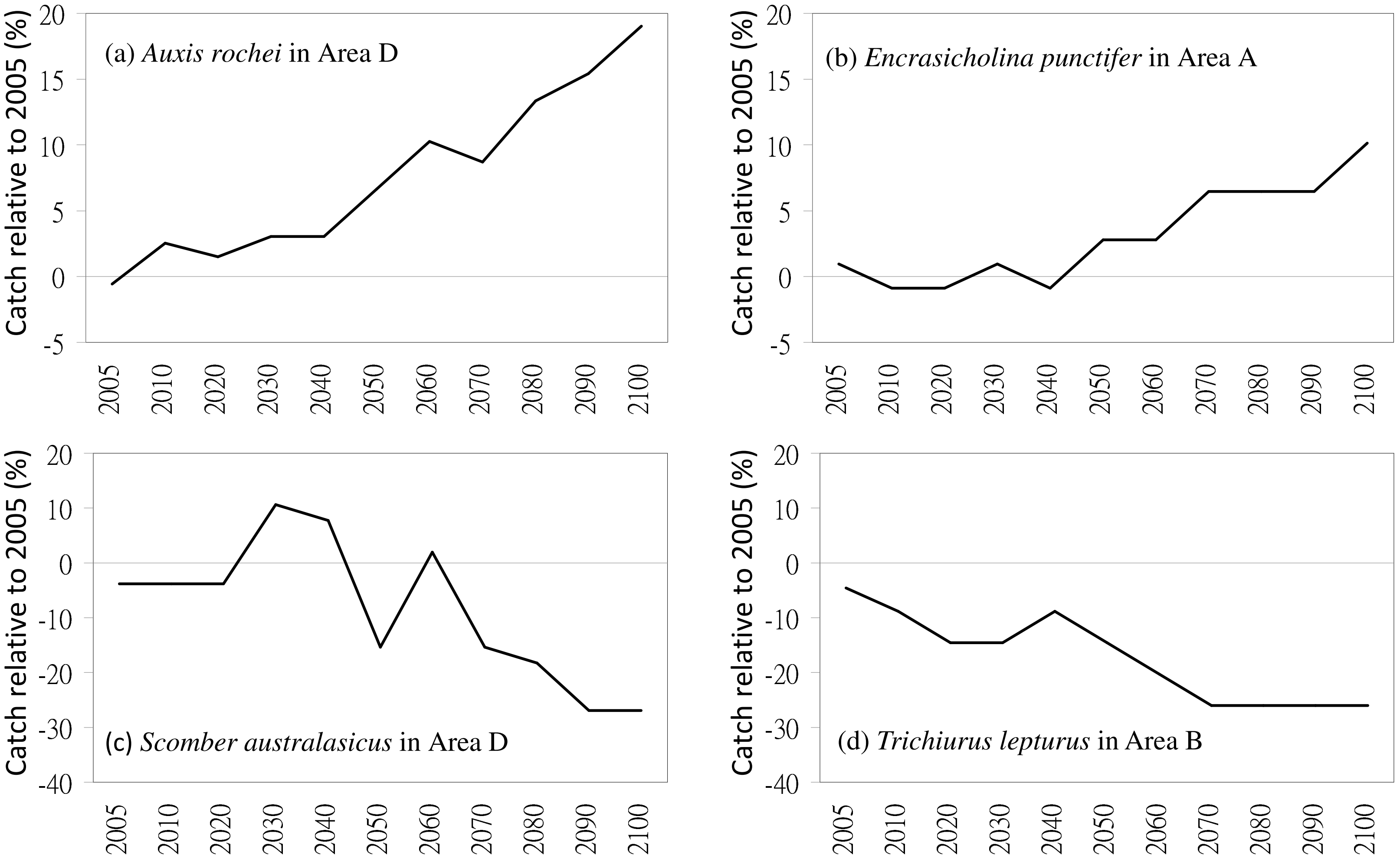


Figure 10: Catch projection with ECHAM4/OPYC3 model projection of SST under SRES A2 scenario for (a) *Auxis rochei* in Area D; (b) *Encrasicholina punctifer* in Area A; (c) *Scomber australasicus* in Area D; (d) *Trichiurus lepturus* in Area B.

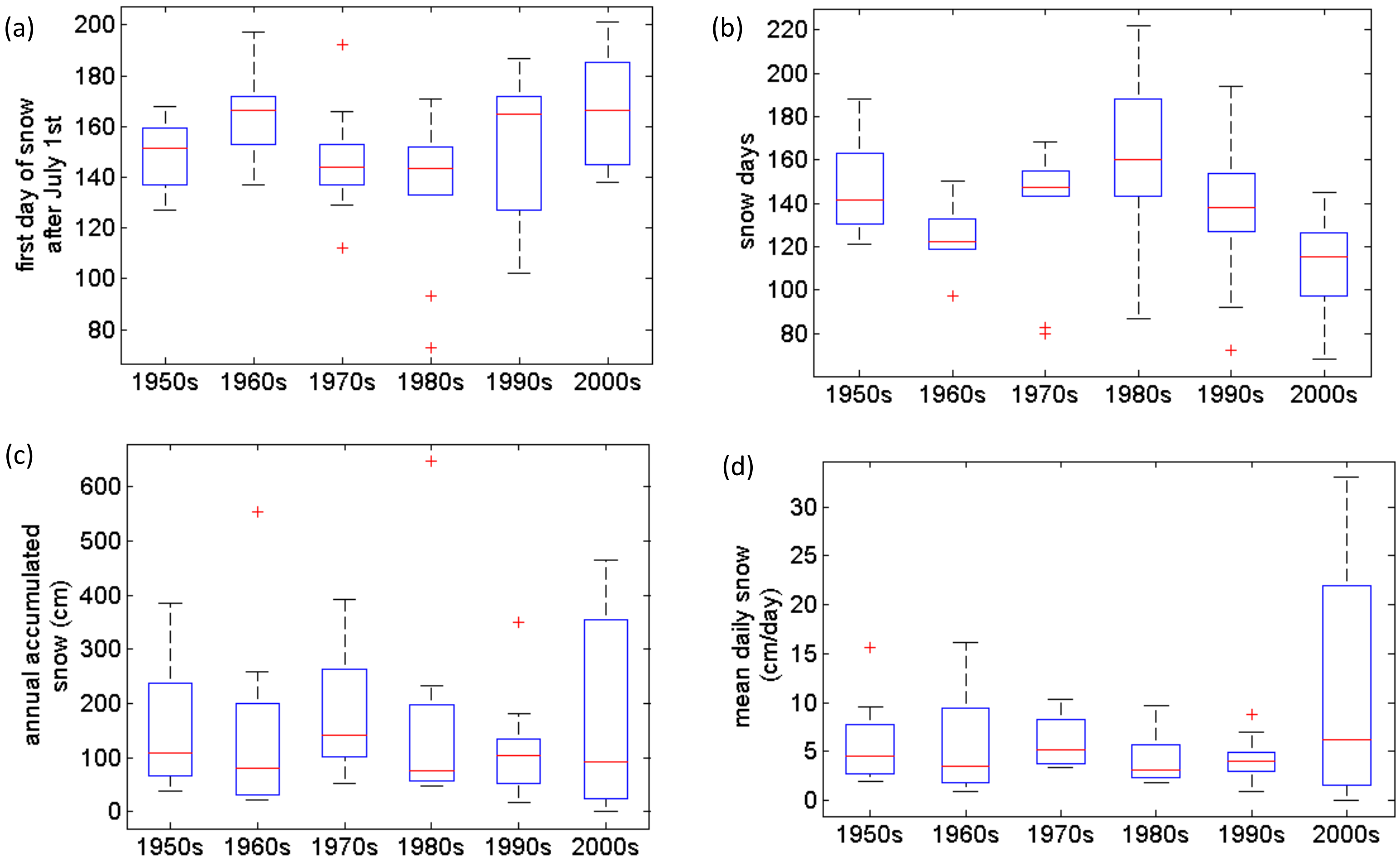


Figure 11: Box plot of The decadal change of (a) the 1^{st} day of snow after July 1^{st}, (b) the annual total snow day, (c) the annual accumulated snow and (d) the mean daily snow at Yushan high-elevation station, i.e. 3,858m a.s.l. (Marked in Fig. 1). Each box consists of the 75% percentile, medium and the 25% percentile, with dashed lines extending to the upper adjacent value (UAV) and the lower adjacent value (LAV) and sometimes a cross to represent the maximum or the minimum value.