ANALYSIS OF TEMPERATURE IMPACTS ON RICE PRODUCTION IN THAILAND DURING 1983-2012

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A THESIS SUBMITTED AS A PART OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN ENVIRONMENTAL TECHNOLOGY

THE JOINT GRADUATE SCHOOL OF ENERGY AND ENVIRONMENT AT KING MONGKUT'S UNIVERSITY OF TECHNOLOGY THONBURI

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ABSTRACT

This study analyzed the 30-year trends of temperatures during 1983-2012 and evaluated the potential impacts of daily maximum temperature, mean daily temperature and daily minimum temperature on rice production in Thailand. The maximum temperatures records at 78 meteorological stations, minimum temperature at 80 meteorological stations and mean temperatures records at 69 meteorological stations of the Thai Meteorological Department in were used for this study. It was found that the average daily maximum and mean temperature had increased with increasing rate of 0.13°C and 0.10 °C per decade, respectively. Minimum temperatures had significant increased with increasing rate of 0.29°C ($p \leq 0.01$) per decade. Using the temperature indices derived from daily maximum temperature of ≥35°C and mean daily temperature of ≤22°C, at which adverse effects on rice production have been suggested, revealed that rice cultivation in Thailand would have experienced high and low temperature stress. However, the overall impacts were considered as low for all stations except at Prachin Buri, Kosum Phisai and Thong Pha Phum station where the impact level was moderate, and Phatthaya, Phriu Agromet, Ranong, Ko Samui, Phuket Airport and Naratthiwat where there was no potential impact. On the monthly basis it was found that the potential impacts of high temperature on rice production were during February – May (vegetative growth state of rice), and in November (reproductive stage). In most case the impacts for these months were moderate, except in at Prachin Buri, Kosum Phisai and Thong Pha Phum station where these were high. For low temperature stress, the overall impacts were considered as low for all stations except at meteorological station in south Thailand where no potential impact was identified. On the monthly basis, it was found that the potential impacts of low temperature were in January and December (ripening stage). In most case the impacts for these months were moderate in north Thailand. These analysis indicate that the daily maximum temperature and mean daily temperature, both in terms of magnitude and frequency, may have exerted the adverse impacts on rice production in Thailand. Further in-depth analysis with sufficient observation data will further improve our understanding of potential impacts as well as provide guidance for counter measures in the future.

Keywords: Daily maximum temperature; Mean daily temperature; Daily minimum temperature; High temperature stress; Low temperature stress; Rice production; Potential impact of temperature

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CHAPTER 1
INTRODUCTION

1.1 Rationale

Rice is the world's most important food crop, and it serves as staple food for about half of the world's population. The demand for rice is expected to increase as the rice consuming population grows (Dowling *et al.*, 1998). It is projected that climate change will result in more extreme c limatic conditions and rice production are more likely subject to the events of high temperature during its growing period (IPCC, 2013). Vulnerability of the rice production system to the change in climate will have severe impacts on the world rice market and food supply.

Rice has long been Thailand's traditional food crop and the country's main export product. Over 80% of the Thai population eats rice as their main meal, with annual per capita consumption totaling 101 kg. The production usually exceeds the domestic needs, and thus, rice export and rice-related products are very important components of the Thai economy. In addition to its importance as the source of food, rice production is also providing other services. One of the examples is energy generation from rice biomass including rice husk and rice straw. In 2009, rice husk was used to generate energy about 1,234 Mtonne of oil equivalent (DEDE, 2012). Thus, with respect to rice production it not only affect food security but the production of raw material for renewable energy.

Based on water management schemes, rice cultivation in Thailand can be divided into irrigated and rainfed rice ecosystems. Irrigated rice (most of central Thailand) is usually cultivated year-round, while rainfed rice is cultivated during the rainy season (late April-December). The dependence of rainfed rice on climatic conditions such as timing, duration and intensity of rainfall and variations in temperature makes it very vulnerable to climate change and variability.

The global mean surface air temperature has increased by approximately 0.85°C in the 20th century and is projected to further increase by 0.3 - 4.8°C (IPCC, 2013). In Thailand, the averaged maximum temperature has increased by 0.57 °C during the 56-years period from 1965-2006 and the averaged mean temperature has increased more than the global mean temperature by 0.016 °C per decade (Limjirakan *et al.*, 2008). In addition, the mean temperature in Thailand is projected to increase by 3.4 °C during middle of the

21st century (2045-2065) (START, 2010). Climate change directly affected precipitation and temperature, with rise in temperatures leading to water deficit and floods in the future, changing soil moisture status, and pest and disease incidence (Kawasaki and Herath, 2011).

Rising temperature and its extremes are expected to become a major detrimental factor to rice production in most rice-growing regions. Extreme temperature, for example, if taking place at the stages when rice plants are most vulnerable such as during heading stage would potentially affect rice yields. Exposing rice during this stage to high temperature stress, it was found that pollen formation and development, insemination and spikelet fertility were severely damaged (Yoshida, 1981; Sun and Huang, 2011). In addition, grain-filling process was also affected, resulting in reduction of single-grain weight (Sun and Huang, 2011). In 2012, Thailand's rice yield reduced 4.8% from 2011 (TREA, 2013), this may attribute to climate variations especially in dry season that affected to yield more severely than in the wet season.

The threshold of high temperature that exerts damage on rice production has been suggested as the daily maximum temperature of ≥35°C (Yoshida, 1981; Sun and Huang, 2011). Exposing rice plant to this temperature for one hour was sufficient to induce sterility in rice (both indica and japonica genotypes). Kim *et al.* (2011) also found that during heading stage this high temperature stress can significantly reduce grain yield, spikelet fertility, and grain weight by accelerating the panicle senescence. The threshold of low temperature that exerts damages to rice production has been suggested as mean daily temperature of ≤22ºC for indica genotypes and ≤ 20ºC for japonica genotypes (Jing and Jichao, 2012). The damages of low temperature are poor and delayed germination, stunted seedling growth and leaf yellowing during early growth, and inhibited rooting and tillering during the vegetative stage. The reproductive stage showing inhibited panicle initiation and development, spikelet degeneration and disturbed pollen formation during reproductive stage. The ripening stage, low temperatures induce poor grain filling and rapid leaf senescence (Lee, 2001).

Efforts have been made to evaluate the impact of long-term climate change on rice yield in Thailand by relating climate change observations to census yields and using model simulations. However, our knowledge and understanding of the potential impacts associated with climate variability and extreme events are still very poor. The temperature is one of the critical parameters that affects rice production and high quality temperature records are available in Thailand over the long-term period. This study is proposed to evaluate the potential impacts of temperature variation on rice production in Thailand.

1.2 Literature Review

1.2.1 Temperature variations and trends in Thailand

TMD, (2013) reported that the annual and monthly mean temperatures in 2013 were higher than in 2012. This was, particularly obvious in winter season (December-January) when the temperature was 2-3°C warmer.

Limjirakan *et al.* (2008) reported the results of temperature analysis since 1960 - 2006 based on temperature records of several organizations in Thailand. They found that the increases in maximum, mean, and minimum temperatures per decade were 0.12-0.91, 0.09-0.61 and 0.11-0.80 °C, respectively. Western region was found highest increased trend for maximum and minimum temperature with 0.39 and 0.32°C per decade, respectively. Central region has an increasing trend for minimum temperature with 0.32°C per decade. In addition, during the past 56 years, maximum temperature, mean temperature and minimum temperature have increased 0.57, 0.81 and 0.89 °C, respectively (Figure 1.1). Mean temperature in Thailand has increased with the rate higher than the global mean temperature (0.016°C per decade). The year 1998 was the warmest year during 1966-1990 (Table 1.1).

Table 1.1 Annual mean temperatures in Thailand during 1966 to 2005

Year	Rate of increasing temperature trend (°C) compared with average temperature during 1966-1990
1998	+ 1.48
1997 and 2005	+0.79
2004	+0.73
2003	+0.69
2000	+0.68

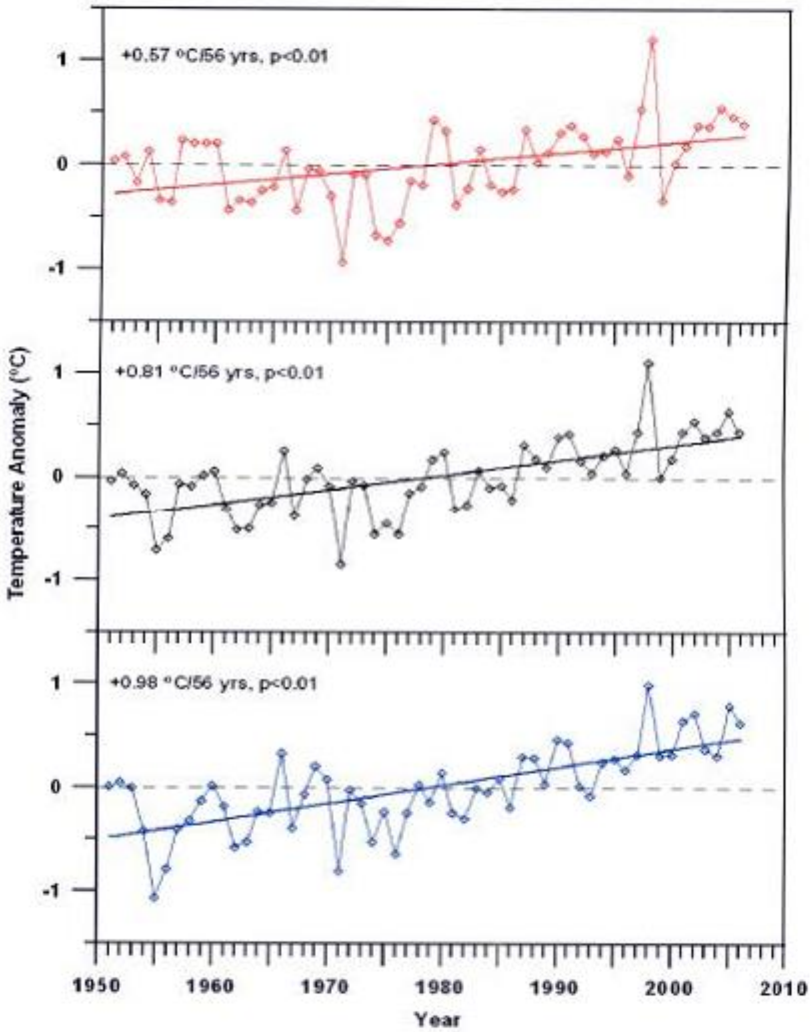


Figure 1.1 Trend in annual maximum temperature, mean temperature and minimum temperature in Thailand during 1950-2006 (Limjirakan *et al.,* 2008).

1.2.2 Analysis of Climate Change effects on Rice Production

Kawasaki and Herath (2011) studied the impact of climate change on rice production in Khon Kaen Province, Thailand using ECHAM4-PRECIS climate models under SRES B2 GHG scenarios and DSSAT crop model. The model experiment included five rice varieties (KDML 105, Suphanburi, Chainat, RD6 and Sanpatong) in three soil series (Re, Np, and Pp) during the rainy season (May-November) and the dry season (December-May) under climate conditions and three levels of N fertilizer application, 25, 50, and 75 kg per ha to improve yield. They reported the possible adaptation of crop yield through a change in month of planting under major soil series and climate conditions during the years 2010-2019, 2050-2059, and 2090-2099. KDKL 105 had high yields in Pp soil during rainy season, while Suphanburi, Sanpathong and Chainat could grow very well in Ng, and Pp soil series for the dry season of the years 2010-2019 with planting done on December or January. RD6 had high yield in Ng and Pp soil series during both rainy and dry seasons. All of the rice varieties appear to show a decreasing trend in productivity during the years 2050-2059 and 2090-2099, which is presumably due to the difficulties in rice cultivation under the unpredictability of the climate.

Pannangpetch *et al*. (2008) studied the impacts of global warming on rice production in Thailand by using a DSSAT crop model linked with GIS, and driven by weather data from ECHAM4-PRECIS climate models. Simulation was conducted under the conditions of no pest and crop management as recommended by the Ministry of Agricultures and Cooperatives. Results showed that CO_2 and temperature increases had insignificant effect on long term changes in yields of rice. On the other hand, yield variability, an important determinant of risk, was high with mean annual variation of 14 percent for rainfed and irrigated rice. Spatial yield variability was even higher, 33 percent for rainfed and irrigated rice. Impacts of climate change were most pronounced in the Northeast region for rainfed rice, in the Central plain and Northeast for irrigated rice.

Sun and Huang (2011) studied the changes in extreme low- and high-temperature stress in the major developmental stages of irrigated rice across mainland China over the period 1961-2008 by quantifying the indices of temperature stress (TSI). The results suggest that the indices of low- or high-temperature stress can be used to explain the year-to-year changes in rice yield. Analysis using the TSI indicated that low-temperature stress (LTS) in the seedling and heading-flowering stages of single rice in northeast China, the seedling stage of early rice and the heading-flowering stage of late rice in the double rice regions has reduced. No significant trends in LTS were detected during the booting stage. Moreover, global warming did not enhance high-temperature stress (HTS) in the heading-flowering stage over the same period, except in early rice in the mid-lower Yangtze River Valley where the HTS in the 2000s was higher than in previous decades.

Lansigan *et al*. (2000) studied the agronomic impact of climate variability on rice production in the Philippines. Long-term climate variability influences sowing date, crop duration, crop yield, and the management practices adapted in rice production. Short-term weather episodes can also affect yield by inducing changes in temperature, potential evapotranspiration, and moisture availability. The degree of vulnerability of crops to climate variability depends mainly on the development stage of the crops at the time of weather aberration. The vulnerability and risk of crop production due to weather fluctuations and climate variability can be minimized if future weather variations can be adequately predicted and a suitable process-based eco-physiological crop yield forecasting model can be identified to produce real-time yield forecasts.

1.2.3 Effect of Temperature on Rice Production

Guan *et al*. (2008) studied the responses of yield characteristics to high temperature during the flowering stage by field experiments at the China National Rice Research Institute, Hangzhou, China, during 2005-2006. A super hybrid rice combination Guodao 6, and a conventional hybrid rice combination Xieyou 46 (as control) were used. The results indicated that the spikelet sterility increased as the temperature increased in both hybrid rice combinations. The seed setting rate decreased as the average and maximum daily temperatures increased. The effects of the average daily temperature and the daily temperature difference during 11–15 days after flowering on grain weight decreased.

Jagadish *et al*. (2007) studied high temperature stress and spikelet fertility in rice (*Oryza sativa* L.). The effect of high temperature at anthesis on spikelet fertility was studied on IR64 (lowland *indica*) and Azucena (upland *japonica*) at 29.6 °C (control), 33.7 °C, and 36.2 °C tissue temperatures. The objectives of this study were to: (i) determine the effect of temperature on flowering pattern; (ii) examine the effect of time of day of spikelet anthesis relative to a high temperature episode on spikelet fertility; (iii) study the interactions between duration of exposure and temperature on spikelet fertility. The result indicated that in IR64, high temperature increased the number of spikelet reaching anthesis, while in Azucena number were reduced. In both genotypes ≤1 h exposure to ≥33.7 °C at anthesis caused sterility.

Kim and Pang (2009) studied the relationship among rice yields and weather variables in South Korea using a stochastic production function. The results reveal that average rice yield is positively related to temperature and negatively associated with precipitation. Both temperature and precipitation, which are risk-increasing inputs, are positively related to rice yield variability. The widened yield variability can be transferred to the fluctuation of rice production and rice price instability. Larger market risk is expected in the future since both temperature and precipitation are anticipated to increase. An evaluation of climate change impact on rice yield variability reveals that it may increase by up to 10%~20%.

Krishnan *et al*. (2007) used crop simulation model (ORYZA1 and INFOCROP) for estimated impacts of temperature on rice yield in eastern India based on three General Circulation Models (GCMs) used, such as the General Fluid Dynamics Laboratory (GFDL) model, Goddard Institute of Space Studies (GISS) model, and the United Kingdom Meteorological Office (UKMO) model. The results reveal that the ORYZA model suggested the decreases of -7.63, -9.38 and -15.86% in yield for the GDFL, GISS and UKMO scenarios, respectively. For the corresponding scenarios, INFOCROP indicated larger reductions at -9.02, -11.30 and -21.35%, respectively. Almost all the sites except one showed the declining trend in yields as shown in Tables 1.2 and 1.3.

Table 1.2 Estimated changes in rice yield predicted[a] by the INFOCROP rice model for each observation site in the eastern India under the three GCM scenarios.

Sites	Rice yield (t/ha)	GFDL		GISS		UKMO	
		Predicted change (%)	Predicted yield (t/ha)	Predicted change (%)	Predicted yield (t/ha)	Predicted yield (t/ha)	Predicted yield (t/ha)
Bhubaneswar	4.46	-23.87	3.40	-27.45	3.24	-37.22	2.80
Chinsurah	5.18	-7.03	4.82	-7.38	4.80	-8.11	4.76
Cuttack	4.93	-25.44	3.68	-27.67	3.57	-40.87	2.92
Faizabad	4.72	-13.55	4.08	-17.65	3.89	-28.34	3.38
Jabalpur	7.54	-10.7	6.73	-14.04	6.48	-25.66	5.61
Jorhat	3.83	13.51	4.35	12.32	4.30	7.55	4.12
Kalyani	3.55	-8.73	3.24	-11.65	3.14	-22.38	2.76
Pusa	3.82	-3.74	3.68	-4.35	3.65	-5.26	3.62
Raipur	3.75	-1.71	3.69	-5.11	3.56	-18.01	3.07
Ranchi	4.50	-8.89	4.10	-12.01	3.96	-35.15	2.92
Average change (%)	4.63	-9.02	4.18	-11.50	4.06	-21.35	3.60

[a] Predicted rice yield is adjusted by the simulated changes in the experimental rice yield obtained.

Table 1.3 Estimated changes in rice yield predicted[a] by the ORYZA1 model for each observation site in the eastern India under the three GCM scenarios.

Sites	Rice yield (t/ha)	GFDL		GISS		UKMO	
		Predicted change (%)	Predicted yield (t/ha)	Predicted change (%)	Predicted yield (t/ha)	Predicted yield (t/ha)	Predicted yield (t/ha)
Bhubaneswar	4.46	-17.33	3.69	-20.36	3.55	-27.53	3.23
Chinsurah	5.18	-8.03	4.76	-8.72	4.73	-9.59	4.68
Cuttack	4.93	-19.67	3.96	-20.32	3.93	-30.75	3.41
Faizabad	4.72	-9.02	4.29	-11.27	4.19	-18.82	3.83
Jabalpur	7.54	-11.05	6.71	-14.08	6.48	-21.05	5.95
Jorhat	3.83	12.13	4.29	12.64	4.31	8.31	4.15
Kalyani	3.55	-7.75	3.27	-9.76	3.20	-16.51	2.96
Pusa	3.82	-4.93	3.63	-6.31	3.58	-6.58	3.57
Raipur	3.75	-2.79	3.65	-5.22	3.55	-10.09	3.37
Ranchi	4.50	-7.87	4.15	-10.35	4.03	-25.98	3.33
Average change (%)	4.63	-7.63	4.24	-9.38	4.16	-15.86	3.85

[a] Predicted rice yield is adjusted by the simulated changes in the experimental rice yield obtained.

Chun *et al*. (2008) studied the effect of high temperature at meiosis stage on seed-setting rate in rice. To evaluate the effect of high temperature on rice yield, 2 rice genotypes, Huajing 1 (japonica) and Teyou 559 (indica hybrid) were treated with ladder temperatures (31, 33, 35, 37, 39, and 41ºC) for 1, 3, and 5 d at meiosis stage in Artificial Climate incubators. The high temperature stress was conducted for 5 h (8:40–13:30) at each treatment day. The natural temperature treatment was set as the control. The result indicated that the seed-setting rates of both cultivars were slightly affected when temperature was lower than 33ºC. However, with the increase of temperature and its duration, seed-setting rate decreased gradually. The relationship between daily relative seed-setting rate (RSS) and temperature was fitted by a quadratic equation. The total effect of high temperature at meiosis stage on RSS was described with the products of daily RSS.

Ishii *et al*. (2011) studied the effects of high water temperature during vegetative growth on rice growth and yield under a cool climate by rice plants to a higher (by +2.7 to +2.8 °C) water temperature (T_w) during the vegetative growth period (for 35–50 days) under three levels of N fertilization. High T_w during vegetative growth made the heading stage occur 4–7 days earlier for all levels of N fertilization in both years. The result indicated that the crop growth rate during the treatment period had been greatly enhanced by high T_w: by 51–82% in 2008 and by 49–62% in 2009. There was no T_w×N fertilizer interaction. This increased growth was associated with increased leaf expansion and increased canopy radiation capture rather than with increased radiation-use efficiency. However, the positive effect decreased during subsequent growth stages under all levels of N fertilization, leading to no significant differences in total biomass at maturity. High T_w during vegetative growth greatly reduced SPAD values during the grain-filling stage compared with SPAD values in the control T_w treatment, for all levels of N fertilization, and decreased leaf photosynthesis during the mid-grain filling stage. Grain yield was not significantly affected by high T_w at any N fertilizer level or in either year.

Ranga *et al*. (2011) studied the effects of high temperature and water stress on pollen germination and spikelet fertility in rice. In this study, five rice genotypes were exposed to high temperature, water stress and combined high temperature and water stress during flowering to quantify their response through spikelet fertility. Microscopic analyses revealed significant differences in anther dehiscence between treatments and genotypes, with amoderately high association with the number of germinated pollen grains on the stigma. There was a strong relationship between spikelet fertility and the number of germinated pollen on stigmas. Although, all three stress treatments resulted in spikelet sterility, high-temperature stress caused the highest sterility in all five genotypes. A cumulative linear decline in spikelet fertility with increasing duration of independent high-temperature stress and in combination with water stress was quantified. Better anther dehiscence, higher in vivo pollen germination, and higher spikelet fertility were observed in both the N22 accessions compared with IR64, Apo and Moroberekan under high temperature, water stress and combined stress, indicating its ability to tolerate multiple abiotic stresses.

The increasing temperature had no important effect on long-term changes in yields of rice, but it was the highest factor affecting rice growth and grain yield. China and the Philippines have attempted to potential the impact of climate variability on the period of rice growth and rice yields. The results indicated the temperature stress affect to rice growth and development, and rice yield in different regions. For Thailand, there little is evidence available to prove whether extreme temperature stress during the period of rice growth has increased as a result of global warming.

1.3 Research Objective

To evaluate the potential impacts of temperature on rice production in Thailand.

1.4 Scope of Research Work

To fulfill the research objective mentioned above, this study collected and analyzed temperature variability in Thailand using weather data from the Meteorological Department of the Royal Thai Government. The data included: (1) daily maximum temperature (DMAX), (2) daily minimum temperature (DMIN) and (3) mean daily temperature (MDT) spanning the period from 1983 to 2012 from 122 locations spread throughout Thailand. Data quality control was performed before all analysis. This study was not involved the field experiments. Extreme temperature exceeds the optimal range of rice growth were then analyzed, classified into different magnitudes that imply different levels of potential impacts. The results were presented spatially corresponding to the meteorological station where data were derived.

CHAPTER 2

THEORIES

2.1 Climate Change Issues Related to Growth of Rice

Climate is one of the major controlling factors for the well-being of the residents of the world. The global climate has been changing due to natural forcing as well as anthropogenic activities, especially the emissions of greenhouse gases and aerosols, and land use changes in recent decades. Climatic factors, such as temperature, rainfall, atmospheric carbon dioxide, and solar radiation, are closely linked with agricultural production. As a result, it is concerned that major agricultural activity in Thailand such as rice production would be adversely affected by climate change. This thesis chapter will review the important climatic factors and their potential impacts to rice production.

2.1.1 Trends in Atmospheric Carbon Dioxide Concentrations (CO_2)

The IPCC (2013) reported that the concentration of atmospheric CO_2 had increased by 11.7 to 390.5 ppm in 2011. From 1980 to 2011, the average annual increase in globally averaged CO_2 was 1.7 ppm per year (Figure 2.1).

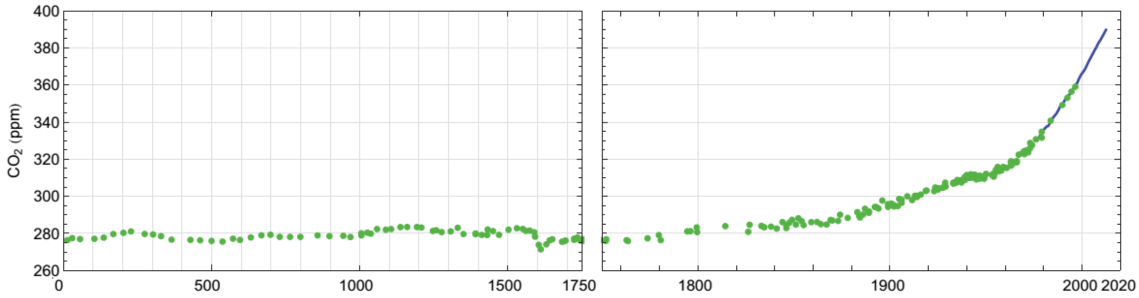


Figure 2.1 Atmospheric CO_2 concentrations over the industrial era (right) and from year 0 to the year 1750 (left) (IPCC, 2013).

In recent decades, emissions of CO_2 have continued to increase (Figure 2.2). Global annual fossil CO_2 emissions increased from an average of 6.4 ± 0.4 GtC per year in the 1990s to 7.2 ± 0.3 GtC per year in the period 2000 to 2005. Estimated CO_2 emissions associated with land use change, averaged over the 1990s, were 0.5 to 2.7 GtC per year, with a central estimate of 1.6 GtC per year (IPCC, 2007). Figure 2.2 also shows annual changes in global mean CO_2 concentration (grey bars) and their five-year means from two different measurement networks (red and lower black stepped lines). Uncertainties in the five-year means are indicated by the difference between the red and lower black lines and are of the order 0.15 ppm. The upper stepped line shows the annual increases that would occur if all fossil fuel emissions stayed in the atmosphere and there were no other emissions (IPCC, 2007).

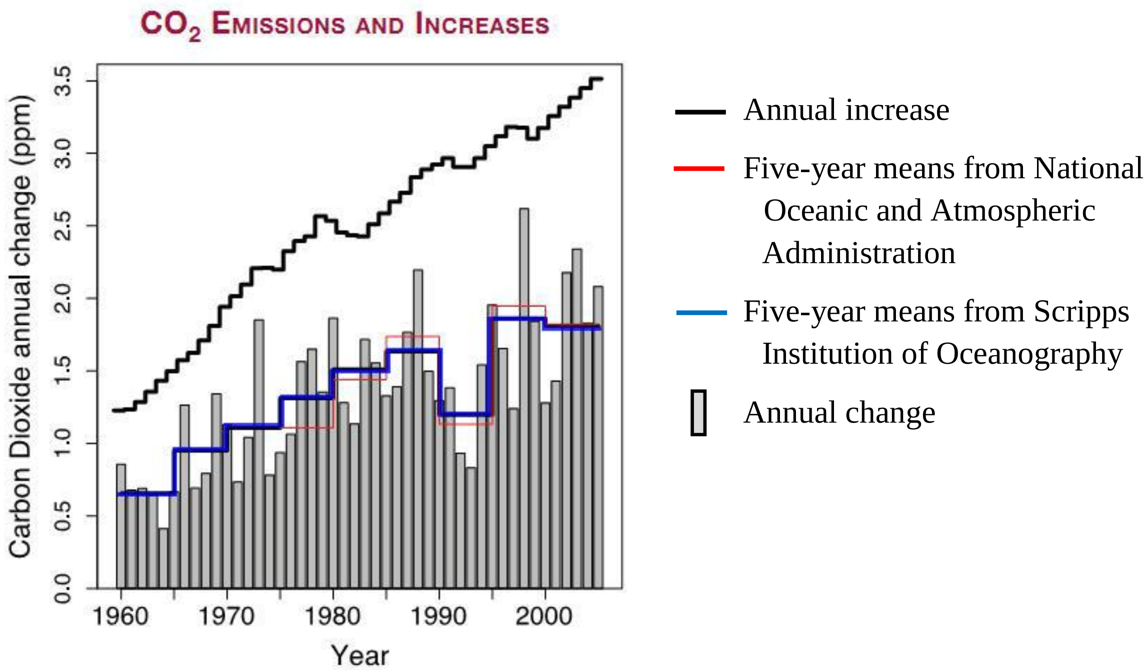


Figure 2.2 Annual changes and increasing in global mean CO_2 concentration (IPCC, 2007).

By the end of the 21st century, this additional CO_2 varies between 20 and 220 ppm for the two extreme models with most of the models lying between 50 and 100 ppm. Atmospheric CO_2 concentrations simulated by these coupled climate-carbon cycle models range between 730 and 1,020 ppm by 2100. Figure 2.3 shown 21st-century atmospheric CO_2 concentration as simulated by the 11 C^{4}MIP models for the SRES A2 emission scenario (red) compared with the standard atmospheric CO_2 concentration used as a forcing for many IPCC AR4 climate models (black).

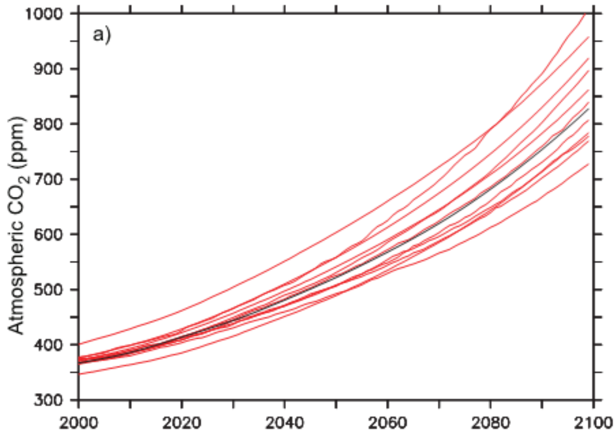


Figure 2.3 The 21st-century atmospheric CO_2 concentration as simulated by the 11 C^4MIP models (IPCC, 2007).

2.1.2 Global Temperature

The global mean surface temperature has increased since the late 19th century. The 132-year linear trend (1880-2012) was 0.85 °C. The overall temperature increase from 1850-1900 to 2003-2012 was 0.78°C. In addition, trends based on short records are very sensitive to the beginning and end dates and do not in general reflect long-term climate trends. For example, the rate of warming over the past 15 years (1998–2012; 0.05 °C per decade), which begins with a strong El Niño, is smaller than the rate calculated since 1951 (1951–2012; 0.12 °C per decade) (Figure 2.4) (IPCC, 2013).

A few areas have cooled since 1901, most notably the northern most part of the Atlantic near southern Greenland. Warming during this time has been strongest over the continental interiors of Asia and northern North America. However, as these are areas with large year-to-year variability, the most evident warming signal has occurred in parts of the middle and lower latitudes, particularly the tropical oceans. In the lower left panel of Figure 2.5, which shows temperature trends since 1979, the pattern in the Pacific Ocean features warming and cooling regions related to El Niño (IPCC, 2007).

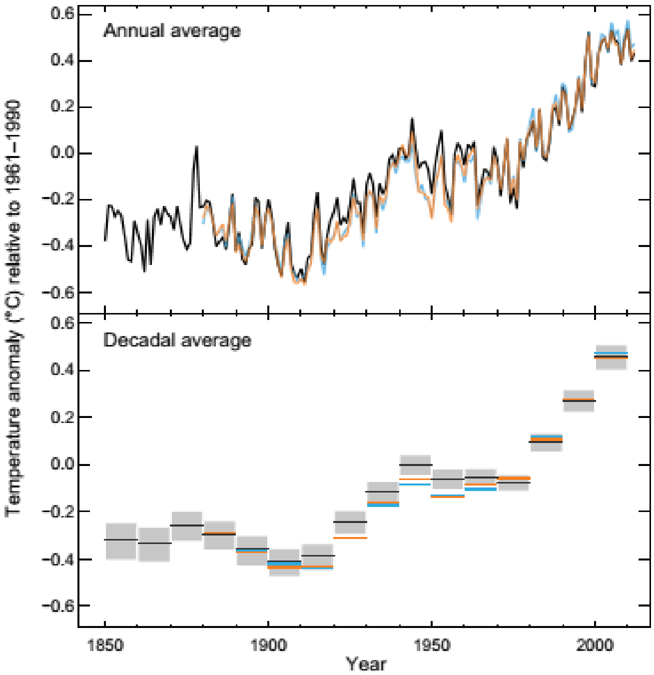


Figure 2.4 Global annual mean temperature anomalies from 1850 to 2012 (IPCC, 2013).

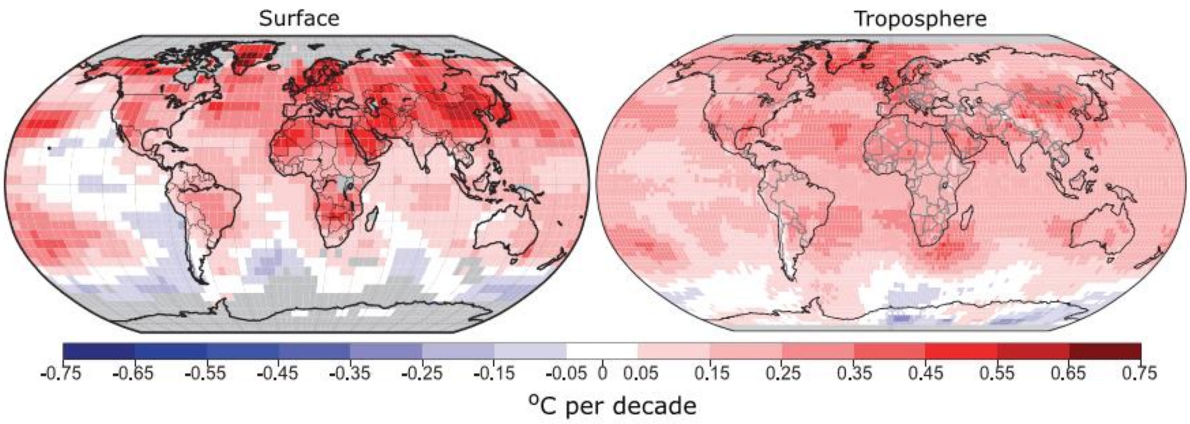


Figure 2.5 Patterns of linear global temperature trends from 1979 to 2005 estimated at the surface (left), and for the troposphere (right) (IPCC, 2007).

Analysis of long-term changes in daily temperature extremes has recently become possible for many regions of the world (parts of North America and southern South America, Europe, northern and eastern Asia, southern Africa and Australasia). Especially since the 1950s, these records show a decrease in the number of very cold days and nights, and an increase in the number of extremely hot days and warm nights. The length of the frost-free season has increased in most mid- and high-latitude regions of both hemispheres. In the Northern Hemisphere, this is mostly manifested as an earlier start to spring (IPCC, 2007). As we can see that the warming temperature appears over Asia which has the most rice areas, and northern North America.

2.1.3 Precipitation

IPCC (2007) reported that precipitation has generally increased over the land north of 30°N over the period 1900 to 2005, but downward trends dominate the tropics since the 1970s. From 10°N to 30°N, precipitation increased markedly from 1900 to the 1950s, but declined after about 1970. Downward trends are present in the deep tropics from 10°N to 10°S, especially after 1976/1977. Tropical values dominate the global mean. It has become significantly wetter in eastern parts of North and South America, northern Europe, and northern and central Asia, but drier in the Sahel, the Mediterranean, southern Africa and parts of southern Asia. Patterns of precipitation change are more spatially and seasonally variable than the temperature change.

Trends in global annual land precipitation were analyzed using data from the Global Historical Climatology Network (GHCN), using anomalies with respect to the 1981 to 2000 base period. The observed GHCN linear trend (Figure 2.6) over the 106-year period from 1900 to 2005 is statistically insignificant, as is the Climatic Research Unit (CRU) linear trend up to 2002. However, the global mean land changes (Figure 2.6) are not at all linear, with an overall increase until the 1950s, a decline until the early 1990s and then a recovery. Although the global land mean is an indicator of a crucial part of the global hydrological cycle, it is difficult to interpret as it is often made up of large regional anomalies of the opposite sign.

In the tropics, precipitation is highly seasonal, consisting of a dry season and a wet season in association with the summer monsoon. The downward trends in this zone are also found in southern Asia. The linear trends of rainfall decreases for 1900 to 2005 were 7.5% in both the western Africa and southern Asia regions. The area of the latter region is much greater than India, whose rainfall features strong variability but little in the way of a century-scale trend. Southern Africa also features a strong overall downward trend, although with strong multi-decadal variability present. Often the change in the rainfall in these regions occurs fairly abruptly, and in several cases, occurs around the same time in association with the 1976–1977 climate shift.

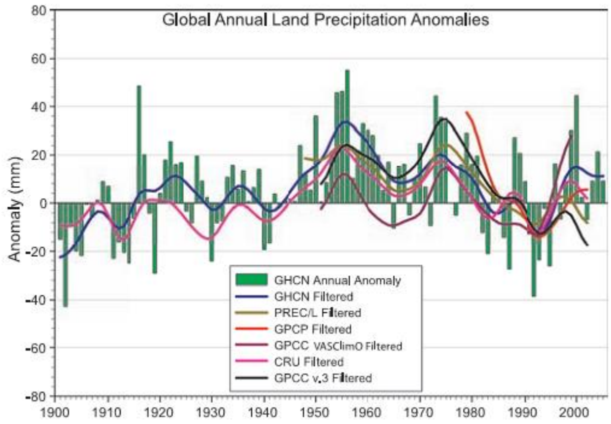


Figure 2.6 Global annual land precipitation anomalies (IPCC, 2007).

2.1.4 Drought and Soil Moisture

Droughts have become more common, especially in the tropics and subtropics, since the 1970s. Observed marked increases in drought in the past three decades arise from more intense and longer droughts over wider areas, as a critical threshold for delineating drought is exceeded over increasingly widespread areas. Decreased land precipitation and increased temperatures that enhance evapotranspiration and drying are important factors that have contributed to more regions experiencing droughts. In the western USA, diminishing snow pack and subsequent reductions in soil moisture also appear to be factors. In Australia and Europe, direct links to global warming have been inferred through the extreme nature of high temperatures and heat waves accompanying recent droughts. Agricultural drought relates to moisture deficits in the topmost 1 metre or so of soil (the root zone) that affect crops.

Soil moisture is often the most important factor controlling plant growth and agricultural production. Globally, models predict significant soil moisture changes with decreases in some regions and increases in others. Large reductions in summer soil moisture will occur in the midcontinental regions of the mid to high latitudes, for example, the North American Great Plains, Western Europe, Northern Canada, and Siberia.

Figure 2.7 shows drought indicated by cumulative deficits in surface land moisture using Palmer Drought Severity Index (PDSI) for 1900 to 2002. The lower panel shows how the sign and strength of this pattern has changed since 1900. Red and orange areas are drier (wetter) than average and blue and green areas are wetter (drier) than average when the values shown in the lower plot are positive (negative). The smooth black curve shows decadal variations. The time series approximately corresponds to a trend, and this pattern and its variations account for 67% of the linear trend of PDSI from 1900 to 2002 over the global land area. It therefore features widespread increasing African drought, especially in the Sahel, for instance. Note also the wetter areas, especially in eastern North and South America and northern Eurasia.

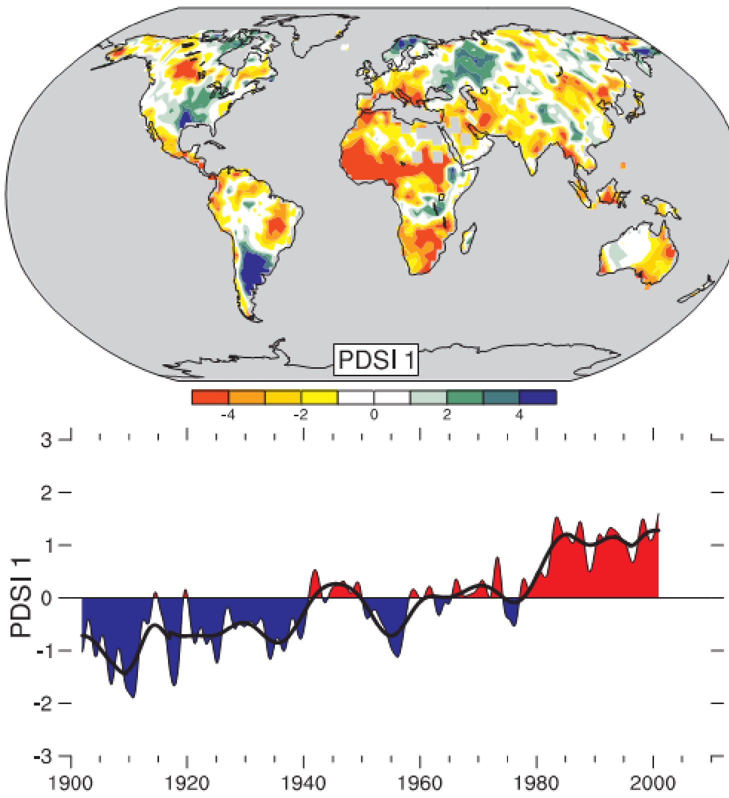


Figure 2.7 The spatial pattern of the monthly Palmer Drought Severity Index (PDSI) for 1900 to 2002 (IPCC, 2007).

2.1.5 Solar Radiation

IPCC (2007) reported that continuous monitoring of total solar irradiance now covers the last 28 years. The data show a well-established 11-year cycle in irradiance that varies by 0.08% from solar cycle minima to maxima, with no significant long-term trend. New data have more accurately quantified changes in solar spectral fluxes over a broad range of wavelengths in association with changing solar activity. The estimated direct radiative forcing due to changes in the solar output since 1750 is +0.12 W m^{-2}.

2.1.6 Ocean Salinity

Salinity is a current problem, which is expected to exacerbate due to climate change and sea level rise. Salinity intrusion due to reduction of freshwater flow from upstream, salinisation of groundwater and fluctuation of soil salinity are major concern globally. Cyclones and tidal surge is adding to the problem. Tidal surge brings in saline water inside the polders in the coastal area. Due to drainage congestion, the area remains waterlogged, increasing the salinity (Abedin, 2010). Much larger areas of coastal wetlands may be affected by flooding and salinity in the next 50–100 years (Allen *et al.,* 1996). This excludes the additional expected increase in sea levels due to melted ice leading to increased coastal salinity. Furthermore, greater than half (55%) of the total ground water is naturally saline (Ghassemi *et al.,* 1995). Secondary salinization, specifically due to the injudicious use of water and fertilizers in irrigated agriculture could increase the percentage of brackish ground water. The ground water table, if it rises and is brackish in nature, becomes ruinous to most of the vegetation. A rise of 1000 mm sea level due to thermal expansion is estimated for 3.58 °C increase in temperature. Higher temperature aggravates the situation by excessive deposition of salt on surface due to capillary action which is extremely difficult to leach below the rooting zone.The increased temperature will also disrupt weather patterns, leading to more frequent occurrence of problems associated with floods, drought, and salinity (Wassmann *et al.,* 2009). In addition, changes in precipitation and evaporation over the oceans are suggested by freshening of mid- and high-latitude waters together with increased salinity in low-latitude waters (IPCC, 2007).

Figure 2.8 shows the linear trends (1955 to 2003) of zonally averaged temperature anomalies (0 to 1,500 m) for the World Ocean. The contour interval is 0.01 per decade and dashed contours are ±0.005 per decade. The dark, solid line is the zero contour. Red shading indicates values equal to or greater than 0.005 per decade and blue shading indicates values equal to or less than –0.005 per decade.

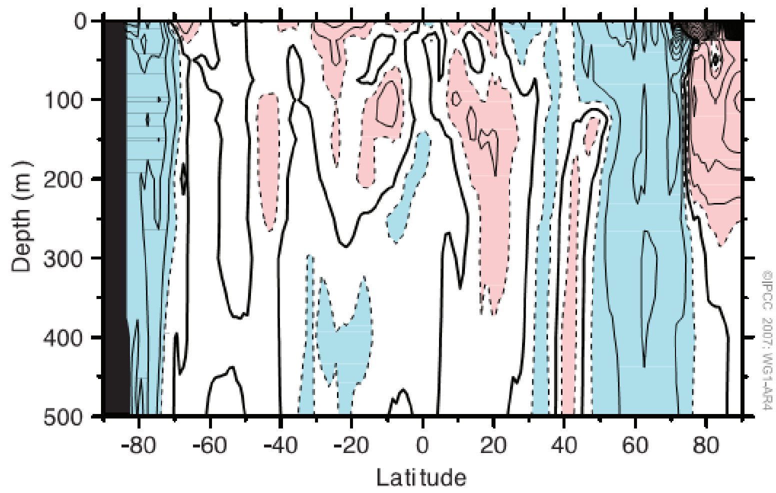


Figure 2.8 Linear trends (1955–1998) of zonally averaged salinity for the World Ocean (IPCC, 2007).

Due to changes in sea levels, over the 1961 to 2003 period, the average rate of global mean sea level rise is estimated from the tide gauge data to be 1.8 ± 0.5 mm yr^{-1} (Figure 2.9).

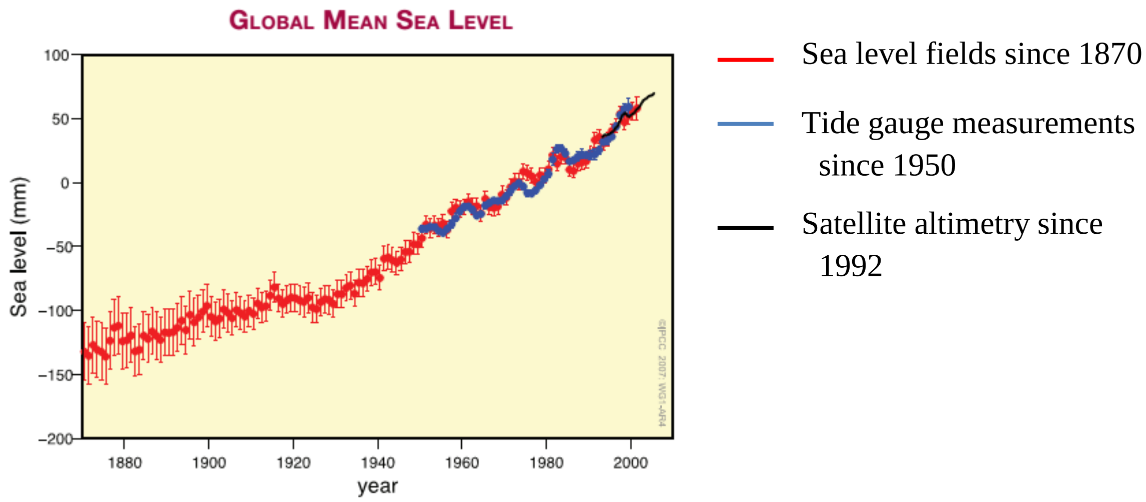


Figure 2.9 Annual averages of the global mean sea level (IPCC, 2007).

2.2 Ecological Aspects of World Rice Cultivation

2.2.1 Origins of Rice

Rice is believed to have evolved within a 2,000-mile-long belt that stretches underneath the Himalaya Mountains along the Ganges River plains of India, across Bangladesh and Bhutan, through northern Burma, Thailand, Laos, and Vietnam, and into southern China. Archaeological discoveries of rice remains, fossil imprints of rice glume, or pottery imprints at sites within rice's evolutionary belt date as early as 4000 B.C., while pottery shards bearing the imprint of both grains and husks of the cultivated rice species *Oryza sativa* were discovered at Non Nok Tha in the Korat area of Thailand. Plant remains from 10000 B.C. were discovered in Spirit Cave on the Thailand-Myanmar border (Maclean *et al.,* 2002). And also remains from the Hemudu excavation in eastern China date to about 5000 B.C. After being cultivated for perhaps millennia, rice culture was introduced into Japan apparently from about 1000 to 300 B.C. The culture of rice spread westward across India by 2000 B.C. and southward into Malaysia, reaching the Philippines by 1400 B.C. (Smith *et al.,* 2002).

In China, the popular claim in the past was that rice was among the five cereals that the mythological Emperor Sheng-Nung (2737-2697 B.C.) taught the people to cultivate. Many scholars in the West have questioned the validity of this myth and raised the question of whether wild rice had been found in ancient times. The finding of the character "tan" carved on the bone oracles of the Ying Dynasty (1766-1922 B.C.) provided a more reliable time period than that of earlier accounts. Archaeological evidence came from the imprint of a rice glume on clay pottery unearthed from Yang-shao site (Honan Province) and its estimated age was 3200-2500 B.C. Soon after, an excavation at Ho-Mo-Tu (Hemudu) in Chekinag province revealed a large, well-preserved collection of carbonized grains, straw, earthen cooking utensils, spades made from bones of large animals, and advanced wooden huts – all these point to a community structure of early rice growers (Smith et al., 2002). Moreover, archeological evidence points to the middle Yangtze and upper Huai rivers as the two earliest places of *O. sativa* rice cultivation in the country. Rice and farming implements dating back at least 8,000 years have been found. Cultivation spread down these rivers over the following 2,000 years (Maclean *et al.,* 2002).

In India, references to rice appear in ancient Hindu scripts (estimated to be 1500 to 1000 B.C.). Up to the 1950s, the oldest excavation of rice grains was found at Hasthinapur

(U.P.) dated between 1000 and 750 B.C. A 1980 report on excavations made in Koldihwa at Mahagasra (U.P.) pushed the date back to 6570-4530 B.C. In African, rice is believed to have been grown in the primary area of diversity in West Africa since 1500 B.C., while the secondary areas began 500 to 700 years later, although no archaeological evidence has been provided (Smith *et al.,* 2002). The last, origin of rice believed to have been grown in Asia, especially, in South Asia and Southeast Asia because these are the low land and more rice varieties having good adaptation to the area.

2.2.2 Genetic Diversity

The genus *Oryza* is small, including only about 23 species, but is remarkable in the diverse ecological adaptations of its species. Wild *Oryza* species are distributed throughout the tropics. They can be grouped into four complexes of closely related species (Table 2.1).

The rice species are important for human nutrition: *O. sativa* is grown worldwide, and *O. glaberrima* is grown in parts of West Africa.

The diversification of *O. sativa* reached its peak in Asia. Most rice workers agree that the tropical races, later called the *indica race,* served as the primary source of variations in the other ecogentic races. In Japan, this temperate-zone race was named the *japonica* type. A third ecogeographic race having a large plant size, slower growth, and large and bolder grains was recognized by Japanese workers and given the collective name *javanica* (Smith *et al.*, 2002). Ecological diversification in *O. sativa,* which involved hybridization-differentiation-selection cycles, was enhanced when ancestral forms of the cultigen were carried by farmers and traders to higher latitudes, higher elevations, dryland sites, seasonal deepwater areas, and tidal swamps. Within broad geographic regions, three major ecogeographic races were differentiated as a result of isolation and selection: (1) *indica,* adapted to the tropics; (2) *japonica,* adapted to the temperature regions and tropical uplands; and (3) *javanica* (Figure 2.10) (Maclean *et al.,* 2002). The three races are contrasted in Table 2.2 Despite some deficiencies, the terms *indica, japonica* and *javanica* are useful, as there is genetic incompatibility in their hybrid progenies (Smith *et al.,* 2002).

Table 2.1 Taxa in the genus Oryza: the complexes and distribution (Maclean *et al.*, 2002).

Complex/taxon	**Distribution**
O. schlechteri	Papua New Guinea
O. brachyantha	Africa
O. ridleyi complex	
O. longiglumis	Papua New Guinea
O. ridleyi	Southeast Asia
O. meyeriana complex	
O. granulata	South and Southeast Asia
O. meyeriana	Southeast Asia
O. officinalis complex	
O. officinalis	Tropical Asia to Papua New Guinea
O. eichingeri	East and West Africa
O. rhizomatis	Sri Lanka
O. minuta	Philippines, Papua New Guinea
O. punctata	Africa
O. latifolia	Central and South America
O. alta	Central and South America
O. grandiglumis	South America
O. australiensis	Australia
O. sativa complex	
O. glaberrima (cultigen)	West Africa
O. barthii	Africa
O. longistaminata	Africa
O. sativa (cultigen)	Worldwide
O. nivara	Tropical Asia
O. rufipogon	Tropical Asia
O. meridionalis	Tropical Australia
O. glumaepatula	South America

O. glaberrima varieties can be divided into two ecotypes: deepwater and upland. In West Africa, *O. glaberrima* is a dominant crop grown in the flooded areas of the Niger and Sokoto River basins. It is broadcasted on hoed fields. On shallow flooded land, a rainfed wetland crop is either directly sown by broadcasting or dibbling, or it is transplanted. About 45% of the land planted to rice in Africa belongs to the upland (dryland) culture, largely under bush fallow or after the ground has been hoed. Some African farmers still use axes, hoes, and bush knives in land preparation. In hydromorphic soil, *O. glaberrima* behaves like a self-perpetuating weed. In wetland fields planted to *O. sativa, O.glaberrima* has become a weed.

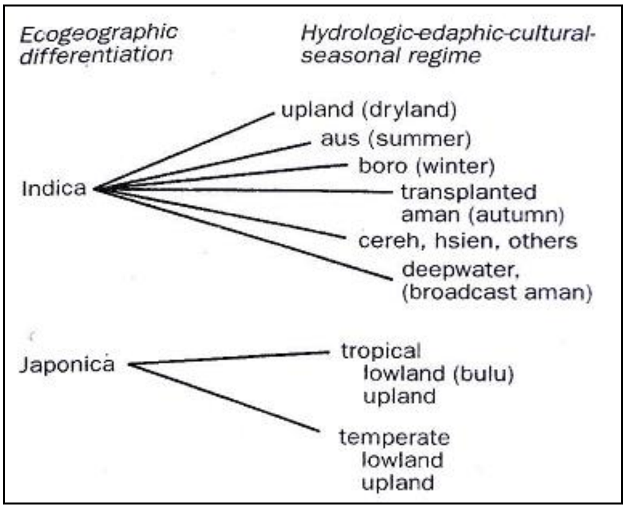


Figure 2.10 Grouping of Asian rice cultivars by ecogeographic race, hydrologic-edaphic-cultural regime, and crop season. Cultivars grown in standing water belong to the lowland type (Maclean *et al.,* 2002).

Table 2.2 Ecogenetic Races of Oryza sativa: comparison of their morphological and physiological characteristics (Smith *et al.*, 2002).

Indica	Japonica	Javanica
Broad to narrow, light green leaves	Narrow, dark green leaves	Broad, stiff, light green leaves
Long to short, slender, somewhat flat grains	Short, roundish grains	Long, broad, thick grains
Profuse tillering	Medium tillering	Low tillering
Tall to intermediate plant stature	Short to intermediate plant staure	Tall plant stature
Mostly awnless	Awnless to long-awned	Long awned or awnless
Thin, short hair on lemma and palea	Dense, long hairs on lemma and palea	Long hairs on lemma and palea
Easy shattering	Low shattering	Low shattering
Soft plant tissues	Hard plant tissues	Hard plant tissues
Varying sensitivity to photoperiod	Zero to low sensitivity to photoperiod	Low sensitivity to photoperiod
23-31% amylose	10-20% amylose	20-25% amylose
Variable gelatinization temperatures (low or intermediate)	Low gelatinization temperation	Low gelatinization temperation

O. sativa, the dominant rice species, is believed to have originated somewhere in Southeast Asia. Today, it is cultivated in Asia, Africa, Europe; North, Central, and South America; and Oceania. Production statistics reveal that Asia is not only the home area of *O. sativa* but also the major rice-growing area of the world. However, *O. sativa* is a newly introduced crop on the other continents, including Africa where *O. glaberrima*, the other cultivated species of *Oryza*, originated. The *indica* rice are widely grown in tropical regions such as Southeast Asia; *japonica* rice, which are adapted to cooler areas, are largely grown in temperate countries such as central and northern China, Korea, and Japan. Both *indica* and *japonica* rice can also be grown in subtropical regions such as Taiwan.

2.2.3 Growth of Rice plant

The growth duration of cultivated rice ranges from 80 to 280 days, with U.S. cultivars ranging from 105 to 145 days. Cultivars can generally be divided into three maturity groups: early-maturing cultivars (80 to 130 days), intermediate-maturing cultivars (130 to 160 days), and late-maturing cultivars (160+days) depending on the variety and the environment under which it is grown. During this period, rice completes basically two distinct sequential growth stages: vegetative and reproductive. The reproductive stage is subdivided into preheading and postheading periods. The latter is better known as the ripening period. Yield capacity, or the potential size of crop yield, is primarily determined during preheading. Ultimate yield, which is based on the amount of starch that fills spikelets, is largely determined during postheading. Hence, agronomically, it is convenient to regard the life history of rice in terms of three growth stages: vegetative, reproductive, and ripening. The vegetative stage refers to a period from germination to the initiation of panicle primordia; the reproductive stage, from panicle primordia initiation to heading; and the ripening period, from heading to maturity (Figure 2.11). A 120-day variety, when planted in a tropical environment, spends about 60 days in the vegetative stage, 30 days in the reproductive stage, and 30 days in the ripening period (Yoshida, 1981).

2.2.3.1 Vegetative phase

The vegetative phase begins with seed germination and proceeds with a repetitive production of shoot units until panicle initiation. Each shoot unit produces a leaf, tiller, and root primordial. Plant development has synchrony, with main stem leaf emergence being highly conserved (i.e. a consistent character for a given cultivar across environments). The rate of main stem leaf emergence is used to describe plant development. Emergence of tiller and roots is more environmentally sensitive, but there is a steady increase in numbers and sizes of all three plant parts. Growth during this phase results in cultivar development that is morphologically distinct with respect to leaf characteristics (number on the main clum, shape, size, color, and erectness) and culm characteristics (number and erectness).

I. Germination

Seeds germinate upon absorption of water and initiation of the biochemical processes involved in embryo growth. The process begins with imbibition and ends with sufficient swelling and growth of the plant primordial to cause an opening of the hull and visible signs of radicle and/or coleoptile protrusion (Figure 2.12A and 2.15A). Germination is affected by moisture, seed dormancy, aeration, and temperature.

Seeds generally germinate at 15% moisture and attain full germination at 25% moisture. When soaked, a seed rapidly absorbs water for the first 18 hours (Yoshida, 1981). The process has been found to be triphasic.

Phase A : Imbibition stage

Phase B : Activation stage

Phase C : Post-germination growth stage

Water uptake is rapid during phases A and C, and controlled by seed coat permeability. Phase B is regulated by gases (oxygen, carbon dioxide, and ethylene), endogenous inhibitors or hormones, and enzymatic activity. Seed coat permeability is also a factor affecting gas exchange during germination.

The seed coat can inhibit germination by reduced permeability to water and gases, and also for reasons related to dormancy. Several dormancy factors, or chemicals, are contained in the seed coat. Therefore, removal of the seed coat will often bring about even more rapid germination.

Dormancy refers to low germinability of viable, freshly harvested kernels. It generally is overcome by heat treatment at 40 to 50 °C for 5 days. Cultivars show varying levels of dormancy and requirements for heat treatment. High dormancy in some cultivars allows their seed to remain viable in the soil for several years.

Aeration determines the order of coleorhiza and coleoptile emergence from the hull: under aerobic conditions, the coleorhiza emerges first or together with the coleoptile (Figures 2.12A and B). Under anaerobic conditions, the coleoptile emerges first (Figure 2.15). Rice shows adaptation to hypoxic and anoxic conditions by anaerobic fermentation. The coleoptile is the only organ of the embryo that can emerge from the seed on energy derived solely from anaerobic fermentation. Adaptability to anaerobic germination varies with cultivar.

Temperature is one of the most important factors affecting germination. Germination percentages of 90 to 97% occur within 48 hours if temperatures are between 27 and 37 °C (Yashida, 1981). Germination drops sharply below these temperatures (e.g. at 10 °C, germination proceeds slowly and radical emergence may take more than 30 days).

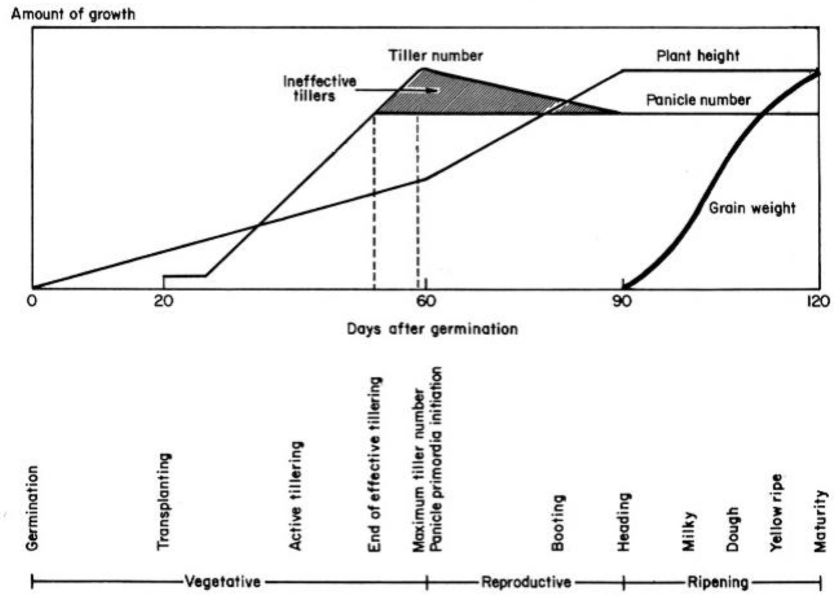


Figure 2.11 Life history of a 120-day variety grown in the tropics under the transplanting cultivation system (schematic) (Yoshida, 1981).

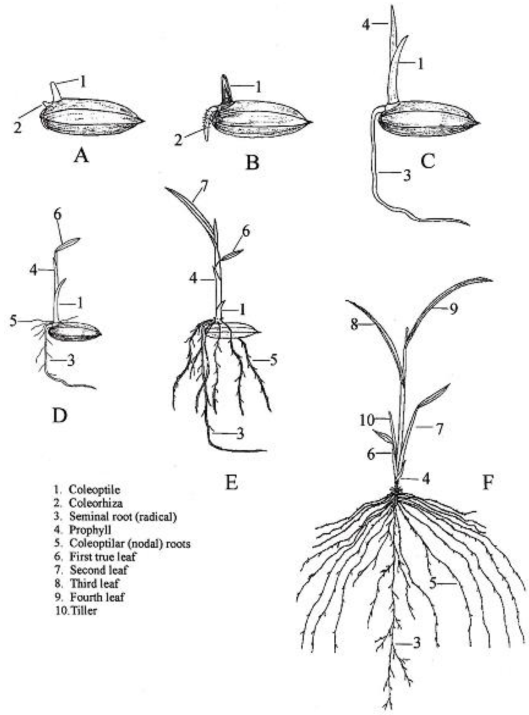


Figure 2.12 Seedling development under aerobic, light conditions (shallow upland seedling): (A) germinated seed; (B) developing coleorniza and coleoptile; (C) emerging prophyll and seminal root; (D) V1 growth stage; (E) V2 growth stage; (F) V4 growth stage (Smith *et al.,* 2002).

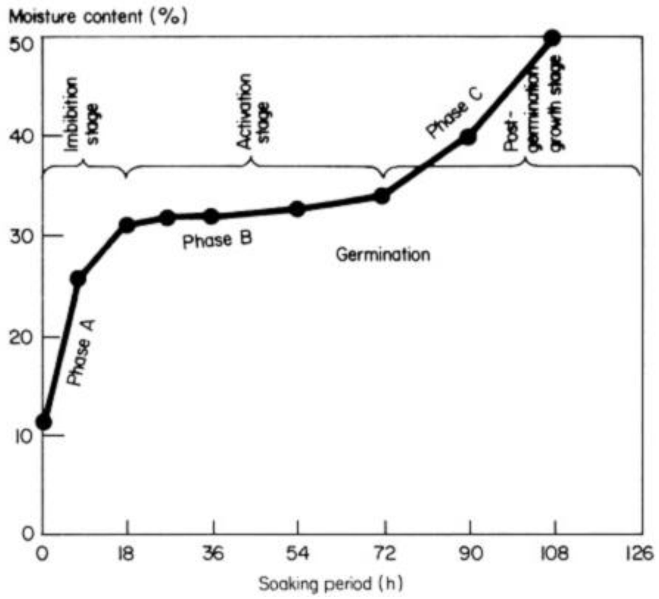


Figure 2.13 The pattern of water absorption during the germination of rice seed (variety: Ou-no 200) at 20°C on filter paper (Yoshida, 1981).

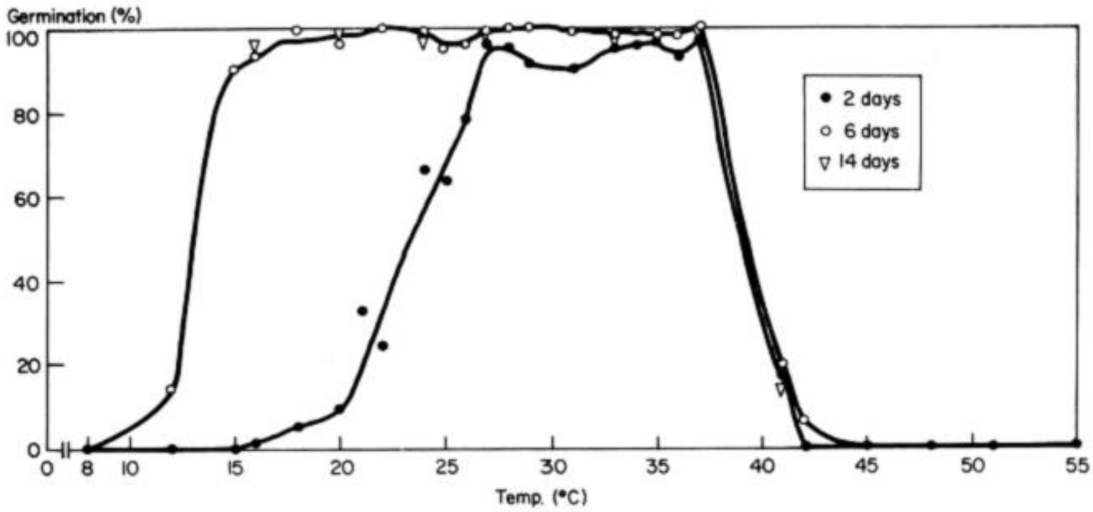


Figure 2.14 Germination percentages of rice seeds at different temperatures after 2, 6, and 14 days of incubation (Yoshida, 1981).

II. Seedling Development

Seedling growth continues after germination with extension of the coleoptile and coleorhiza, and the emergence of the prophyll and radicle. During this growth stage, rice seedlings exhibit great morphological plasticity in response to changes in aeration, light, and temperature. Rice is a semiaquatic plant and has many characteristics that facilitate establishment under either aerobic or anaerobic conditions.

Under the *aerobic conditions* of the water seedling, the coleoptile elongates without simultaneous development of other tissues. Emergence of the coleorhiza, seminal root, and prophyll are delayed (Figure 2.14) until the coleoptile emerges from the floodwater surface and oxygen levels to the root are increased. Oxygenation and root development also can be promoted by draining flood waters. Under anaerobic conditions, roots have been observed to develop few, if any, root hairs.

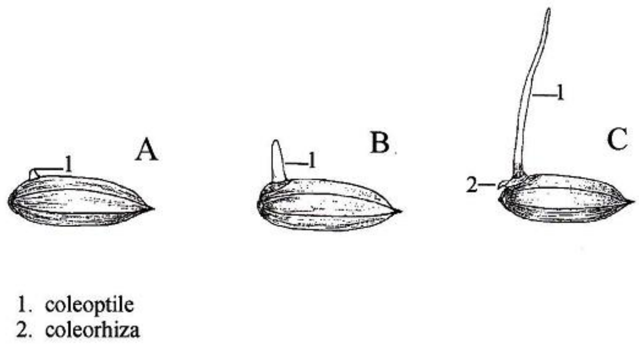


Figure 2.15 Seedling development under anaerobic conditions (water seedling) :
(A) germinated seed; (B) developing coleoptile; (C) developing coleoptile and delated coleorhiza (Smith *et al.*, 2002).

Light conditions affect mesocotyl elongation. With adequate light, or under conditions of shallow planting, the mesocotyl does not elongate (Figure 2.12D). However, in the dark, or under conditions of deep planting, the mesocotyl elongates to promote seedling emergence from the soil (Figure 2.16A). Under conditions of very deep planting, or chemical treatment, roots may develop from the mesocotyl (Figure 2.16B).

Environmental effects on coleoptile and mesocotyl elongation have been attributed to changes in the composition of the gaseous environment (oxygen, carbon dioxide, ethylene) and/or hydration. There are also pronounced cultivar differences in seedling response.

Temperature affects the rate of seedling growth. Effects are most pronounced during the first week of growth, when temperatures between 22 and 31 °C are required for linear growth rates. This reflects temperature effects on enzymatic activity associated with the breakdown of seed carbohydrate reserves. Following the first week, temperature effects on rice growth are less pronounced. Optimal temperatures are between 22 and 31 °C, with a critical maximum at 40 °C and a critical minimum at 10 °C.

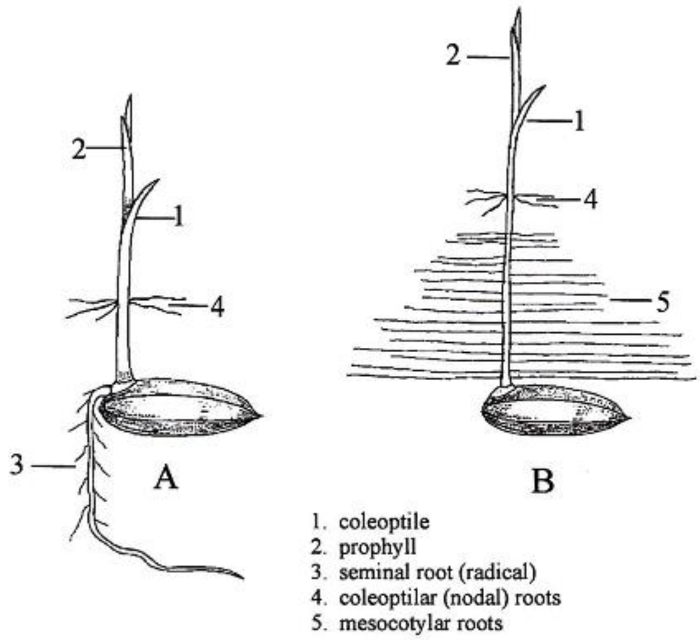


Figure 2.16 Seedling development under aerobic, dark conditions (upland seedling): (A) elongation of the mesocotyl at 1-inch planting depth; (B) further elongation of the mesocotyl with deeper planting, with possible development of mesocotylar roots (Smith *et al.*, 2002).

Plant growth stage can be determined by marking and counting leaves as they emerge. The first leaf to emerge from the coleoptile, the prophyll, is not a true leaf since it lacks a blade. It may or may not be counted as leaf 1 when describing shoot development. The first true leaf to develop is the second leaf.

The *V1 stage* is a seedling with a prophyll and a fully emerged first true leaf (leaf collar present). This seedling also has five roots from the coleoptilar node.

The *V2 stage* is defined by full emergence of the second true leaf and is synonymous with the *three-leaf stage* if the prophyll is counted as the first leaf. Seedlings at this stage have roots emerging from the first node. At this stage, plants become autotrophic, meaning that endosperm seed reserves are exhausted and photosynthesis contributes 100% of the carbohydrate used by the plant.

If seedlings have been grown completely in the dark, they will stop to grow beyond the *V2 stage.* If seedlings are grown in light, photosynthesis contributes to an increasing proportion of total carbohydrates with time. During the first week of growth, it contributed <30%; during the second week, it contributed >84%; and by approximately the third week (second true leaf) it contributes 100%.

The *V4 stage* is defined by full emergence of the fourth true leaf and is synonymous with the *five-leaf stage* if the prophyll is counted as the first leaf (Figure 2.12F). This growth stage is usually considered the end of the seedling stage. Seedling height is usually measured at this growth stage (Smith *et al.*, 2002).

III. Plant Growth Rate

Plant growth rate is determined by the rate at which leaves are initiated in the shoot apex. This is done in a rhythmic fashion. Before leaf initiation, the apical meristem widens, undergoes pronounced changes in shape, and then narrows again with the appearance of the new leaf primordium. This period of rhythmic change between the emergence of a successive leaf primordium is called the *plastochron.* The duration of plastochron change determines the rate of plant growth and development. In rice, the plastochron is not uniform throughout the life cycle of the plant and is also susceptible to environmental influences.

The rate at which leaves visibly develop on the main culm is called the *phyllochron*, which is strongly tied to the plastochron in rice and other grasses. Due to this synchrony, there is orderly shoot development. This synchrony also allows the leaf number to be used as a developmental index for plant growth. By knowing the total number of leaves that have developed on the main culm, one can relate a given leaf number to a particular growth stage for that variety. This system accurately identifies the onset of reproductive growth (panicle initialtion) and the developmental stage of the panicle prior to heading.

IV. Tillering

First tillering usually occurs at, or before, V4 (Figure 2.12F). Tiller and root emergence are delayed relative to the leaf. Leaves emerge visibly from a given shoot unit while the corresponding root and tiller primordial are just being initiated. The latter do not become visible protrusions until the leaf from the third node above beings to emerge. Thus for a given leaf that is emerging at the n^{th} node of the plant, there are crown roots and a tiller bud potentially emerging at the $(n\text{-}3)^{th}$ node. Although primordial for roots and tillers always are initiated by the plant, they do not always develop or may show delayed development.

Active tillering refers to the growth period when tillers emerge in rapid succession (and coincides with a phase of rapid leaf development). Tillers can potentially emerge three nodes below each emerging leaf, in a continuous pattern up the culm. These primary tillers emerge from unelongated internodes and result in a branching pattern that remains close to the ground. After the onset of reproductive growth, tillers do not develop from the upper three to five elongating internodes, but they may continue to develop from preexisting tillers to expand branching further in widely spaced plants.

Cultivars vary in tiller number as well as in earliness and vigor of tillering. Some cultivars tiller very early and profusely; others show delayed and/or sparse tillering. Tillering also is affected by plant spacing and soil fertility. When seeds are drilled or broadcast densely, and the plant density is high, maximum tiller number is low (one to three tillers per plant) and is reached within 30 days of seedling emergence (Yoshida, 1981). When planting densities are low, the tiller number increases (10 to 30 per plant) and the duration of tillering is extended. In turn, this, can stagger the development of mature panicles and may also be associated with high levels of ineffective tillers.

Tillering characteristics are important to yield, because they affect the number of culms per square meter, the uniformity of ripening in the field, and grain yields per panicle. Profuse tillering is considered disadvantageous, because it can cause excessive increases in leaf area, mutual shading, numbers of ineffective tillers, and lower yields by increased blanking. At the other extreme, the elimination of tillering at excessive planting densities does not increase yields either.

Moderate numbers of vigorous early tillers are considered the most advantageous. These tiller characteristics compensate for low stand densities under conditions of poor establishment and optimize yields by producing uniformly maturing panicles.

The basic processes in the life history of rice can be applied to any cultivation system with some modifications.

First, differences in growth duration are primarily due to differences in the length of the vegetative growth stage. The length of the reproductive stage plus the ripening period may be considered about the same for any variety under a given environment. Early maturing varieties have short vegetative stages. As a consequence, they may initiate panicle primordia before the maximum tiller number stage (Type A in Figure 2.17) and heading may be staggered because later tillers may produce panicles. Late-maturing varieties have long periods of the vegetative stage and may reach the maximum tiller number stage before the initiation of panicle primordia (Type C in Figure 2.17). The period from the maximum tiller number stage to initiation of panicle primordia is sometimes referred to as vegetative-lag phase. When the length of the vegetative stage is adequate, the plant initiates panicle primordia right after the maximum tiller number stage (Type B in Figure 2.17). In the tropics, this is normally attained by a 120-day variety.

Second, direct-seeded rice normally starts tillering earlier than transplanted rice because its growth proceeds without the setback caused by growth damage during uprooting. Each direct-seeded rice plant, however, usually produces 2–5 tillers while each transplanted rice plant produces 10-30. Thus, tillering is much less important in direct-seeded rice.

Third, the growth duration of the same variety may be slightly different between the transplanted and direct-seeded crops. Transplanted rice usually takes about 1 week more to mature because its growth has been disturbed by uprooting (Yoshida, 1981).

V. Root development

Development of primary roots during germination and seedling growth is described in earlier sections on root morphology and seedling growth. Root lengths in field grown rice show rapid linear increases during vegetative growth and reach maximum length by panicle initiation.

Root branching during vegetative growth is synchronized with leaf emergence. For a given leaf emerging at the n^{th} node and primary roots emerging at the $(n\text{-}3)^{th}$ node, there are many short secondary roots that develop from primary roots at the $(n\text{-}4)^{th}$ node. At the $(n\text{-}5)^{th}$ node, teriary roots begin to develop from secondary roots. This pattern continues, resulting in the fullest expression of branching in the older roots.

Soil aeration has a fundamental effect on root growth and overall morphology. Under upland, aerobic conditions, the roots develop hairs and grow downward, reaching rooting depths of 1 m or more. Under flooded, anaerobic conditions, there may be no root hair development, growth is more horizontal, and rooting depths seldom exceed 40 cm. Rooting depths are increased when soil densities do not restrict downward movement of floodwater and when flooding is delayed by 2 weeks (Smith *et al.,* 2002).

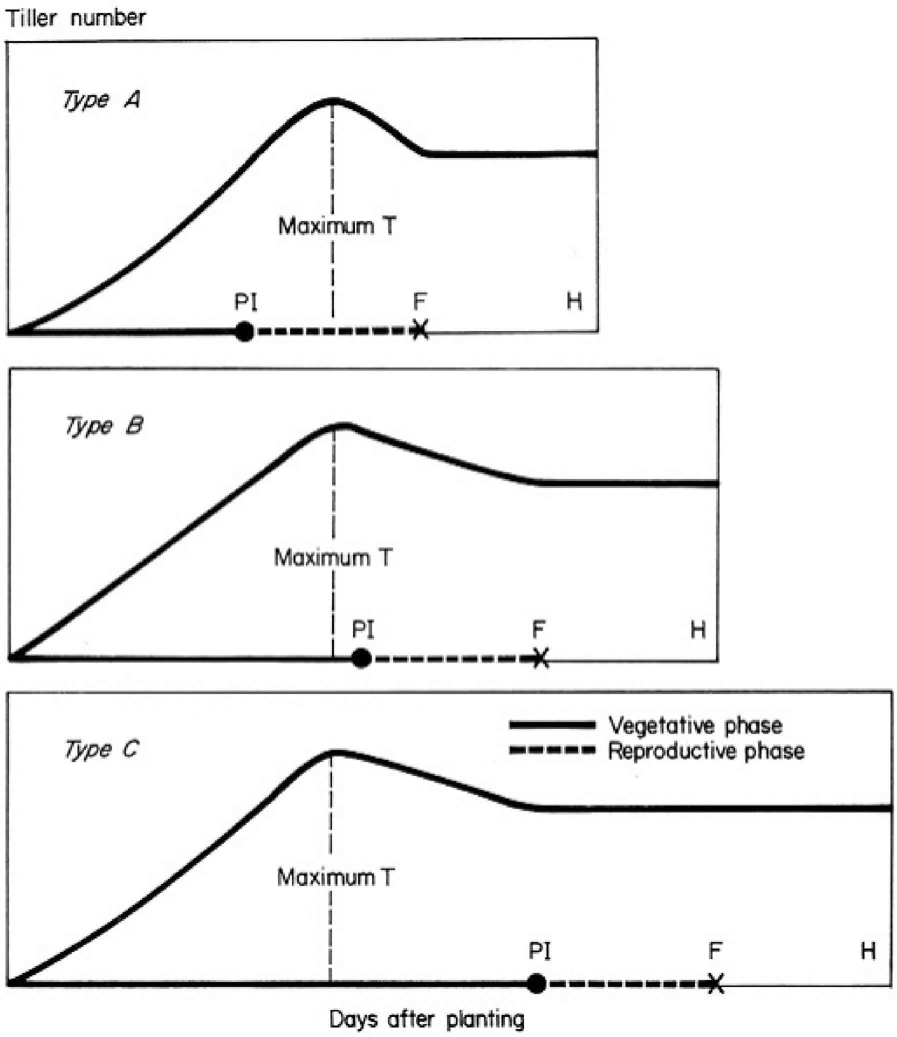


Figure 2.17 Phasal development of the rice plant (adapted from Tanaka, 1976). PI =panicle primordia initiation, F = flowering, H = harvest. Maximum T = maximum tiller number stage (Yoshida, 1981).

2.2.3.2 Reproductive phase

The reproductive phase, from panicle initiation (PI) through anthesis, is characterized by changes in vegetative growth characteristics and formation (differentiation) of the panicle. Internode elongation results in increased plant height, with a concomitant reduction in tillering and root growth. Leaf architecture during the reproductive phase is critical to optimizing yields and reducing lodging. Panicle formation is synchronized with the development of the uppermost four leaves on the culm. Environmental conditions and crop management directly influence the number of spikelets formed and pollen fertility (second and third yield components).

I. Internode Elongation

Internodes begin to elongate at, or near, panicle initiation (PI). In late-maturing cultivars, internodes may begin to elongate before panicle initiation, while in intermediate and short-season cultivars, internode elongation coincides with panicle initiation. Internode elongation also signals the beginning of the development of the final three to five internodes of the stem. Internode lengths increase from 2 cm in the first internode to elongate after PI to 30 cm in the final one (the peduncle of the panicle). The final and longest internode grows about 15 to 20 cm during the 2 days before heading and continues to grow for up to 2 days after heading. This is the greatest growth increment in the life of the plant.

II. Leaf development and canopy architecture

Leaves developing after panicle initiation can have different shape, erectness, and color relative to leaves developing during the vegetative phase. Thus, plants with long, droopy leaves during the vegetative phase may have short, erect ones during reproductive growth, and vice versa. Unless there are prolonged cloudy periods, lack of sunlight during early vegetative growth is not considered to limit rice yields. Large leaves during this stage of development have been considered advantageous because they favor crop establishment and competition with weeds. However, during reproductive growth, canopy light conditions are critical to optimizing yields. Erect leaves have been shown to optimize light interception and reduce mutual shading. Since light reduction in the canopy can increase panicle sterility as well as internode elongation mutual shading was linked directly to yield reductions and increased lodging. Thus the short-statured, erect leaved plant type was found to be fundamentally important to the development of high-yielding varieties of rice. The synchrony between development of the upper four leaves and the developmental stage of the panicle is described under panicle differentiation.

III. Tiller development

Early-maturing varieties have short vegetative stages, and panicle initiation either coincides with or may occur before maximum tillering. Heading may not be uniform within the plant because late tillers produce late panicles. Medium- and late- maturing varieties have long periods of vegetative growth and may reach maximum tillering well before panicle initiation. The period between maximum tillering and panicle initiation in late varieties is referred to as the *vegetative lag phase*.

The number of plants and the tiller number per plant determine the total number of panicles per unit area (first yield component). There is often a trade-off between tiller number and panicle size: few tillers with large panicles versus many tillers with small panicles.

Late-maturing tillers can lower head rice yield by the reduction of milling quality. The first three tillers mature about the same time as the main culm, but additional tillers may mature progressively later and have reduced milling quality.

IV. Root development

Root growth typically remains constant from panicle initiation to heading. This has been observed with respect to root numbers emerging from a given node as well as total root length measurements. Roots developing at this time in flooded rice typically have a horizontal, shallow-growth habit, forming a root mat at the soil surface.

V. Panicle formation

Panicle initiation marks the onset of the reproductive phase and begins with the first (microscopic) differentiation of the bract primordial at the shoot apex. The timing of this event is about 30 (±2) days prior to heading in most intermediate-maturing cultivars. In early-maturing cultivars, panicle initiation can occur only 15 days before heading. Panicle initiation is not visible to the naked eye. The first visible sign that is briefly visible at the lowermost internode prior to its elongation. This is the agronomic definition of panicle initiation and is used to time management practices.

Panicle differentiation stage is an agronomic term referring to the growth stage where panicle formation is first visible. It occurs when the panicle is 1 to 2 mm long and the internode below it has elongated 1 to 2 cm (Figure 2.18). This stage is often referred to as the *half-inch elongation stage*. It usually occurs 3 to 5 days after microscopic panicle initiation. The process of *panicle differentiation* is from initiation until heading. This process is synchronous with leaf development (Table 2.3) (Smith *et al.*, 2002).

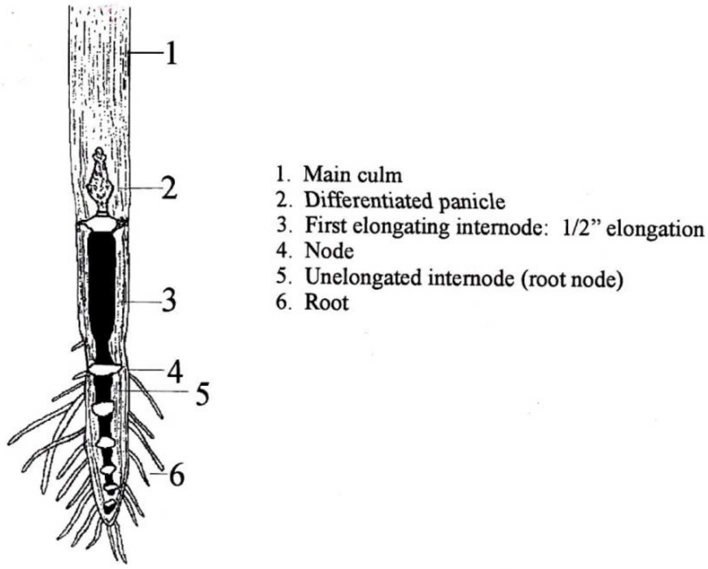


Figure 2.18 Cross-section of the culm at agronomic panicle differentiation stage. Panicle is 1 to 3 mm long; the first internode below has elongated ½ in (Smith *et al.,* 2002).

Table 2.3 Synchrony of panicle differentiation with leaf emergence (Smith *et al.,* 2002).

Leaf number from top	**Panicle developmental stage**
Fourth leaf	Necknode differentiation, initiation of panicle primordial
Third leaf	Branch differentiation
Second leaf (penultimate leaf)	Spikelet differentiation
First leaf (flag leaf)	Microsporogenesis, pollen formation

The last process to occur prior to heading is microsporogenesis and pollen formation. Microsporogenesis can be estimated morphologically by the movement of the flag leaf. Meiosis begins when the flag leaf auricle is 3 cm below the auricles of the penultimate leaf (flag leaf auricle still within the sheath, but flag leaf blade partially emerged). The end of meiosis coincides with the auricle of the flag leaf reaching 10 cm above the auricle of the penultimate leaf, without hasing fully emerged.

The period of panicle formation represents a very vulnerable period in the growth of a rice plant. During this period, environmental factors such as temperature extremes, drought, nutrient deficiencies, or toxicities can reduce the numbers of panicle branches and/or spikelets and reduce pollen viability. This affects directly the second and third yield components (i.e. number of spikelets and percentage of filled grains).

Booting is the period where the leaf sheath visibly thickens during panicle formation. The panicle doubles in size every 3 days during its formation, and booting is generally defined by the first visual evidence of panicle swelling within the leaf sheath. It can also be defined as beginning 10 to 13 days after PI or 6 days prior to heading.

Heading means panicle exsertion from the flag leaf sheath. There is variability in heading among the culms of a single plant and between plants in the same field. Thus, crop heading may take as long as 14 days. When the tiller number is small and/or planting densities high, the crop heading time is relatively short (4 to 5 days) and heading is uniform. When tillering is prolonged under sperse planting, crop heading is prolonged. Agronomically, heading is defined as the time when 50% of booting culms have partially exserted panicles. The degree of panicle exsertion is a genetic characteristic of the plant (Figure 2.19) that is selected for in breeding programs since poor panicle exsertion can lead to increased disease incidence.

Anthesis (flowering) begins with panicle exsertion or on the following day. As the panicle emerges, spikelets at the uppermost tip of the panicle begin to undergo anthesis and proceeds in a descending order down the panicle. It can take 7 to 10 days for all the spikelets on the panicle to complete anthesis, with most completed within 5 days. Anthesis refers to events between the opening and closing of the spikelet (floret). It lasts 1 to 2.5 hours and usually occurs between 9.00 A.M. and 2.00 P.M. At lower temperatures and on cloudy days, anthesis may begin later and take longer, lasting well into the afternoon. It can be inhibited completely by temperatures below 22 °C or above 32 °C, causing sterility.

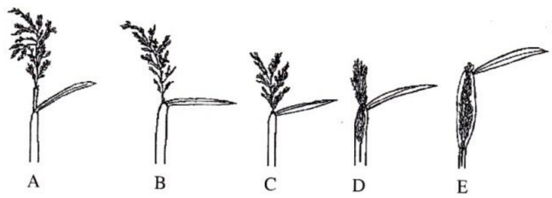


Figure 2.19 Categories of panicle exsertion: (A) well exserted; (B) moderately well exserted; (C) just exserted; (D) partly exserted; (E) enclosed (Smith *et al.*, 2002).

During anthesis, the spikelet opens with a movement of the lemma. Anthesis filaments elongate and are exserted, and the tip of the feathery stigma may become visible. Anther filaments continue to elongate to bring the anther completely past the tips of the lemma and palea. Then the spikelet closes, leaving the anthers outside to die. Anther dehiscence (pollen shed) occurs just before, or as, the palea and lemma open. Pollen grains thus fall onto the stigma, resulting in rice being predominantly self-pollinated. Once outside the floret, pollen grains are released into the air and may blow to other spikelets. However, since self-pollination precedes cross-pollination, the fraction of cross pollinations is only 1 to 4% on average. Pollen grains are viable for only about 10 minutes after dehiscence, whereas the stigma can be fertilized for 3 to 7 days. Fertilization of the ovary by the pollen grain generally is completed within 5 to 6 hours after pollination. Once pollination is completed, the ovary becomes a rice grain.

2.2.3.3 Ripening phase

I. Grain-Ripening Process

Grain ripening begins 3 weeks after fertilization and usually takes 25 to 50 days. It is accompanied by senescence of leaves and roots. The steps in the ripening process are :

- *Milk stage.* Developing starch grains in the kernel are soft and the interior of the kernel is filled with a white liquid resembling milk.
- *Soft dough stage.* Starch is beginning to form, but is still soft.
- *Hard dough stage.* Whole kernel is firm, moisture content is greater than 20%.
- *Mature.* Whole kernel is hard and moisture content is less than 20%.

Rice yield is usually reported as rough rice at 14% moisture.

During ripening, grain growth is characterized by increases in size and weight despite fresh weight decreases due to water loss from 58% to 20%. All plant parts, including grain, also undergo a color change from green at early stages to brownish at maturity.

Most Arkansas cultivars ripen in 35 days, with the exception of some medium-grain cultivars that require 45 days (Mars) and short-grain cultivars that require 50 days (Nortai). Cool temperatures can extend the ripening period to 60 days. Cool temperatures can extend the ripening periods, which are associated with higher yields due to increased grain weights and/or improved grain quality with respect to starch packing. Rapid seed filling results in loose packing of starch granules, and higher incidence of chalky grains.

II. Senescence

The five upper leaves provide photosynthate to the ripening panicle with the flag leaf being the primary supplier. These upper leaves have the longest physiological lifespan on the plant. In some cultivars, they remain green throughout the ripening phase.

Root length measurements decline after heading. This has been attributed to senescence, a decrease in the numbers of roots emerging from nodes, and a change in root morphology. During this developmental stage, emerging roots have been observed to be shorter and to have more branching near the root tip. This gives them a “lion’s tail” appearance. These superficial roots are especially conductive to root mat formation (Smith *et al.,* 2002).

2.2.4 Environment Conditions

2.2.4.1 Rainfall

In most tropical countries, paddy cultivation is entirely dependent on seasonal rainfall. In fact, the water supply for about 80 per cent of the world’s area planted to paddy comes directly from rainfall. Most tropical South-east Asian countries receive more than 2000 mm rainfall annually. The high variability of tropical rain renders the success of paddy cultivation uncertain in areas other than the great deltas and basins of large rivers such as the Mekong, Irrawaddy, Chao Phraya, Brahmaputra, Ganges and Indus, where the major problem is drainage.

There is no relationship between the total quantity of rain and yield. Countries such as Egypt, Italy, Australia and the United States are characterized by moderate rainfall, but provided with irrigation facilities, whereas in parts of Bangladesh, Burma, Thailand, Cambodia and Vietnam and a number of other countries, there is often too much rainfall during the season. Drainage is therefore impossible, planting delayed and carried out in deep water with overgrown seedlings. Crops, therefore, suffer from poor planting conditions as well as floods in their active growing stage.

The view that a paddy requires a humid atmosphere is probably erroneous, for in many countries, such as Egypt, California and parts of Japan, where growth and yields are satisfactory humidity is very low. In parts of northern India and Pakistan irrigated paddy is grown in areas of less than 280 mm rainfall. Paddy, however, provides its own micro-climate, raising the relative humidity within the crop much above that of adjacent unirrigated areas (Grist, 1986).

2.2.4.2 Temperature

Temperature, along with photoperiods, is the main driving force for crop development. The optimum temperature for the normal development of rice ranges from 27 to 32 °C (Table 2.4) (Shah *et al.*, 2011).

Yoshida (1981) studies that subject to varietal and stage growth differences, air temperatures above 35 °C adversely affect plant growth, as the plant is most sensitive about nine days before flowering. The occurrence of sterility is attributed to disturbed pollen shedding and impaired pollen germination but not to an inactivated pistil.

Table 2.4 Response of the rice plant to varying temperatures at different growth stages (Yoshida, 1981).

Growth stage	Critical temperature [a] (°C)		
	Low	High	Optimum
Germination	10	45	20–35
Seedling emergence and establishment	12–13	35	25–30
Rooting	16	35	25–28
Leaf elongation	7–12	45	31
Tillering	9–16	33	25–31
Initiation of panicle primordia	15	-	-
Panicle differentiation	15–20	38	-
Anthesis	22	35	30–33
Ripening	12–18	30	20–25

[a] Refers to daily mean temperature except for germination.

2.2.4.3 Wind

Considering the great damage to the paddy crop in many countries occasioned by high winds, it is surprising that, outside Japan, where annual typhoon damage to the crop is estimated at 3 to 6 per cent, winds in relation to rice production have attracted little research. While gentle winds are probably beneficial to the crop, strong winds, especially of long duration, have an adverse effect on, yields of grain. It causes plants to lodge and in so doing impedes the translocation of nutrients to various parts of the plant, ripening is delayed, shattering encouraged and grains germinate in the ear. The damage is related to wind velocity, duration, humidity and temperature, the variety of rice, its growth stage and cultural conditions. If damage occurs before heading, there will be a decrease in the number of spikelets. A heading, the number of empty glumes increases or brown-colour grains form due to non-fertilization. High wind is particularly damaging when it occurs five to ten days after heading since it increase the number of abortive endosperms.

In areas subject to strong winds, rice varieties resistant to lodging and shattering should be planted and the application of nitrogenous fertilizers restricted. Deep submergence will minimize damage by avoiding violent waving of stems and leaves.

2.2.4.4 Light

Light plays an important role in the growth and yields of paddies. The investigation established the fact that the number of tillers and ears increase with the intensity and quantity of light, while the yield response to high levels of nitrogen occurs only when the crop receives high light levels. Light is not necessarily a limiting factor to growth in the early stages of growth but becomes progressively more critical with age of the plant and particularly so at panicle differentiation. Shade has been observed greatly to retard the attainment of the 'critical' stage of tiller formation. The shading causes a decrease in the number of spikelets per panicle but does not affect the percentage of fertile grains. Leafy varieties may produce better yields at low fertility levels but will fail to respond to high nitrogen application. New rice varieties having short, narrow and upright leaves are being developed to utilize sunshine more effectively.

The sum of the hours of sunshine required throughout the growing period of a paddy is 1,200 hours. Necessarily, the figure will depend on the maturation period of the variety of rice.

2.2.4.5 Length of daylight

The rice growth responds to daylength. In warm-temperate zones, it grows in the summer months when there is a difference of up to four hours between the lengths of the day and the night, while in the tropics the maximum difference is about one hour. Based, therefore, on their response to daylength (photoperiod), rice varieties are grouped as sensitive and non-sensitive. Sensitive varieties flower when the daylength is decreasing and when it reaches a critical value for induction of the flowering stage. The inducement of flowering by the shortening daylength influences their ripening period. Non-sensitive varieties do not respond to differences in photoperiod, their length of life being independent of daylength so that they can be grown at any season. Among sensitive varieties, there are variations in the degree of response to photoperiods (Grist, 1986).

2.2.5 Rice production

2.2.5.1 Global rice production

In the years since World War II, world rice area, yield, and production have changed considerably (Table 2.5). From 1948 to 1990, the area planted for rice increased by almost 71%, the mean yield obtained from that area went up by 110%, and total production more than tripled. During those four decades, rice became ever more important as a human food. World rice demand is predicted to increase at about 1% per year from 2001 to 2025, roughly equal to population growth in Asia during that period.

Table 2.5 World rice area, yield, and production, various years (Maclean *et al.*, 2002).

Year	Arable land + permanent crop [a] (10^3 ha)	Rough rice		
		Area (10^3 ha)	Yield (t/ha)	Production (10^3 t)
1948	1,232,000	86,700	1.68	145,400
1953	1,332,000	109,025	1.82	197,906
1958	1,390,000	117,017	1.92	224,093
1963	1,355,864	120,277	2.05	247,139
1968	1,377,311	129,449	2.23	288,714
1973	1,397,696	136,824	2.45	334,988
1978	1,423,870	143,638	2.68	385,106
1983	1,454,147	143,074	3.14	449,048
1988	1,497,719	146,252	3.34	488,292
1993	1,504,732	145,811	3.63	529,803
1998	1,380,239	152,002	3.81	578,786
1999	1,511,766	156,462	3.88	607,780
2000	1,511,766	153,766	3.89	598,852

[a] This column reports land in both temporary and permanent crops. Source of basic: FAO production yearbook, 1952; FAOSTAT database.

From 1965-67 through 1989-91, the improvements in productivity spawned by the Green Revolution spread rapidly. During those years, total rice production almost doubled. Most of this increase came from increases in yields and cropping intensity, although some resulted from new land brought under cultivation or shifted into rice from other crops. Much of the yield increase could be traced to the introduction of the dwarfing gene and to the increased use of fertilizer, irrigation water, and other inputs. Further yield increases have been constrained by diminishing returns and have been increasingly difficult to achieve.

Of the global rice yield in 2011, 90.4% was in Asia, 3.6% was in Africa, 3.3% was in South America, 1.6% was in North America, 0.6% was in Europe and 0.5% was in Oceania and Central America, as shown in Figure 2.20.

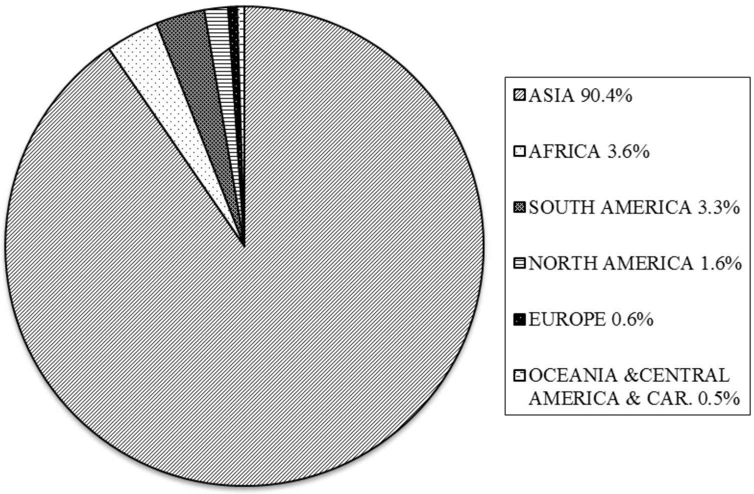


Figure 2.20 Rice yield share of the world in 2011 (FAO, 2010).

Most of the rice yield of the countries in 2011 are 197.2, 144, 66.5, 50.3, 40.0, 36.0, 30.8 and 16.7 million tonnes in China, India, Indonesia, Bangladesh, Vietnam, Thailand, Myanmar and the Phillippines, as shown in Figure 2.21

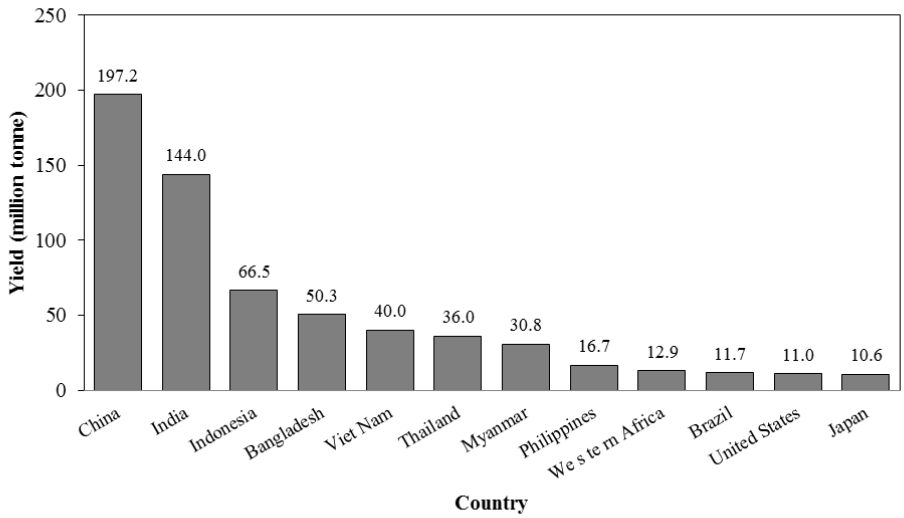


Figure 2.21 Rice yield of each country in 2011 (FAO, 2010).

The highest rice yields have traditionally been obtained from plantings in high-latitude areas that have long day lengths and where intensive farming techniques are practiced, or in low-latitude desert areas that have very high solar energy levels. Southwestern Australia, Hokkaido in Japan, Spain, Italy, northern California, and the Nile Delta provide the best examples (Maclean *et al.*, 2002).

2.2.5.2 Rice growing areas

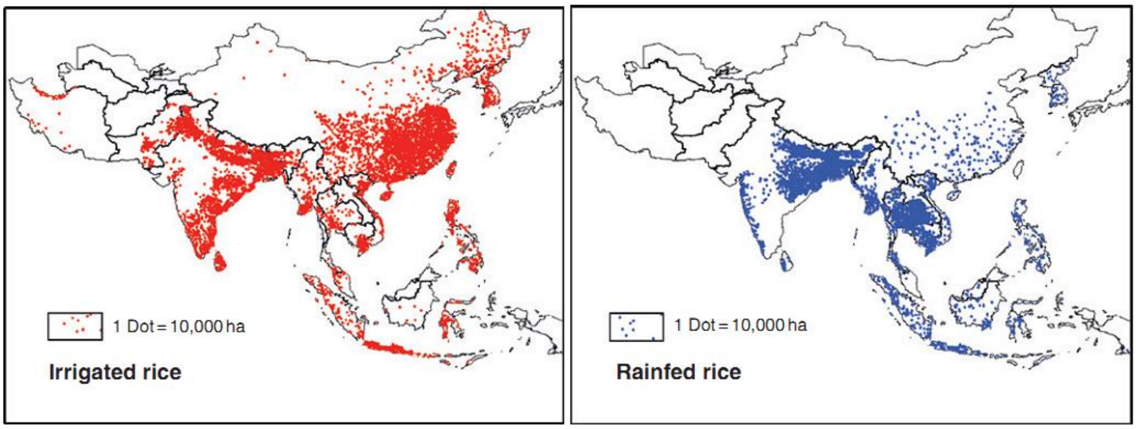


Figure 2.22 Irrigated and rainfed rice in East, South and Southeast Asia (Wassmann *et al.*, 2009)

The rice plant flours under such widely differing climatic conditions such that it is difficult to define those most suitable for its development. Yields obtained when the crop is grown in subtropical and warm-temperate climates are almost invariably higher than when grown under fully tropical conditions. This is attributable to the longer daylength during the growing period, the varieties grown, coupled with the occurrence of cold winters which may favourably influence soil conditions. Moreover, in most subtropical and warm-temparate countries where rice is produced, paddy forms part of a regular rotation, a feature which is most certainly conducive to high yields. In fact, the highest yields are recorded between 30 and 40 °N. The area within latitudes 45 °N and 40 °S, where the most extensive areas under the crop are found, embraces Central America, the entire continent of Africa, the whole of Australia, India, most of China, Japan, the Malay archipelago and the Pacific islands. The areas cultivated at considerable elevations is small because in such region there are difficulties in water supply and control and in finding extensive areas of reasonably flat land (Grist, 1986).

Ninety percent of the world's rice is produced and consumed in Asia, where irrigated and rainfed rice ecosystems form the mainstay of food security in many countries (Figure 2.22) (Wassmann *et al.*, 2009).

2.2.5.3 Types of Cultivation

Rice ecosystems are divided into four cultivation practices: upland, rainfed lowland, flood-prone, and irrigated.

Upland rice is grown with small amounts of external inputs in unbunded fields. The soil may be cultivated when dry and planted by direct seeding. Upland rice is also dibbled directly into the uncultivated soil after land clearing and burning. Surface water does not accumulate for any significant time during the growing season. Landforms for upland rice vary from low-lying valley bottoms to undulating and steep sloping lands with high surface runoff and lateral water movement. Upland rice constitutes only 10% of the global rice area and 3.8% of total world rice production. The countries with the largest upland rice areas are India, Brazil, and Indonesia (Dobermann and Fairhurst, 2000).

Rainfed lowland systems have rice direct seeded in puddle soil on level, slightly sloping, or diked (i.e. bunded) fields. The depth and duration of flooding is dependent on local rainfall, so the system is subject to yield fluctuations. The difference between this approach and the upland pluvial rice cultivation is solely one of topography (Trinkley and Fick, 2000). Rainfed rice accounts for around 25% of the world's total rice land. Rainfed lowland rice is found in Asia. It is the most common system in the subhumid subtropics (Eastern India, Myanmar, Thailand) and large parts of the humid tropics (Bandladesh, Cambodia, Loa PDR). The counties with the largest rainfed lowland rice areas are India, Thailand, and Bangladesh.

Flood-prone rice is grown in inland and ridal (coastal) wetland areas where the depth of floodwater is >50 cm throughout the growing season. It is found in South and Southeast Asia. Rice grown under such conditions must be adapted to a temporary submergence of 1-10 days, long periods (1-5 months) of standing (stagnant) water ranging in depth from 50 to 400 cm or more, or daily tidal fluctuations that sometimes also cause complete submergence. Rice yields are very small and very variable mainly due to poor soils and the unpredictable incidence of drought and flooding. The flood-prone ecosystem accounts for only 4% of global rice production (Dobermann and Fairhurst, 2000).

Irrigated rice cultivation requires that rice be transplanted or directly seeded in puddled soil on level fields with water control, generally in lowland areas (Trinkley and

Fick, 2000). Irrigation is the main water source in the dry season and is used to supplement rainfall in the wet season. Irrigated rice accounts for 55% of the global harvested rice area and contributes 75% of global rice production. Irrigated rice is found in East Asia (China, Taiwan, Japan, Korea), South Asia, and Southeast Asia. The countries with the largest areas of irrigated rice are China, India, Indonesia, and Vietnam (Dobermann and Fairhurst, 2000).

2.2.5.4 Methodology of Rice Production

2.2.5.4.1 Upland Rice

Upland rice refers to rice grown on both flat and sloping fields that are not bunded, that are prepared and seeded under dry conditions and that depend on rainfall for moisture.

Land Preparation. – In most of Asia, little mechanization is used to prepare land for planting. As soon as enough rain has fallen to permit initial land preparation, the field is plowed with an animal drawn implement, and then harrowed with a comb harrow to prepare a good seedbed and to firm up the soil. Sometimes the weed seeds are allowed to germinate for a week, and then the field is harrowed for the final time, destroying all germinated seeds. The methods vary greatly from country to country in Latin America. In the shifting cultivation areas of Peru, for example, mature secondary forests are cut and burned during the drier months from July to September. Upland rice is then seeded by dibbling without further land preparation. Shifting cultivation in Peru is quite similar to the slash-and-burn methods that precede planting in Malaysia, Burma and Thailand.

Sowing Time, Methods, Seed Rate and Row Spacing. – Upland rice farmers have learned though experience to plant early where rainfall distribution is unimodal and the rainy season lasts about 4 mouths. Upland rice gives the highest grain yield and the best nitrogen response if planted shortly after the first monsoon shower. In the shifting cultivation areas of Asia, the land is cleared by the ‘slash and burn’ method and seeds are then dibbled into the soil. In West Africa, rice is sown by broadcasting or dibbled. On the 40% of the upland area with annual rainfall of less than 1500 mm, seeds are dibbled into rows made with a pointed stick or a narrow bladed hoe. On the 60% that has more than 1,500 mm annual rainfall, seeds are broadcast in dry soil. Seeding methods vary greatly among Latin American countries. In Peru, 8 to 10 rice seeds are normally planted in holes dug with a pointed stick at irregularly wide spacings, about 50 x 50 cm. the seeds are not covered with soil.

Variety and Fertilizer Application. – The taller types are favored for upland rice. Regardless of varietal type, it is better to apply nitrogen in split doses to minimize lodging and to obtain maximum fertilizer nitrogen efficiency. Results further indicate that banding the fertilizer close to the seed (10 cm deep) greatly helps increase nitrogen efficiency in upland rice. In phosphorus deficient areas, banding of both nitrogen and phosphorus complements and increase the efficiency of both elements under upland rice culture.

Harvesting. – Over the world, the major portion of rice is harvested by hand sickle, because it can be done under a wide range of weather and field conditions, is adapted to small plots where rice maturity varies from plot to plot, can harvest as panicles ripen, and can eliminate weeds from the harvested material. In highly mechanized rice producing areas, rice is harvested entirely with high capacity self-propelled combine harvesters but often inoperable under these conditions.

Threshing of hand-harvested sheaves usually requires adequate pre-threshing or post-threshing drying (Bor, 1996).

2.2.5.4.2 Rainfed Lowland Rice

On most unirrigated farms, rice is grown during the wet season and the land lies fallow or is planted with low input crops through the dry season. Because of the farmers' dependence on both the fickle monsoon rains and conventional late maturing rice varieties, this has been the only feasible cropping system for centuries. The practices followed are much more complex and variable in rainfed lowland areas than in irrigated areas.

- **Transplanted Rice. -** The onset of the monsoon determines the planting time, and thus, the day length and solar radiation available during the growing period. In lowland rice culture, transplanting is the major system of rice culture.

Land Preparation: Effects of puddling and flooding. The traditional method of preparing land for transplanted paddy rice consists of plowing and puddling the soil. The method has been widely adopted because it greatly reduces the weed population. In addition, puddling substantially increases the amount of water retained by the soil and reduces the amount of water lost through percolation.

Plant Spacing. In monsoon Asia, high tillering cultivars are very desirable for the culture of transplanted rice. Cultivars with improved plant type and high tillering capacity can be planted at a wide range of spacing and still produce an adequate number of tillers per unit area. The tiller number per unit area in a rice population is largely a function of planting density. The tiller number is correlated with grain yield either positively or negatively depending on the rice cultivar and crop environment.

Water Management and Moisture-stress effect. Rice requires adequate water to grow and develop at its maximum potential rate. Unlike other crops, rice is usually grown in flooded soil. With an adequate water supply from rain, continuous flooding from 5 to 7 cm of water is desirable on most soils for the best moisture supply. It also gives the best weed and insect control with granular chemicals and high nutrient availability with minimum loss of nutrients from fertilizer and soil. Thus, wherever possible, flooding from 5 to 7 cm should be maintained even in rainfed rice. It is imperative that levees be kept in good repair to minimize surface runoff of excess water when it rains.

In rainfed areas, the paddies often become dry and the crop suffers from various degrees of moisture stress. Moisture stress is perhaps the chief factor that limits economical and stable yields of rainfed rice.

Fertilizer Management. The development and dissemination of fertilizer responsive cultivars of rice has encouraged a steady increase in the use of fertilizer in the development world. Fertilizer responsiveness is a key factor in differentiating among the traditional rice and the new high yielding cultivars. Only where the levels of fertility are at least modest, do yield differences between the new and the old become significant. Without fertilizer, the new cultivars yield little better than do the old. In contrast, with fertilizer, the yield potential is often double or even triple that of the traditional ones.

Several factors determine fertilizer efficiency in rice. A few that influence the level of fertilizer efficiency achieved at the farm level are soil, cultivar, season, time of planting, water management, weed control, insect and disease control, cropping sequence, sources, and rates and time of fertilizer applications.

A great deal of attention has been devoted to the evaluation of the relative merits of various fertilizers for lowland rice. The yield response of rice to different sources of nitrogen is affected by soil conditions and management practices, particularly water management, and the time and method of nitrogen application. The best time to topdress nitrogen is at tillering (20-30 days after transplanting) and at panicle initiation.

The sources, method and time of application of phosphorus and potassium would not be any different for irrigated and rainfed areas. Generally, rainfed rice needs more phosphorus than irrigated rice does. This is because more phosphorus is brought into solution under good water conditions, such as continuous flooding, than under rainfed rice culture where moisture stress is a factor affecting nutrient availability.

Weed Control. – In many rainfed areas, water accumulates in the bunded field as the crop grows. In other situations, the crop starts as a lowland crop and finishes as an upland crop. With those uncontrolled water conditions, weeds generally develop in large numbers and greater diversity of species than with rice grown in puddled soil under good irrigation.

Lack of water control is a major practical management factor that increases the amount of labor required for weeding. Precise water management with continuous flooding is ideal for a number of reasons, particularly to minimize weed growth. Since most fields in South and Southeast Asia could not be flooded continuously, indirect and direct complementary practices are essential for effective weed control at the farm level.

Under the existing conditions of high weed density, relatively low cost of labor and the availability of some chemicals, the necessity of weed removal is more important than how it is achieved. In the Asia tropics, either hand weeding or use of a rotary weeder is effective in rainfed transplanted rice fields, although both are tedious, time consuming and somewhat expensive. Or selective herbicides are somewhat more effective against a wide spectrum of weeds, particularly under the area of relatively poor water control.

Insect and Disease Control. – The control of rice insect pests depends largely on the use of pesticides. For diseases of rice, chemical control of blasts or of the vectors of virus diseases is possible, though this control is neither practical nor economical. Cultigenic resistance to these diseases and to the vectors of virus diseases is the only economic solution to these problems.

Harvesting and Threshing. – In the Asian tropics, in the past, harvesting was done by hand. The straw was usually cut about 15 to 25 cm above the ground, although in some areas, particularly Indonesia and some upland rice areas in the Philippines, the panicles were clipped off with a sharp knife. Nowadays, harvesting is done by machinery.

In the past time, the threshing was done by hand by beating the rice heads on a perforated platform made of bamboo. Occasionally, threshing was done by having animals tread on the harvested rice crop. Threshers are rarely used in tropical Asia. Nowadays, threshing is done by machinery.

- **Direct Seeded Lowland Rice.** – Directly seeded lowland rice culture is an important system for the Asian tropics. Pre-germinated seeds are broadcast onto puddled fields without much standing water. Direct seeding is done primarily by broadcast methods. Fields are prepared under wet conditions. The degree of pudding depends on the amount of moisture accumulated from the rain. Stand establishment is often poor because of poor land preparation and insufficient water control.

Water Management. – Water control is more critical for broadcast seeded rice than for transplanted rice. For better stand establishment, it is best that the field be kept saturated, but not flooded, from the time of seeding to about 6 days after. Due to the lack of precise water control, germinating rice seeds are often covered with muddy water thereby reducing stand. When that occurs, it is best to reseed with pre-germinated seeds in the areas where germination is poor.

Weed Control. – In this system of rice culture, weeds grow alertly. Selective herbicides would control weeds under rainfed rice culture.

Other Cultural Practices. – In rainfed areas, fertilizer application, insect control, harvesting and threshing will not differ markedly between directly seeded and transplanted rice culture (Bor, 1996).

2.2.5.4.3 Flood Prone Rice

Deep water rice or flood prone rice, the ecosystem (0.5-2.5 m depth) normal lowland rice varieties fail to grow successfully. Prolonged waterlogging for most part of the crop growth reduces tillering and normal growth of the rice crop, sometimes flash flood inundates in standing crop for 8-10 days at a stretch, resulting in mortality. To overcome that problem, deep water rice varieties were introduced in the seasonal waterlogged areas. These varieties have to adopt more complex ecosystem than those of rice of other ecosystem, which changes from rainfed upland conditions with drought in the early growth stages to a deeply flooded condition with variable flooding patterns during the rest of the growth cycle. Deep water rice grows under rainfed dry land conditions for 1-1.5 months before the onset of flood, when plant produces basal tillers. With inundation, the plant becomes an emergent microphyte and grows in an aquatic environment for the remaining 3-4 months of its life. Nodal roots absorb nitrogen, phosphorous and probably other nutrients from floodwater. Stem elongation is stimulated by partial submergence; it results from cell division and the elongation of cells in the control of two complementary genes. The performance of deep water rice varies in waterlogged situations.

2.2.5.4.4 Irrigated Rice

In irrigated areas of the world, rice is grown as follows: transplanted, direct seeded onto puddled soil, drill seeded into dry soil and direct seeded into water. The cultural practices in these systems of rice culture often vary a great deal. This report describes specifically to transplanting and direct seeding onto puddled soil.

- **Transplanted Rice.** – Most of the rice in irrigated areas of Asia.

Land Preparation. – Land preparation for irrigated transplanted rice is no different from that for rainfed transplanted rice as discussed earlier. The water requirement for land preparation in the lowland field varies from 150 to 200 mm.

Water Management. – Rice requires adequate water to grow and develop at its maximum potential rate. Submergence has other advantages, however, such as better weed control, higher efficiency of fertilizer, and better insect and weed control with granular herbicide. Considering all factors, continuous submergence with 5 to 7 cm of water is probably the best for irrigated rice.

Fertilizer Management. – Much of the fertilizer nitrogen applied for a rice crop is not taken up by the rice plants. Depending upon soil type, and the method and the time of fertilizer application, 20 to 60% of the fertilizer is utilized by the crop in a given growing season. Some of the remainder is combined with organic forms by soil microorganisms in the soil, and may be released too late for crop uptake.

There are 2 stages in the growth of transplanted rice at which the efficiency of fertilizer nitrogen utilization appears to be the highest. One is soon after transplanting to encourage maximum tillering. The second is just before or at panicle initiation to encourage the maximum number of panicle and grain numbers per panicle. It was shown that for 2 lines with medium maturity requirements (between 124 and 127 days), fertilizer nitrogen supplied just before panicle initiation gave the highest efficiency of use. The shorter seasoned line showed highest efficiency after basal application but responded well to the treatment applied just before panicle initiation.

Water management may directly affect the efficiency of nitrogen utilization by lowland rice. When topdressing with nitrogen, it is generally believed that temporary drainage is necessary to bring the fertilizer material in contact with the soil particles. The data have shown that if the water depth of the field is maintained at 5 cm, temporary drainage at the time of nitrogen topdressing does not necessarily result in increased grain yields, so it is not recommended in areas where there is no assured water supply.

Yield differences do not always correlate with differences in nitrogen uptake. The proper placement of nitrogen fertilizer within the flooded system is of extreme importance. Fertilizers containing ammonium nitrogen are stable provided they are placed 8 to 10 cm below the surface of the flooded rice field. This is because microorganisms capable of oxidizing ammonium nitrogen cannot function in an oxygen deficient reduced zone. Fortunately, rice readily uses ammonium as well as nitrate nitrogen.

In general, phosphorus is applied at planting. If needed, the application can be postponed, but not later than the time of active tillering. It has been reported that the early application of phosphorus is essential for root elongation. Phosphorus applied during the tillering stage is most efficiently utilized for grain production.

The phosphatic fertilizer needs of rice on deficient soils can be reduced if the varieties that can extract phosphorus efficiently from the soil can be developed. That would be a real boon to the poor farmers of the tropics where most of the phosphorus deficient soils occur, especially since phosphate fertilizers have now tripled in price.

Due to the current fertilizer situation, inorganic fertilizers should be supplemented with green manure, compost and other organic manures, and rice straw. Quantitative experimental data are needed to assess the value of organic manures in realizing high yields from the modern rice varieties. Under Indian conditions, organic manures contain good amounts of micronutrients which are beneficial to rice production in certain rice growing areas.

In some Asian countries, straw is available in large quantities as a source of organic matter and nutrients. In other countries, rice straw is used for cattle feed and hence not available for field use. In clay soils, straw incorporation has limited nutritional value, but in sandy soils of low CEC, the effects may be of some significance.

Weed Control. - Weed control does not differ greatly between irrigated transplanted rice as discussed earlier. Good land preparation and good water control make weed control less difficult for irrigated transplanted rice than for rainfed transplanted rice. Hand weeding is commonly used in almost all areas in South and Southeast Asia. Rotary weeding seems common in some Southeast Asian countries although not in others. Herbicides are used most commonly in areas with inadequate labor and high wages, particularly in East Asia-Taiwan, Korea and Japan.

Insect and Disease control. - Insects do far more damage to rice in the tropics than in temperate regions. In fully irrigated areas in the tropics, where year round rice culture is practiced, pest problems become much more serious than in the cool temperate climates where only 1 crop can be grown each year. The control of rice insect pests in the tropics currently depends largely on the use of pesticides, even though many traditional cultivars have some resistance to 1 or more insect pests or diseases. These have played and will continue to play a major role in successful rice production.

In biological control studies, it was found that a predator (Crytorhinus lividipennuis) can kill an average of 0.6 brown planthopper nymphs per day, or 50 green leafhopper nymphs per day, for at least 4 consecutive days. The predator prefers to prey on nymphs rather than adults, and prefers green leafhoppers to brown planthoppers.

For diseases of rice, resistant lines have been identified and incorporated into the elite breeding lines. Although chemical control of blast or of the vectors of virus diseases is possible, this control is neither practical nor economical. Cultigenic resistance to these diseases and to the vectors of virus diseases is the only economic solution to these problems.

Harvesting, Threshing. Drying and Storage.- In the tropics, rice matures about 30 days after heading. Harvest must occur on time, otherwise the grain may be lost through damage caused by rats, birds, insects, shattering and lodging. Timely harvest ensures optimum grain quality. In the Asian tropics, harvesting is done by hand. The straw is usually cut about 15 to 25 cm above the ground. Nowadays, harvesting is done by machinery.

Threshing is done by hand. The rice heads are beaten on a perforated platform made of bamboo. Occasionally, threshing is done by having animals tread on the harvested rice crop. Threshers are rarely used in tropical Asia. Nowadays, harvesting is done by machinery.

The grain is usually dried in the sun, although this is difficult during the wet season when clouds and rains often disrupt operations.

- **Direct Seeding onto Puddled Soil**.-The practical difficulties of establishing good stands of direct seeded rice under monsoon conditions have been studied to determine whether transplanting is indeed superior to direct seeding under tropical conditions. Evidence suggests that grain yields are similar for directly seeded and transplanted rice. This finding, along with the increasing cost of transplanting, may lead to serious consideration of direct seeding as a desirable alternative at least in areas with controlled irrigation. Although machines are available to drill pre-germinated rice onto puddled soil, the broadcast method is most common.

Directly seeding onto puddled soil is practiced in some parts of India, Bangladesh and the Philippines. In Sri Lanka, 80 to 90 % of the rice acreage is broadcast. Jayasekera (1996) concluded from a number of experiments that high grain yields are possible with properly managed broadcast seeded rice. With broadcast seeding, weed control is a serious problem at low plant density. Cultural practices for direct seeding onto puddled soils are similar to those for transplanted rice in some operations.

Land Preparation. – The preparation of land is closely related to the method of planting rice. The conventional method of tillage for transplanting aims at making a soft puddled soil. This degree of land preparation is often considered a requirement for direct seeded rice, although this is not usually required except to aid air water conservation.

Water Management. – The depth of water determines successful seedling establishment. System of water management for direct seeding onto puddled soil vary widely. In 1 system, fields are flooded just before seeding and kept flooded again. In another system, pregerminated seeds are sown onto a moist but drained field, and the field is reflooded with 3 to 5 cm of water when rice is at the 4 leaf stage and weeds at the 3 leaf stage.

Fertilizer Management. – The management of fertilizer does not greatly differ between direct-seeded irrigated rice and direct-seeded rainfed rice.

Weed Control. – Weed control is more critical and difficult in rice grown from pregerminated seeds broadcast directly into the field than in transplanted rice. Laborers cannot move through broadcast rice to weed by hand without destroying some rice plants. Furthermore, laborers cannot distinguish between young grassy weeds and young rice.

Insect and disease control and other cultural practices are the same for direct seeded as for transplanted rice in most tropical areas.

Harvesting, threshing and storage are also similar.

2.3 Impact of Temperature on Rice Production

Temperature, along with photoperiods, is the main driving force for crop development. The optimum temperature for the normal development of rice ranges from 27 to 32 °C. Low and high temperature affects almost all or the growth stages of rice (Table 2.4) (Shah *et al.*, 2011).

2.3.1 Critical low and high temperatures

Extreme temperatures are destructive to plant growth, and hence, define the environment under which the life cycle of the rice plant can be completed. The critically low and high temperatures, normally below 20°C and above 30°C, vary from one growth stage to another (Table 2.4) (Yoshida, 1981). These critical temperatures require certain temperature conditions at different stages of growth and reproduction. For example, the indica rice requires that the average daily temperature at the seedling stage should maintain above 12°C and the japonica rice is above 10°C. So, the temperature suitable for the seed of rice stabilizes higher than 12 °C while, during the rearing period, the average daily temperature of the japonica types is more than 20°C, and the indica types requires above 22°C. if the average daily temperature is less than 22 °C for more than 3 consecutive days, it tends to cause the phenomenon of Cryogenic false (Jing and Jichao, 2012)

Subjecting the rice plant to temperatures below 20°C at about the reduction division stage of the pollen mother cells usually induces a high percentage of spikelet sterility. Differences among rice varieties in response to low temperatures at this stage have been clearly demonstrated. When Norin 20, a susceptible variety, was held at 15°C for 4 days, 51% of the spikelets were sterile. Hayayuki, a tolerant variety, under the same conditions produced only 5% sterile spikelets. Temperatures as low as 12°C will not induce sterility if they last for only 2 days, but will induce about 100% sterility if they last for 6 days.

The foregoing examples illustrate the complexity of temperature effects on growth and development at different stages of the life cycle. Hence, care must be taken to interpret critical temperatures, such as those shown in Table 2.4.

Low temperature-induced sterility is normally attributed to low night temperatures. High day temperatures, however, appear to alleviate the effects of low night temperatures (Table 2.6). When the plant was subjected to a constant night temperature of 14°C for 9 days at the reduction division stage of pollen mother cells, a day temperature of 14°C induced 41% sterility. The percentage sterility was, however, decreased to 12% when the day temperature was raised to 26°C.

In northern temperate regions where the summer is short, farmers raise rice seedlings in a plastic-protected nursery where the temperature can be maintained higher inside than outside. In this way they can start rice cultivation in the early spring when air temperatures are still below the critical limit for germination and rooting. Seedlings are then transplanted when the air temperature reaches above 13-15°C.

Upland-grown rice seedlings have higher starch and protein content, and thus have higher rooting capacity than lowland-grown seedlings. Therefore, rice seedlings raised in protected upland nursery beds can be transplanted when the daily mean temperature is about 13.0° C –13.5°C, but seedlings raised in lowland nursery beds can be transplanted only when the daily mean temperature rises to 15.0° C –15.5°C (Yoshida, 1981).

2.3.2. Air and water temperature

Numerous studies have shown that temperature plays an important role in rice plant physiology and growth. Air temperature variations influence germination, seedling growth, and vegetative and reproductive growth, and higher and lower air temperatures reduce and extend the lengths of rice plant growth stages, respectively, and influence the length of the total growing season. Table 2.6 shown that when the rice plant is subjected to low temperatures for 3 days, it is more sensitive at the booting stage than at heading, as indicated by the higher percentages of sterility. When the low temperatures are continued for 6-9 days, however, heading is as sensitive as, or even more sensitive than, booting (Yoshida, 1981).

The water temperature in rice production is one of the most important factors affecting the growth and yield of rice. It can affect various growth processes, and response to water temperature can differ according to growth stage. During the vegetative period, cool water reduces the rates of tillering, leaf appearance and leaf elongation which, in some cases, are accompanied by leaf yellowing. Cool water during the reproductive period, particularly around the microspore stage, substantially decreases spikelet fertility, resulting in severe yield decline (Shimono *et al.*, 2002). As the growing panicles reach above the water surface around the reduction division stage, and thereafter, the effects of water temperature decrease. Finally, air temperature becomes dominant in controlling panicle growth and ripening. Thus, the effects of air and water temperatures on grain yield and yield components vary with the growth stage. At early growth stages, the water temperature affects yield by affecting the panicle number per plant, spikelet number per panicle, and the percentage of ripened grains. At later stages air temperatures affect yield by affecting the percentages of unfertilized spikelets and percentages of ripened grains

(Yoshida, 1981). Grain yield can also be reduced by low water temperature during the vegetative period.

Table 2.6 Effect of day and night temperature at 2 critical stages on spikelet sterility and anthesis (Yoshida, 1981).

Duration of low-temperature treatment (days)	Day temperature (8 hours)	Night temperature (16 hours)	Spikelet sterility (%)		Flowered spikelets (%) heading
			Booting stage	Heading time	
3	26	20	2.2	10.7	53.3
		14	8.2	9.2	5.0
		8	11.6	7.2	5.0
	20	20	4.2	9.8	8.3
		14	7.3	8.2	5.0
		8	15.5	8.0	8.3
	14	20	5.9	6.7	11.0
		14	11.2	8.3	0.7
		8	23.0	5.7	0.3
6	26	20	3.7	9.9	95.0
		14	6.4	19.4	36.7
		8	22.5	41.6	13.3
	20	20	6.1	11.5	91.7
		14	6.6	15.5	18.3
		8	28.0	37.4	1.7
	14	20	7.0	14.6	38.3
		14	25.8	21.1	7.0
		8	74.8	48.3	1.3
9	26	20	4.4	12.1	100.0
		14	12.1	38.7	73.3
		8	48.8	71.9	75.0
	20	20	7.4	8.5	98.3
		14	14.4	32.3	76.7
		8	52.5	73.0	16.7
	14	20	12.9	35.4	93.0
		14	41.3	55.6	24.0
		8	76.0	85.8	2.7

Shimono *et al.* (2007) found that low water temperatures (T_w) during panicle development increased sterility (Figure 2.23). Sterility averaged around 55% in the control (52% for ambient CO_2 concentration in 2004, 59% for elevated [CO_2 200 μmol mol^{-1}] in 2004, and 53% for 2005). Compared with the control, the Low-T_w treatment increased sterility, by 11–14% points depending on CO_2 concentration and year. In contrast, the Late-Planting treatment decreased sterility by 9–21% points compared with the control. Sterility tended to be higher under elevated CO_2 concentration than under ambient CO_2 concentration. Spikelet number decreased in both treatments compared with the control at both levels of CO_2 concentration and in both years. The Low-T_a treatment, which lowered both T_a and T_w, increased sterility compared with the control (Figure 2.24), but the Warm-T_w treatment, which lowered only T_a, did not increase sterility.

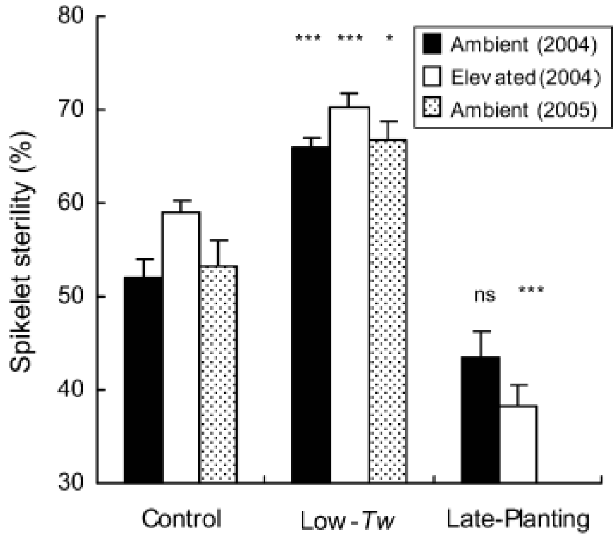


Figure 2.23 Effects of low water temperature (T_w) during vegetative growth and of late transplanting on spikelet sterility and spikelet number in rice at ambient and elevated CO_2 concentration. Significance of differences compared with the corresponding control value: ***p < 0.01; *p < 0.05; ns, not significant (Shimono *et al.*, 2007).

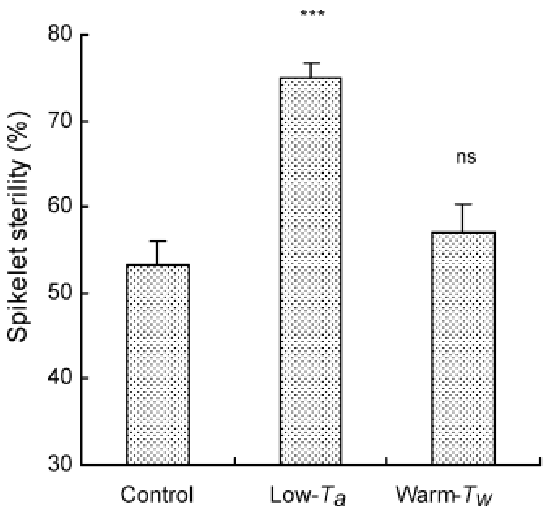


Figure 2.24 Effects of low air temperature (T_a) and warm water temperature (T_w) during vegetative growth on spikelet sterility and spikelet number in rice at ambient and elevated CO_2 concentration. Significance of differences compared with the corresponding control value (Shimono *et al.*, 2007).

2.3.3. Low-temperature stress

a. Occurrence of low-temperature problems. Depending on growth stages, injury to rice may occur when the daily mean temperature drops below 20°C. Cool injury can occur not only in the temperate regions, but also at high altitudes and in dry season crops in the tropics. Countries reporting cool injury to rice include Australia, Bangladesh, China, Colombia, Cuba, India, Indonesia, Iran, Japan, Korea, Nepal, Pakistan, Peru, Sri Lanka, USA, and USSR.

b. Types of cool injury. Common cool injuries are failure to germinate, delayed seedling emergence, stunting, leaf discoloration, panicle tip degeneration, incomplete panicle exsertion, delayed flowering, high spikelet sterility, and irregular maturity. Among them, high spikelet sterility, delayed heading, and irregular maturity are common in many countries.

c. Stunting at seedling stage. Stunting, a reduction in plant height, is a common symptom of cool injury in seedlings and is highly correlated with the weight growths of both the shoot and the root.

d. Delayed heading. In regions where the summers are short, cool weather conditions may delay growth, and hence, heading. Under such conditions, the rice crop may ripen at lower temperatures than the usual and may not complete grain filling before the temperature drops below the critical level for ripening. Raising seedlings in a plastic-covered nursery in early spring and transplanting right after the temperature rises to 13°–15°C is one way of providing more warm days and a greater chance to complete grain filling. There are some degrees of varietal difference in the ability to grow fast under cool weather conditions.

e. Induced sterility. Rice is the most sensitive to low temperatures (15°–20°C) at the young microspore stage after reduction division. It is less sensitive just before and at the leptotene stage of reduction division at about 10–11 days before anthesis. This information has been obtained from a very precise work using uniform, single plant material grown in the phytotron (Yoshida, 1981).

A number of studies have been conducted to determine the physiological mechanism responsible for low temperature-induced spikelet sterility. Damage to the male organ (pollen) caused by low temperature, rather than to the female organ (stigma), has been clarified as a major cause of the observed sterility. A shortage of sound pollen number at flowering stage limits pollination and then results in sterility. During panicle development, the susceptibility of a male organ to low temperatures is extremely high during the booting stage of microspore formation, which occurs approximately 10 days before heading; low temperatures interfere with sound division of pollen mother cells. Drastic changes in susceptibility were clearly demonstrated. They conducted a cooling treatment (12 °C for 6 days) at 2-day intervals during different growth stages. They showed that the sterility of plants treated at the booting stage was especially high (up to 90%), but that sterility of plants treated during other growth stages was less than 20%. Hence, temperature at the booting stage is a critical factor for determining yield losses in cool summers. The sterility induced by low temperature varied greatly among years even when the treatment at the booting stage was identical.

Additional valuable research clarified that differences in temperature, particularly water temperature (T_w), from panicle initiation (PI) to the booting stage change the plant's susceptibility to low temperatures at the booting stage. In particular, warmer T_w prior to the booting stage decreases sterility induced by low temperatures at the booting stage. These results led to the development of cultural solutions that are commonly used in northern Japan, such as flooding before the critical period, which uses the high thermal capacity of water to ameliorate sterility that would otherwise be caused by low temperatures at booting stage. On the other hand, no experiments have yet been conducted to assess the effects of temperatures prior to PI on the plant's susceptibility to low temperature-induced sterility (Shimono *et al.,* 2002).

2.3.4 High-temperature stress

a. Occurrences of high-temperature problems. High temperatures cause high percentages of spikelet sterility in dry season crops in Cambodia, Thailand, and India; in the first rice crop in Pakistan; and in the regular crops in Iran and tropical African countries. High percentages of spikelet sterility occur if temperatures exceed 35°C at anthesis and last for more than 1 hour (Yoshida, 1981).

b. Types of high-temperature injury. When rice is exposed to temperatures higher than 35°C, injuries occur according to the growth stages (Table 2.7).

c. High temperature-induced sterility. Temperatures higher than the optimum induced floret sterility and thus decreased rice yield. Spikelet sterility was greatly increased at temperatures higher than 35 °C. In greenhouse experiments with both *indica* and *japonica* genotypes, Jagadish *et al.,* (2007) found that less than 1 h of exposure to temperatures above 33.7 °C was sufficient to induce sterility (Shah *et al.,* 2011). In addtion, rice is most sensitive to high temperatures at heading and next most sensitive at about 9 days before heading. One or two hours of high temperature at anthesis has a decisive effect on the incidence of sterility (Figure 2.25). High temperatures before or after anthesis have much less effect on sterility (Yoshida, 1981).

Table 2.7 Symptoms of heat stress in rice plants (Shah *et al.,* 2011).

Growth stage	Threshold temperature (°C)	Symptoms
Emergence	40	Delay and decrease in emergence
Seedling	35	Poor growth of the seedling
Tillering	32	Reduced tillering and height
Booting	–	Decreased number of pollen grains
Anthesis	33.7	Poor anther dehiscence and sterility
Flowering	35	Floret sterility
Grain formation	34	Yield reduction
Grain ripening	29	Reduced grain filling

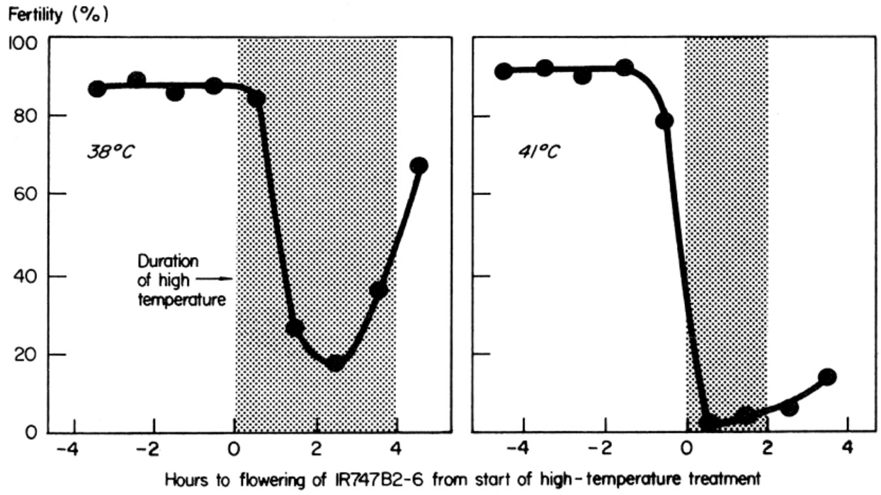


Figure 2.25 Fertility of the spikelets that flowered in the hours before, during, and after high temperature treatments (Yoshida, 1981).

Ecophysiological analysis has revealed the mechanism responsible for heat-induced floret sterility. A key mechanism of high-temperature-induced floret sterility in rice is the decreased ability of the pollen grains to swell, resulting in poor thecae dehiscence. This swelling of pollen grains in the locules is the driving force for anther dehiscence. Endo *et al.* (2009) found that although high-temperature-treated pollen showed a normal round shape, some of the tapetum functions, such as pollen adhesion to the stigma and its subsequent germination, were negatively affected. Endo et al. (2009) also identified some temperature responsive genes in the anther by clustering of microarray data. Some other possible reasons discussed by researchers for decreasing spikelet fertility at high temperature are altered hormonal balance in the floret, disturbance in the availability and transport of photosynthates to the kernel, lack of ability of the floral buds to mobilize carbohydrates under heat stress and changes in the activities of starch and sugar biosynthesis enzymes (Shah *et al.,* 2011).

Significant genotypic variations in high-temperature-induced floret sterility exist. Matsui *et al.* (2001) found a 3°C variation of temperatures causing sterility of 0.5% between the most tolerant and most susceptible cultivars among nine japonica cultivars. Similarly, Sheehy *et al.* (2005) reported altered responses of rice genotypes in terms of spikelet fertility to different levels of temperature increases. Greater increments in temperature resulted in higher proportions of sterility. The exogenous application of growth regulators has been shown recently to have some positive effects on the spikelet fertility and pollination. In fact, their exogenous application increased the level of endogenous antioxidants, and thus, prevented the oxidative damage to the membranes in rice (Shah *et al.,* 2011).

Clear differences exist in the tolerance of rice varieties for high temperature induced sterility (Figure 2.26). At 35°C, N22, upland rice from India, has higher than 80% spikelet fertility, whereas BKN6624-46-2, a lowland selection from Thailand, has about 10% spikelet fertility. If defined as the temperature when spikelet fertility decreases below 80%, the critical temperature is estimated from Figure 2.26 as 36.5°C for N22, 35°C for IR747B2-6, and 32°C for BKN6624-46-2. Thus, the difference in the critical high temperatures between heat-tolerant N22 and heat-susceptible BKN6624-46-2 is more than 4°C.

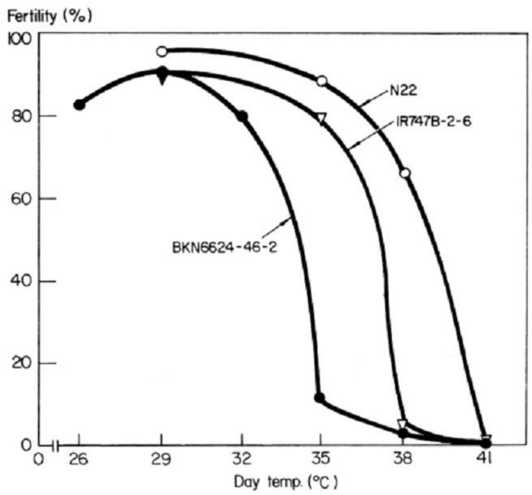


Figure 2.26 Fertility of the spikelets that flowered at different day temperatures (Yoshida 1981).

2.3.5. Interaction between temperature and nutrient supply

a. Number of spikelets per square meter and amount of nitrogen absorbed. A minicrop experiment in the phytotron indicates that the number of spikelets per square meter increases as temperature decreases at a given level of nitrogen, and this effect is most significant at the highest level of nitrogen (Table 2.8). However, the efficiency was higher at lower temperatures and lower nitrogen levels. Thus, temperature appears to be a major climatic factor that affects the efficiency at which nitrogen produces spikelets.

Table 2.8. Effects of temperature on spikelet number and efficiency of nitrogen to produce spikelets (minicrop experiment in the phytotron) (Yoshida, 1981).

Day/night temperature (ºC)	Spikelets (10^2 /m^2)			Spikelets (no./mg N absorbed)		
	150 N [a]	100 N	50 N	150 N	100N	50 N
35/27	278	280	244	1.4	2.0	2.9
32/24	299	308	275	1.6	2.2	3.0
29/21	376	313	288	2.1	2.3	3.3
26/18	482	409	326	2.2	2.5	3.2

[a] Kg N/ha.

b. Low temperature-induced sterility and nitrogen. Nitrogen fertilization affects sterility caused by low temperatures at the reduction division stage. When temperatures are above or far below the critical point, nitrogen supply has little effect on sterility. At moderately low temperatures (16°C), however, the percentage sterility increases with an increasing nitrogen supply (Figure 2.27).

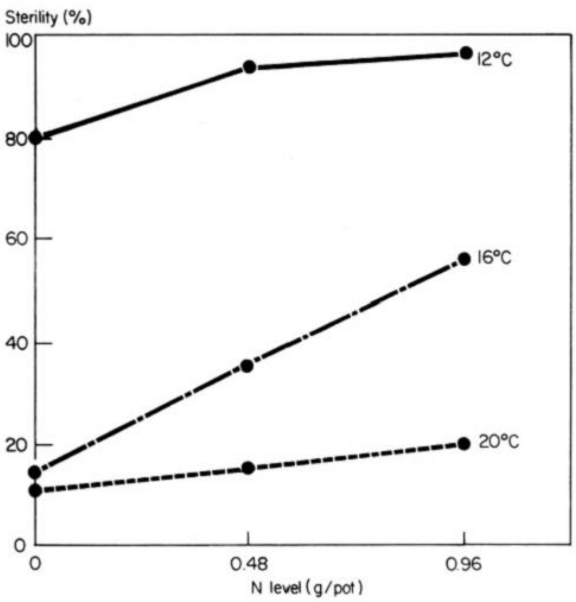


Figure 2.27 Effect of nitrogen on percentage sterility attributable to low temperature at meiotic stage (Yoshida, 1981).

c. Low temperature-induced sterility and phosphorus. The adverse effects of high nitrogen under low temperatures during the reproductive stage can be alleviated by increasing the amount of phosphate applied (Figure 2.28). This experiment confirms a common observation in northern Japan that the effect of phosphorus on rice yield is more significant in cool than in warm years.

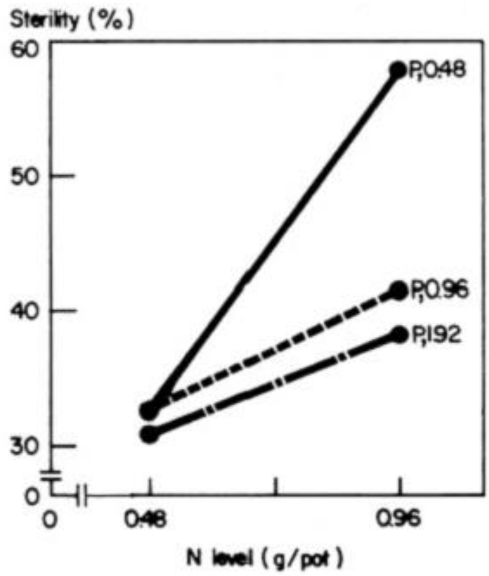


Figure 2.28 Effect of phosphorus application on percentage sterility attributable to low temperature at reduction division stage (Yoshida, 1981).

2.4 Weather Data Preparation and Quality Control

2.4.1 Long and quality-controlled daily observational series

Assessing changes in extremes is not trivial. For statistical reasons, a valid analysis of extremes in the tails of the distribution requires a long time series to obtain reasonable estimates of the intensity and frequency of rare events, such as the 20-year return value (an event whose intensity would be exceeded once every 20 years, on average, in a stationary climate). Also, continuous data series with at least a daily time resolution are needed to take into account the sub-monthly nature of many extremes. This requirement may be particularly problematic because, in various parts of the globe, there is a lack of high-quality daily observation records covering multiple decades that are part of integrated data sets (WMO, 2009).

As noted in IPCC (2007), in many regions of the world it is not yet possible to make firm assessments of how global warming has affected extremes. As a result, far less is known about past changes in extremes than past changes in mean climate. This is because observational time series are generally not available in the required high time resolution digital form. Consequently, the limited spatial coverage of the available data sets with high enough resolution (at least daily values) often hampers regional assessments. Even where the necessary data are available, systematic changes in extremes may be difficult to detect locally if there is a large amount of natural inter-annual variability in extremes.

Example. The first step is assembling available data and selecting the candidate station series for extremes analysis on the basis of series length and data completeness. In many daily resolution climatic time series, a number of observation days are missing. A frequently used completeness criterion allows for at most four missing observations per year. Such a strict criterion is needed because some extremes analyses are critically dependent on the serial completeness of the data. A particular concern regarding missing observation days in the case of an extremes analysis is that an extreme event might have been responsible for the failure of the observing system and thus the fact that the observation for that day is missing; such “censoring” of extremes would result in negatively biased estimates of the intensity of rare events, such as the 20-year event (WMO, 2009).

2.4.2 Quality Control

The main purpose of the subsequent QC procedure is to identify errors, such as manual keying, usually caused by data processing. In many series, obviously wrong values, such as nonexistent dates, need to be removed. Negative daily precipitation amounts are set to missing values, and both daily maximum and minimum temperatures are set to missing values if the daily maximum temperature is less than the daily minimum temperature.

Reek *et al.* (1992) outlined eight rules to identify erroneous data of air temperature and precipitation. They concluded that the errors were due to data reporting and digitizing, typos, unit differences, and the use of different based values in data reporting. In this study, we used three of their rules to check the daily data:

(1) internal inconsistency, which identifies errors such as daily Tx being cooler than Tn, that the daily Td is larger than Tx or less than Tn, and that daily Ws is larger than Wg.

(2) excess diurnal temperature range check, which identifies errors with extraordinarily large daily temperature range (Tx−Tn) while Tx and Tn are within their reasonable ranges; and

(3) a ‘flat line’ check, which identifies data of the same value for at least seven consecutive days (not applied to zero precipitation data). All the identified erroneous data are flagged. For erroneous data detected by the ‘flat line’ check, all the consecutive data are flagged as suspect values, except for the first value.

Next, the QC procedure identifies outliers in daily maximum and minimum temperatures and precipitation amounts. Outliers are daily values that lie outside a particular range defined as unrealistic by the user. For example, for a temperature series, this range can be defined as the mean value of observations for the day of the year plus or minus four times the standard deviation of the value for that calendar day in the entire series. Daily temperature values outside of these thresholds are marked as potentially erroneous, and manually checked and corrected on a case-by-case basis. Each potential outlier can be evaluated using information from the days before and after the event along with expert knowledge about the local climate. Great care must be taken in determining whether identified outliers are truly erroneous, because their inclusion, adjustment, or exclusion can profoundly affect subsequent extremes analyses (WMO, 2009).

Although statistical tests are important for QC, visual checks of data plots can also reveal outliers as well as a variety of problems that cause changes in the seasonal cycle or changes in the variance of the data. In addition, histograms or so-called stem and leaf plots of the data reveal problems that show up when the data set is examined as a whole. Those extreme temperature and precipitation observations that are positively identified as wrong are best removed from the time series (i.e. set to missing values) unless there is an obvious cause of the error, such as a transcription of digits or misplacement of a decimal point, which allows it to be confidently corrected.

Observational data series with an excessive number of problems (typically three or more) that are not easily solved are best left out of the analysis entirely.

2.4.3 Homogeneity

Once data have been quality controlled, it is necessary to assess their temporal homogeneity. Climatic time series often exhibit spurious (non-climatic) jumps and/or gradual shifts due to changes in station location, environment (exposure), instrumentation or observing practices. In addition, the time series from some city stations include urban heating effects, as well as discontinuities resulting from station relocations to out-of-town airports. These inhomogeneities may severely affect the extremes. The station history metadata are vital for resolving these issues.

Experts from different parts of the world have produced a list of classical examples of inhomogeneities (http://cccma.seos.uvic.ca/ETCCDI/example.shtml) in observational series. These examples illustrate the main causes of the inhomogeneities and their possible impacts on climate trend analysis.

Many approaches and statistical techniques have been developed for evaluating the homogeneity of climate time series and for detecting and adjusting inhomogeneities. Nevertheless, further research is required to fully address this difficult issue for high resolution daily time series. At the moment, there are no established methods to determine and adjust inhomogeneities in daily resolution time series, although some techniques are under development. In Europe, the European Cooperation in Science and Technology mechanism (COSTHOME) compares the performance of different methods for the homogenization of long instrumental daily climate records (see http://www.homogenisation.org/), but conclusive results are not yet available. If the available number of records and station density so allow, the safest solution is to remove time series with indications of artificial changes from the analysis altogether. As an alternative, one can decide to use only the part of the series with indications of discontinuities of non-climatic origin that occurs after the time of the last discontinuity. Nevertheless, there may be instances when the use of adjusted time series will be unavoidable, such as in countries or regions with low station density (WMO, 2009).

In the European Climate Assessment and Dataset project (ECA&D; http://eca.knmi.nl), a combination of different statistical tests developed for testing monthly resolution time series was used to evaluate the properties of daily series. This allowed a ranking of these series which can help users to decide which series should be retained for a particular application. The example below is for Canada and is drawn from the expert list of classical examples. It illustrates the use of one particular statistical test which, although developed for homogeneity testing of lower than daily resolution time series, has been successfully applied in the series of workshops organized by ETCCDI. The two-phase regression-based test is part of the homogeneity-testing software program RHtestV2, which is available from the ETCCDI website. It also uses the open source statistical programming language R, and has a graphical user interface. For example, it describes how inhomogeneities were identified in the minimum temperature series of Amos (Canada, 48°34'N, 78°07'W) using RHtestV2. This program consists of a series of R functions to detect and adjust for multiple change-points (shifts in the mean) in a series. It is based on the penalized t-test (Wang *et al.,* 2007) and the penalized maximal F-test (Wang, 2008a).

These tests account for various problems that often affect the methods used for homogeneity analysis. For example, the effects of day-to-day persistence of observations on the properties of these statistical tests are accounted for empirically (Wang, 2008b). The possibility that the time series being tested may have a linear trend throughout the period of the record is also taken into account, and measures have been taken to ensure that change-points are detected with consistent reliability throughout the length of the time series. A homogeneous time series that is well correlated with the candidate series has been used as a reference series. However, the detection of change-points is also possible if a homogeneous reference series is not available.

RHtestV2 is applied to the annual means of the daily minimum temperature series to identify likely inhomogeneities in the data. Once a possible change-point has been identified in the annual series, it is also checked against station history metadata records, if available. Figure 2.29 shows the results for Amos where two change-points have been detected in the series between 1915 and 1995: a step of -0.8°C in 1927 and a step of 1.3°C in 1963. The station history files revealed that the Stevenson screen was located at the bottom of a hill prior to 1963 and was moved onto level ground, several metres away from its original position, after 1963 (Figure 2.30). The former site was sheltered by trees and buildings which could have prevented the cold air from draining freely at night time. The current site has better exposure and the observations are more reliable. The station history files do not provide any information on the cause of the first step. In this case, it is best to use only the part of the series after the second discontinuity for the analysis of extremes (WMO, 2009).

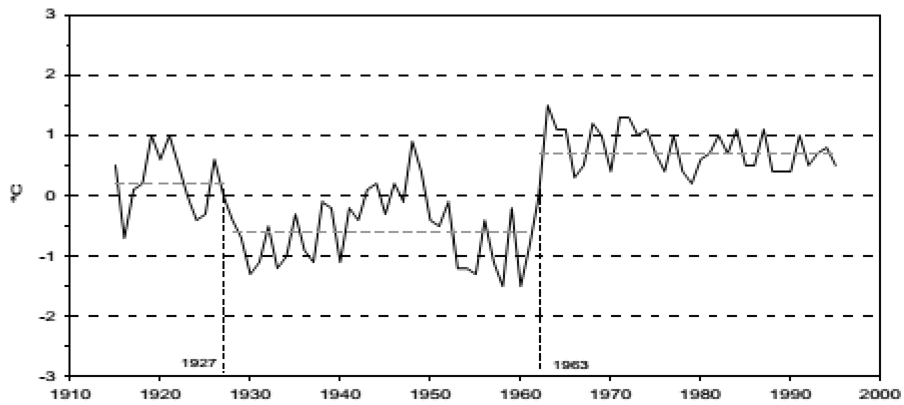


Figure 2.29 Example of data inhomogeneity in the annual average daily minimum temperature series (anomalies relative to a reference series computed from surrounding stations) for station Amos (Canada). On the basis of the two-phase regression model implemented in RHtestV2, two change-points (inhomogeneities) are detected for the years 1927 and 1963 (WMO, 2009).

Figure 2.30 Screen location at station Amos (Canada) before 1963 (left) and after 1963 (right) (WMO, 2009).

CHAPTER 3
METHODOLOGY

3.1 Overview

This research study focuses on evaluating the potential effects of temperature in terms of both magnitude and frequency of temperature change on rice production in Thailand. The evaluation is mainly based on: (1) analyzing the temperature records in the past 30 years and the optimal temperature requirement for rice growth and level of intense temperature that occurred in the past and (2) critical temperature affecting to rice growth. As mentioned in the introduction that the temperature in Thailand has been found to increase and thus it was hypothesized that, may have affected to rice growth and yield. The methodology formulated in responding to this hypothesis is (Figure 3.1):

Step 1: Compilation of meteorological data and rice cultivation data in the past 30 years.

Step 2: Selection of meteorological station.

Step 3: Quality control and homogeneity checks of temperature data.

Step 4: Analysis of temperature changes

Step 5: Determination of temperature index impact to rice production and analysis of temperature indices over 30 years.

Step 6: Evaluation of potential impacts at each meteorological station and display of a monthly map.

3.2 Meteorological Data

3.2.1 Data sources

In this study, a long time series of mean daily temperature (MDT), daily minimum temperatures (DMIN) and daily maximum temperatures (DMAX) spanning the period 1983 to 2012 (30 year-time) were obtained from 122 weather stations spread throughout Thailand (Appendix A). These data were compiled by the Thailand Meteorological Department (TMD). Characteristics and format of temperature data is shown in Table 3.1.

Table 3.1 The structure of temperature data.

StationName	TMD station code	Year	Month	Dday	Julian day	DMAX (°C)	DMIN (°C)	MDT (°C)
Mae Hong Son	300201	1983	1	1	1	…	…	…
…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…
Narathiwat	583201	2012	12	31	366	…	…	…

3.2.2 Internal consistency check and selection of meteorological stations

The examinations of data based on the consistency of the calendar day are as follows: number of days per year, the number of days per month and internal consistency check, which identifies errors such as daily maximum temperature being cooler than daily minimum temperature, that mean daily temperature is larger than daily maximum temperature or less than daily minimum temperature (Feng *et al.,* 2004).

3.2.3 Quality control and homogeneity checks for temperature data

The main purpose of a quality control procedure is identifying errors usually caused by data processing such as manual keying. In this study, the quality controls are divided into 3 procedures, which included temporal outliers check, spatial outliers check and homogeneity check. The quality control procedure is shown in Figure 3.1.

1) *Temporal outliers check*

The temporal outlier check for a particular station is based on the premise that an individual monthly value should be “similar” (in a statistical sampling sense) to values for the same month for other years. In order to make as few assumptions as possible regarding the wide range of data to be checked, outliers were identified utilizing the sample distribution of each calendar month separately for each station. Extreme values are flagged based on limits determined from a multiple of the interquartile range calculated for each station/month. This procedure is common in exploratory data analysis procedures. An outlier is flagged using the formula: (Eischeid *et al.,* 1995; Limjirakan *et al.,* 2008).

$$X_{ij} - q50_j > f * IR_j \qquad (1)$$

where X_{ij} is the observed values on *i* date in *j* month.

$q50_j$ is the median (or the 50th percentile) in *j* month.

f is the multiplication factor (in this study, $f = 5$).

IR_j is interquartile range (75th percentile minus the 25th percentile) in *j* month.

2) *Spatial outliers check*

This method detects the outliers by comparing the data of neighboring stations. Correlation coefficients (r) are computed for each month between the daily data at a station (candidate station) and the other 122 stations. The minimum criterion is that *r* is significant at the 95% confidence level. The value of *r* is calculated using the formula:

$$r = \frac{\sum_{i=1}^{n}(x_{ij}-\bar{x}_j)(y_{ij}-\bar{y}_j)}{\sqrt{\sum_{i=1}^{n}(x_{ij}-\bar{x}_j)^2}\sqrt{\sum_{i=1}^{n}(y_{ij}-\bar{y}_j)^2}} \tag{2}$$

Where x_{ij} is the observed values *i* date in *j* month at the candidate station.

$\bar{x}_j$ is the mean of observed values in *j* month at the candidate station.

y_{ij} is the observed values *i* date in *j* month at the neighboring station.

$\bar{y}_j$ is the mean of observed values in *j* month at the neighboring station.

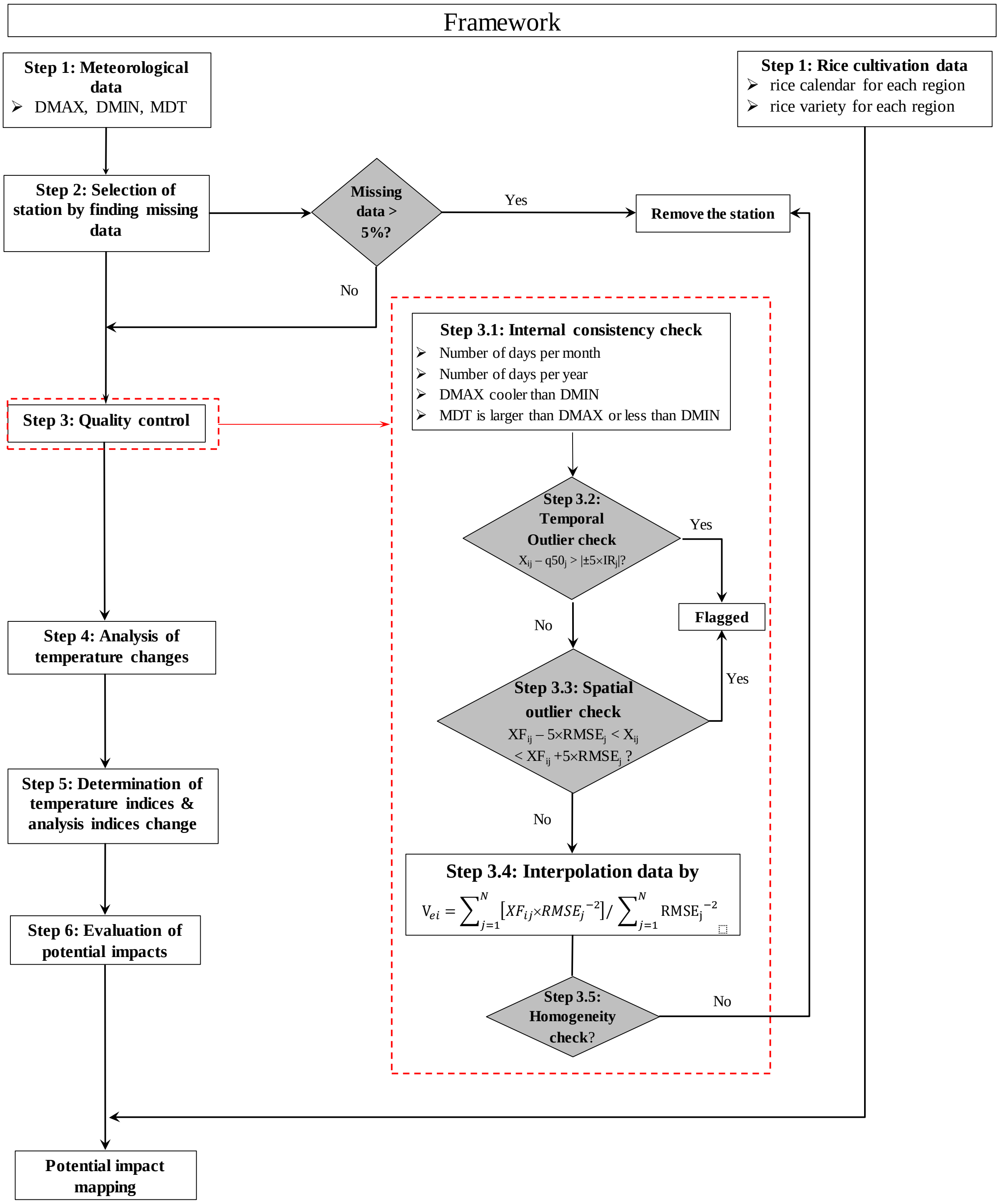


Figure 3.1 Schematic steps and methodology employed for analyzing the temperature data in this study.

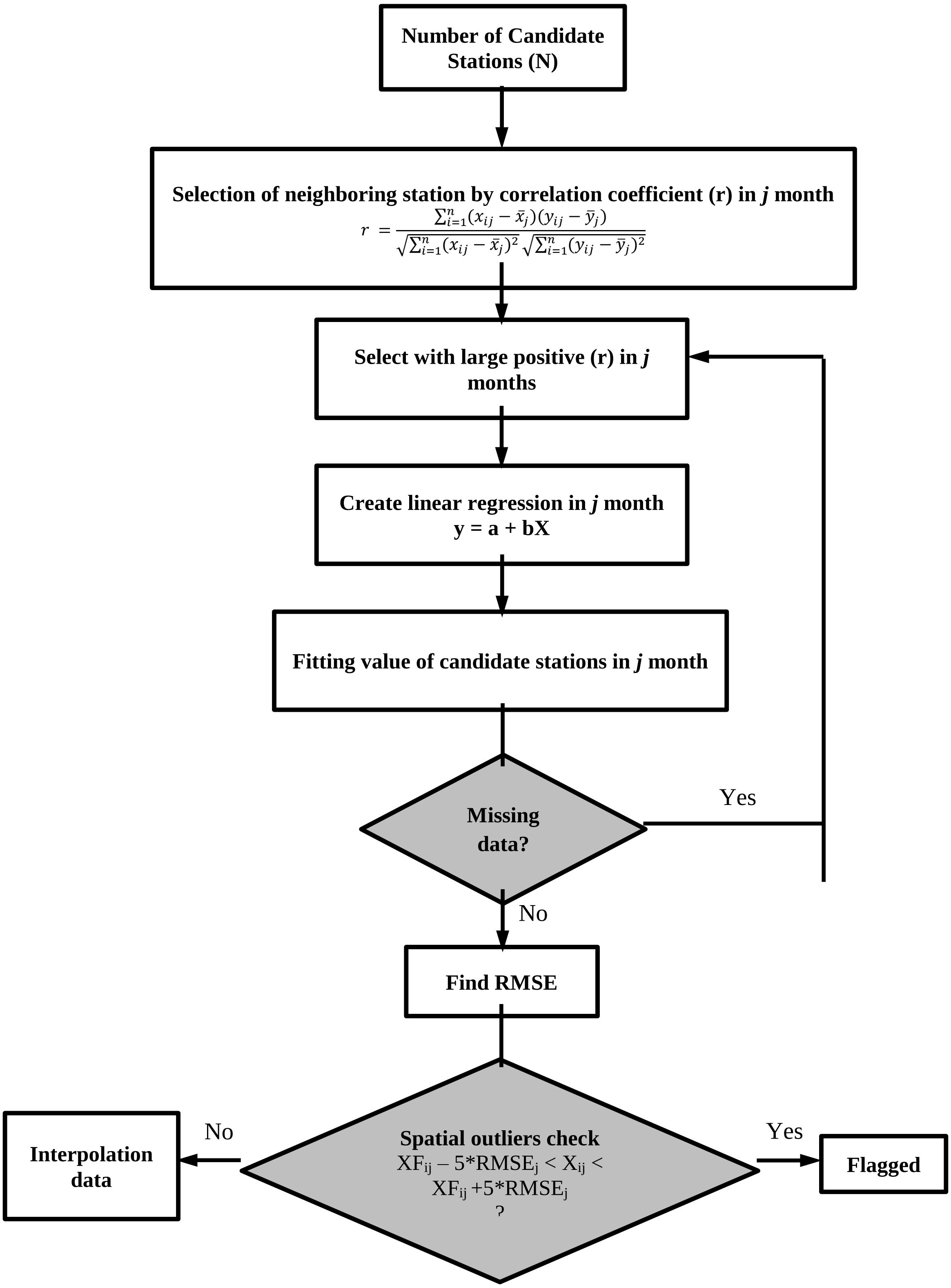


Figure 3.2 Process of Spatial outliers check

Stations with large positive r are used to create their linear regression for the same variables between the neighboring stations and the candidate station. The Root-Mean-Square-Error (RMSE) of the regressions is also computed. The RMSE is calculated using the formula:

$$RMSE_j = \sqrt{\frac{\sum_{i=1}^{n}(X_i - XF_{ij})^2}{m}} \qquad (3)$$

where $j = 1,\ldots, n$ is the number of neighboring stations.

$i = 1,\ldots,m,$ is the specific day in a month and m is the total number of days of that month.

X_i is the observed values i date at the candidate station.

XF_{ij} is the fitted value by linear regression of neighboring station j for day i.

If there are more than three neighboring stations, the one with the lowest RMSE is chosen. After having N regression equations, we assign a daily value X_i of variable to be suspicious if it falls outside the specified confidence intervals for all N pair of stations (Hubbard, 2001):

$$XF_{ij} - f * RMSE_j < X_i < XF_{ij} + f * RMSE_j \qquad (4)$$

Where f defines the desired confidence limit.(in this study, f =5) and the other symbols are the same as in Equation (3).

The process of the spatial outlier check is shown in Figure 3.2

3) Interpolation data

After calculations of monthly values, the missing data (or data gaps) can induce temporal and spatial errors. In this study, the missing data are estimated using the following method (Hubbard, 2001):

$$V_{ei} = \frac{\sum_{j=1}^{n}[XF_{ij} \times RMSE_j^{-2}]}{\sum_{j=1}^{n} RMSE_j^{-2}} \qquad (5)$$

Where V_{ei} is the estimated value and the other symbols are the same as in Equation (3).

We should point out that the number of neighboring stations used in Equation (3) and (4) is not fixed in time. The number varies depending on the availability of station data for the year/month in question. Accordingly, the regression models also change in time. Moreover, the surrounding stations that may be optimal for a particular calendar month (e.g. January) may not be optimal for a different month (e.g. July). Thus, the spatial outlier check and the estimation of missing data are constructed and applied for individual calendar months (Feng *et al.,* 2004).

4) Homogeneity check

Homogeneity data check was evaluated using an R-Base Language program, RHtestsV2 software package, developed at the Climate Research Division of Atmospheric Science and Technology Branch of Canada (Wang *et al.,* 2007). This program is designed to identify multiple step changes based on the penalized maximal *t* test and the penalized maximal *F* test. The in-homogenous data were removed for further analysis (Limjirakan *et al.,* 2008).

3.2.4 Temperature indices

Temperature indices that indicate the potential effects of temperature components on rice growth and yield were analyzed based on the temperature requirements for the growth and production of rice. According to the literature review, rice yield is adversely affected when the maximum temperature is above 35°C (Yoshida, 1981; Shili *et al.,* 2009) and mean temperature below 22°C (Jing and Jichao, 2012). Within individual month and year, and throughout the 30 years period, the number of days with such temperature extreme was analyzed and used for evaluating impact in the next steps. Determination of the temperature indices are shown in Table 3.2.

Table 3.2 Description of temperature indices used in the current study.

ID	Indicator name	Definitions	UNITS
HTS35	High temperature stress	Monthly count when DMAX ≥ 35 °C	Days
LTS22	Low temperature stress	Monthly count when MDT ≤ 22ºC	Days

In this study, the following temperature indices were also analyzed: temporal trends of occurrence days of extreme low-and high-temperature, the number of daily maximum temperatures (DMAX) above 35°C days, the number of mean daily temperatures (MDT) below 22°C days, the magnitudes of temperature for the days that having DMAX above 35°C or MDT below 22°C, and the exposure duration to temperature extremes.

3.2.5 Trend computation

Trends in temperature indices were calculated using the Ordinary least-Square (OLS) method, which is the most widely used and accepted non-parametric trend estimator in hydro-meteorological series (e.g. the work carried out in Canada, Northern Hemisphere oceans and Northeast United States). This estimator is resistant to the effect of outliers and robust to non-normal data distribution. Statistical significance was assessed using the non-parametric two-tailed Kendall's Tau test as those used by Limjirakan *et al.* (2008), in their study of assessment of extreme weather events of Thailand. The formula of OLS method is shown in Equation 6:

$$\hat{y}_i = ax_i + b \tag{6}$$

$$a = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{n\sum x_i{}^2 - (\sum x_i)^2} \tag{7}$$

where $\hat{y}_i$ is the predicted value of temperature for the *i* year.

x_i is the *i* year.

y_i is the observed value of temperature for the *i* year

a is a coefficient representing the slope of the line.

b is a constant. It is calculated using the formula:

$$b = y - ax \tag{8}$$

3.3 Rice Data and Rice Cropping

3.3.1 Rice data

Rice is a monocotyledon annual crop. In Asia, the rice plant is separated into 3 main rice grains: Indica, Japonica and Javanica. In Thailand, the rice grain is Indica. Thailand is famous for its mild aromatic and high grain quality variety Khao Daw Mali 105. Glutinous rice produce account for 30% of rice produced in the country. It is popular in the northeast region. The varieties of main rice-growing season, namely Khoa Dok Mali 105, RD6, RD15, Niaw San-pah-tawng, Hantra 60, Prachin Buri 1 and Prachin Buri 2 and the varieties of second rice-growing season, namely San-pah-tawng 1, Sakon Nakhon, Surin 1, Chai Nat 1, Suphan Buri 1, Suphan Buri 2, Pathum Thani 1 and Phitsanulok 2 are rice cultivation.

In Thailand, the rice-planting area is spread throughout in the country, the total is about 11.2 million ha (OAE, 2011). The majority of rice is grown under rainfed conditions, accounting for nearly 80% of the total rice-planting area. The rest are irrigated rice (ca. 20%). The major rice-planting area appeared in the northeast part of the country and accounted for 60% of total rice-planting areas. A single rice crop grown with traditional high quality rice varieties is the predominant cropping pattern in the region. However, the average rice yield in this region is very low. It was around 2.1 tonne ha^{-1}. Rice-planting areas in the northern part are about 22% of total rice-planting areas. The rice-planting area in the central part is has around 1.2 million ha (ca. 10%), where the majority of the areas are irrigated. The rest of rice cultivation are found in the South (about 2% of total rice-planting area, Figure 3.3).

3.3.2 Rice Cropping

The season for rice cultivation can be separated into two seasons. There are Na-pi (main rice growing season) and Na-prang (second rice growing season). The time of main rice growing season follows the rainy season, which is different in each region and geography. Unlike the main rice growing season, the time of second rice growing season depends on rainy season, irrigation area and water management.

The rice calendar is almost on the period of rainy season and the availability of irrigation water. Thus, there are some differences in each region of Thailand for exact rice cultivation calendar. In Central, North, Northeast, and East regions, the main rice-growing season starts from April or May until September (sowing and transplanting) and harvest is usually during October to February. The second rice-growing season starts from January until April. In southern region, the main rice-growing season is in the June (sowing and transplanting) and harvest is in March. The second rice-growing season appears in April until August (Sawano *et al.*, 2008; Mongkolchat, 2009). The rice cropping for each region is shown in Figure 3.4.

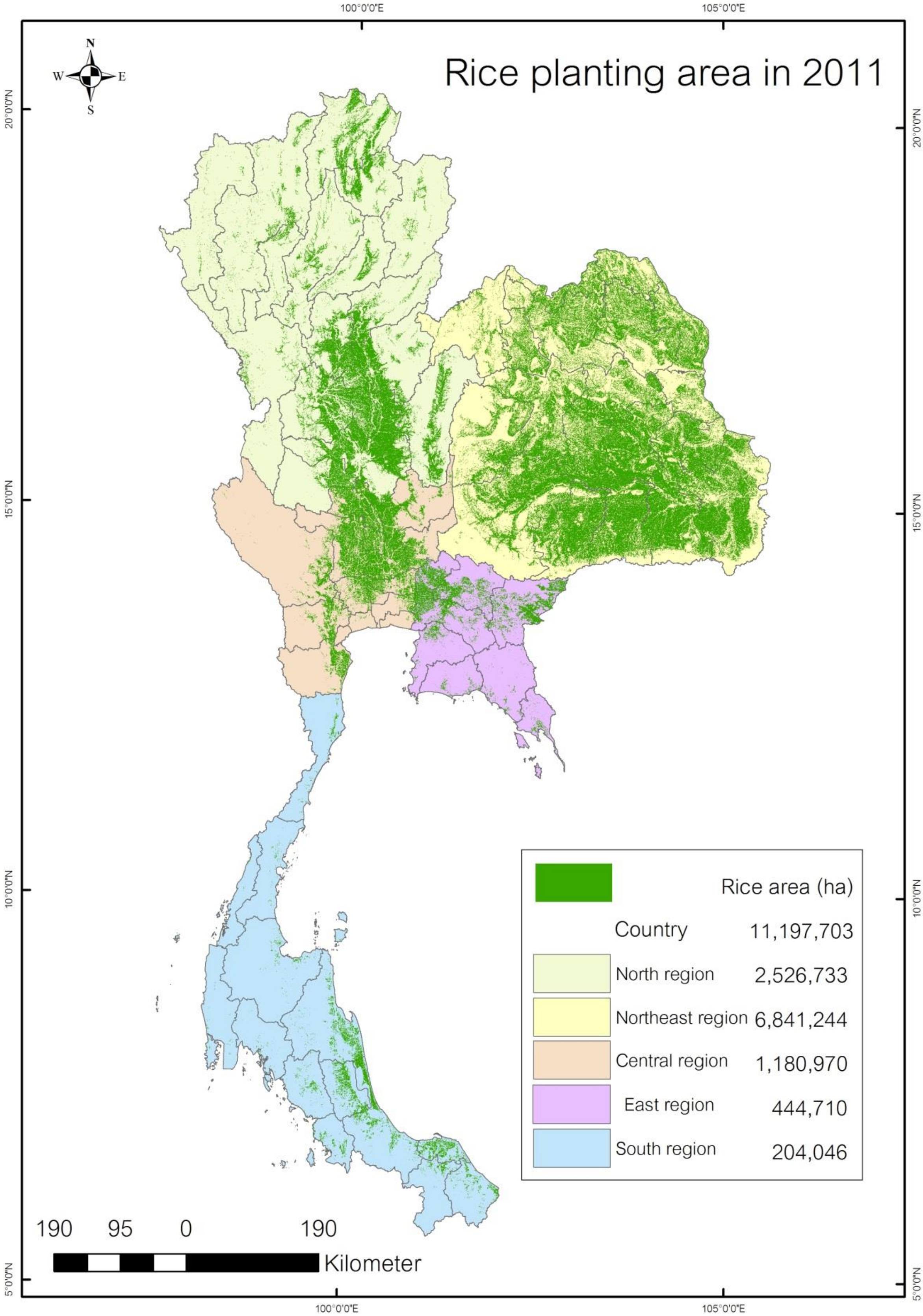


Figure 3.3 The distribution of rice planting areas in Thailand. (LDD, 2011)

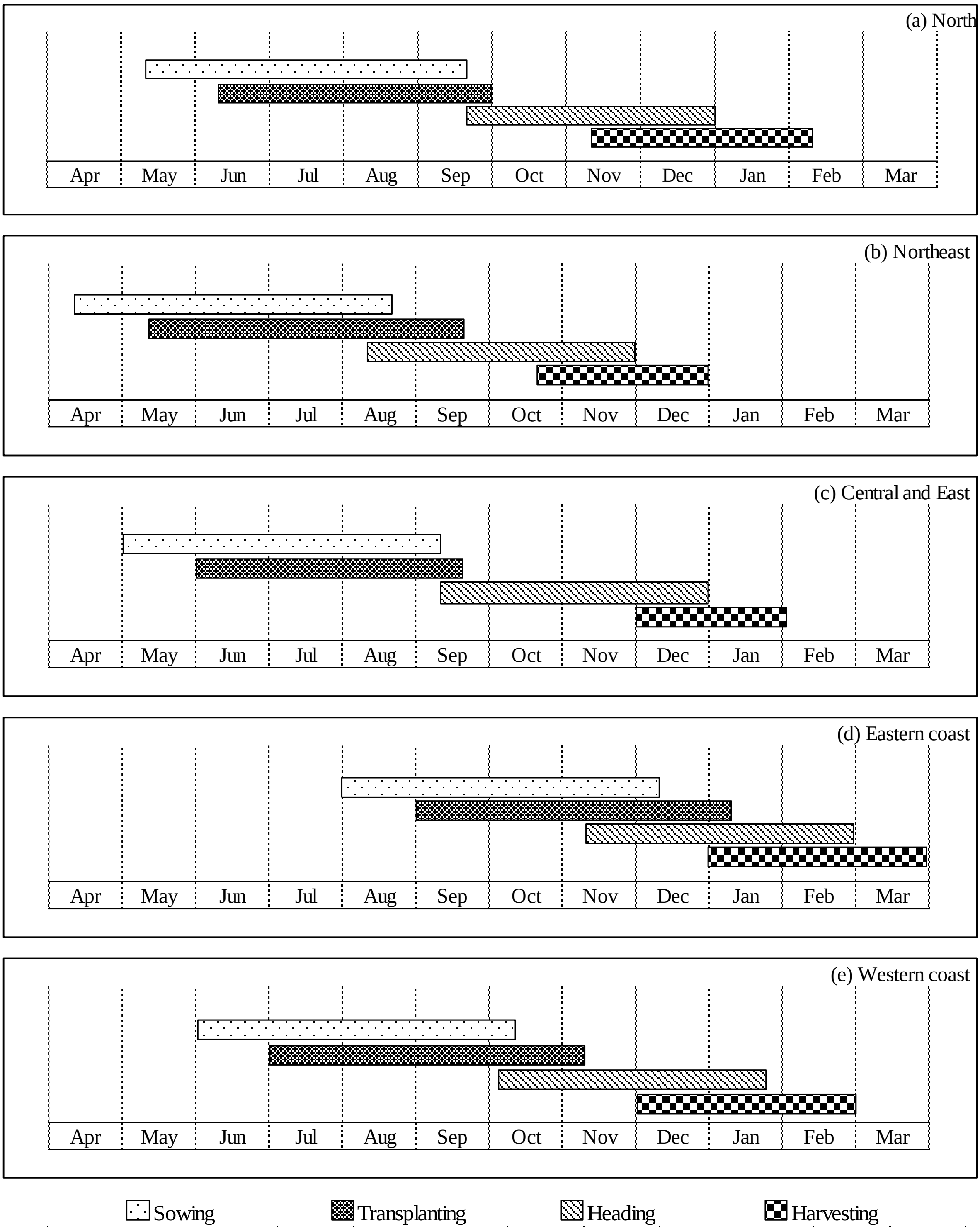


Figure 3.4 Main rice-growing calendars in each region of Thailand (Sawano *et al.*, 2008; Mongkolchat, 2009)

3.4 Evaluation of Potential Impact of Temperature on Rice Production.

The monthly simple potential impact scores (MPIS) at each meteorological station were calculated from a summation product of three indices. MPIS is given below :

$$\text{Impact} = f\,(\text{Rate of change} + \text{Number of times of 3 consecutive days} + \text{Total number of days}) \qquad (9)$$

The first index is the P-value for the rate of change (increasing) in the number of days at the given station having DMAX ≥35 °C over 30 years (number of day/30 years) for high temperature stress and MDT ≤ 22°C over 30 years (number of day/30 years) for low temperature stress. The second index is the numbers of events (i.e. for each month how many times during 30 years the records at particular station consecutively experienced DMAX exceeding 35 °C and lasted for ≥3 days or more for high temperature stress and MDT below 22°C and lasted for ≥3 days or more for low temperature stress).

We selected the duration of ≥3 days or more, because there have been a number of studies suggesting that exposing rice plant to such during can induce significant damages to rice growth and productivity (Yoshida, 1981; Shili *et al.*, 2009; Sun and Huang, 2011). The third index is the numbers of day having DMAX ≥35 °C and numbers of day having MDT ≤ 22°C (accumulative numbers of day during 30 years). Each of index is divided into four levels (levels 0-3) based on magnitude and frequency of occurrence (on another word, its severity). From the combinations of three indices and four levels of severity, impact scores were calculated resulting in totally ten impact levels (score 0 to 9). These were then grouped into 4 levels of potential impact indication; no impact (score 0); low impacts (score between 1 and ≤3), moderate impacts (score 4 but ≤6), and high impacts (score 7-9) as shown in Figure 3.5.

Table 3.3 The level of high temperature stress for each individual station.

Score level	High temperature stress		
	P-value for rate of change in number of days with ≥ 35 °C over 30 years	Number of times of 3 consecutive days (Times)	Total number of days with ≥ 35°C (days/30year)
1	0.05≤ p <0.10	1	1 – 280
2	0.01≤ p <0.05	2	281- 560
3	p <0.01	≥3	561 – 840

Table 3.4 The level of low temperature stress for each individual station.

Score level	Low temperature stress		
	P-value for rate of change in number of days with ≤ 22 °C over 30 years	Number of times of 3 consecutive days (Times)	Total number of days with ≤ 22 °C (days/30year)
1	0.05≤ p <0.10	1	1 – 299
2	0.01≤ p <0.05	2	300- 598
3	p <0.01	≥3	599 – 897

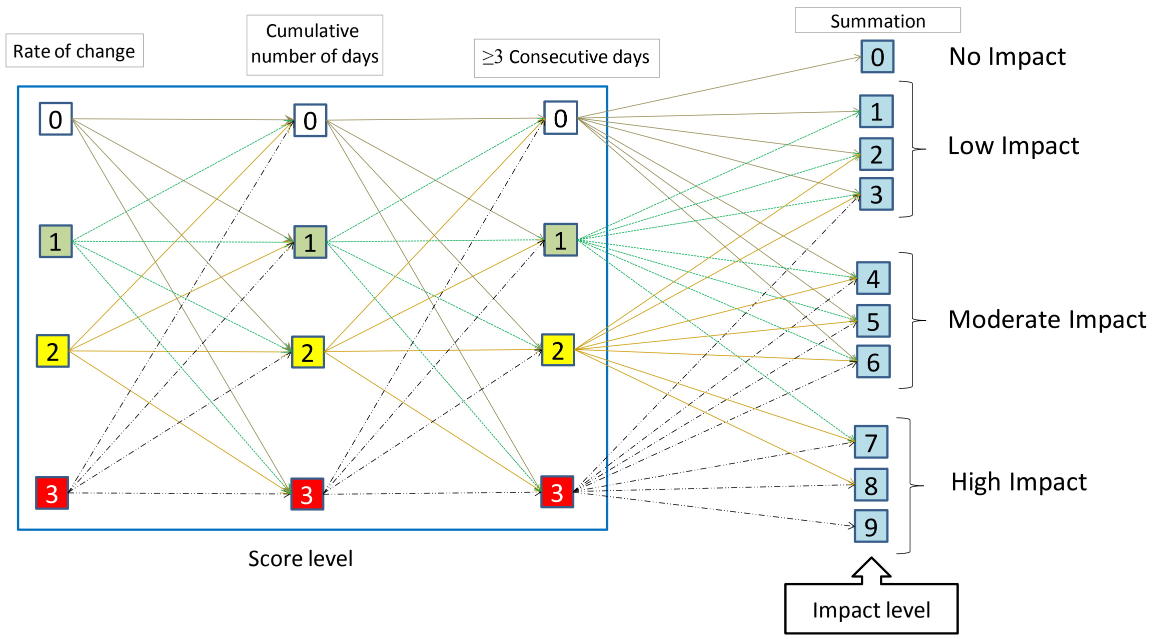


Figure 3.5 The classification of potential impact levels resulting from temperature stresses.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Meteorological Data

Daily temperature data are obtained from the Thailand Meteorological Department (TMD) located throughout Thailand. These data are observations of 3 variables: daily maximum temperature (DMAX), daily minimum temperature (DMIN) and mean daily temperature (MDT). All variables were measured during 1 January 1983 to 31 December 2012 (30 years period). The number of stations that measure DMAX and DMIN has increased from about 100 since 1990 to 119 in 2012. However the number of stations measuring MDT go down, since 1991 to 2004, but has remained stable around 100 since 2005 (Figure 4.1).

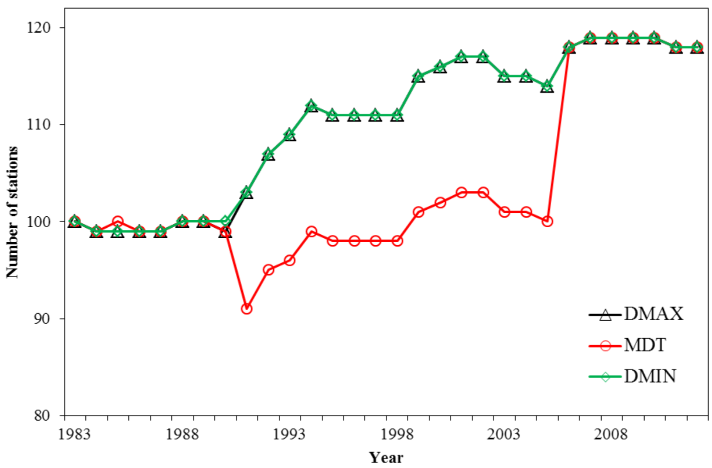


Figure 4.1 Number of TMD meteorological stations that temperature data are used in the current study.

The geographical distributions of the 122 stations are shown in Appendix A. The stations are spread throughout Thailand. In addition, the number of stations distributed in each region of the country is shown in Table 4.1.

Table 4.1 Number of stations for each region in Thailand

Region	Number of stations
1. Northern	31
2. Central	19
3. Eastern	15
4. Northeastern	27
5. Southern	30
Total	122

4.2 Overview of Temperature Data

4.2.1 Basic Statistics and Distribution of Daily Temperature Data

Descriptive statistic includes measures of central tendency, variance, skewness and kurtosis were applied to analyze the temperature characteristics over Thailand (Table 4.2) and to illustrate these in histogram graphs. Distribution of daily maximum temperature and mean daily temperature is fairly symmetric (Figures 4.2a-4.2b), but the daily minimum temperature is distributed towards the high-value (Figure 4.2c).

Table 4.2 Descriptive statistics of the temperature data for the 1983-2012 periods.

Statistic	DMAX	MDT	DMIN
1. Mean	32.6	27.4	22.7
2. Median	32.6	27.8	23.6
3. Variance	7.88	6.71	11.20
4. SD	2.81	2.59	3.35
5. Minimum	13.5	10.8	0.8
6. Maximum	50	38.8	37.7
7. Range	36.5	28.2	36.9
8. Skewness	-0.15	-0.94	-1.45
9. Kurtosis	1.06	1.81	2.42

4.2.2 Examination of data and selection of data

The examinations of data were based on the consistency of the calendar day, number of days per year, and the number of days per month (Appendix A). To total counts of complete temperature records were 10,958 records. Completeness of temperature data was then examined (Table 4.3). Thus, the number of stations with more than 5% of missing data are shown in Table 4.4.

Table 4.3 Percentage of missing data in each variable.

Variable	Number of missing data	(%)
DMAX	6,146	0.60
MDT	7,536	0.85
DMIN	8,014	0.78

Table 4.4 Number of stations with more than 5% of missing data and those were removed from the analysis.

Region	DMAX	MDT	DMIN
1. Northern	7	7	8
2. Central	5	5	5
3. Eastern	3	15	3
4. Northeastern	4	4	3
5. West	1	1	1
6. Southern	9	9	8
Total	29	41	28

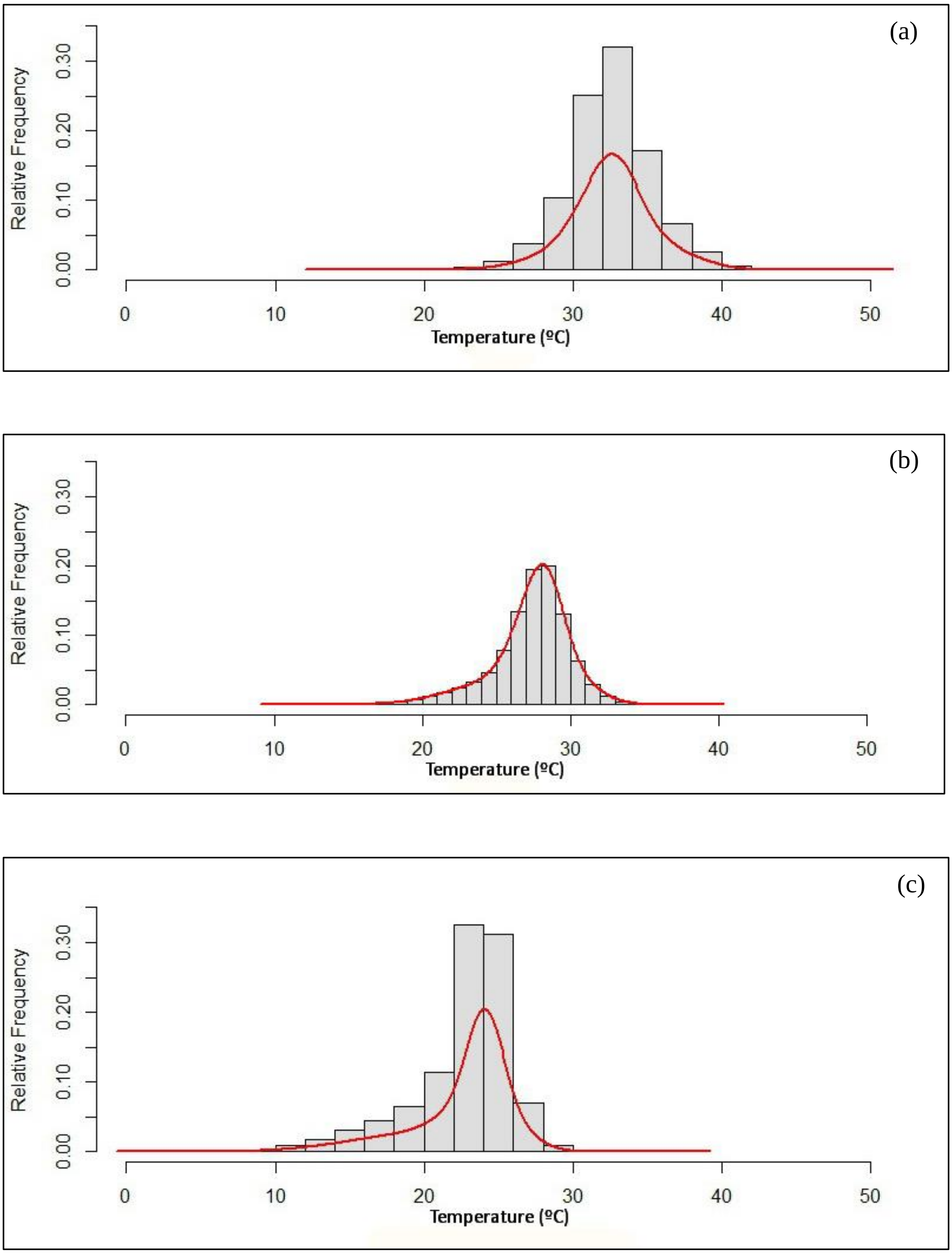


Figure 4.2 Distribution of (a) DMAX; (b) MDT and (c) DMIN of raw data obtained from meteorological stations.

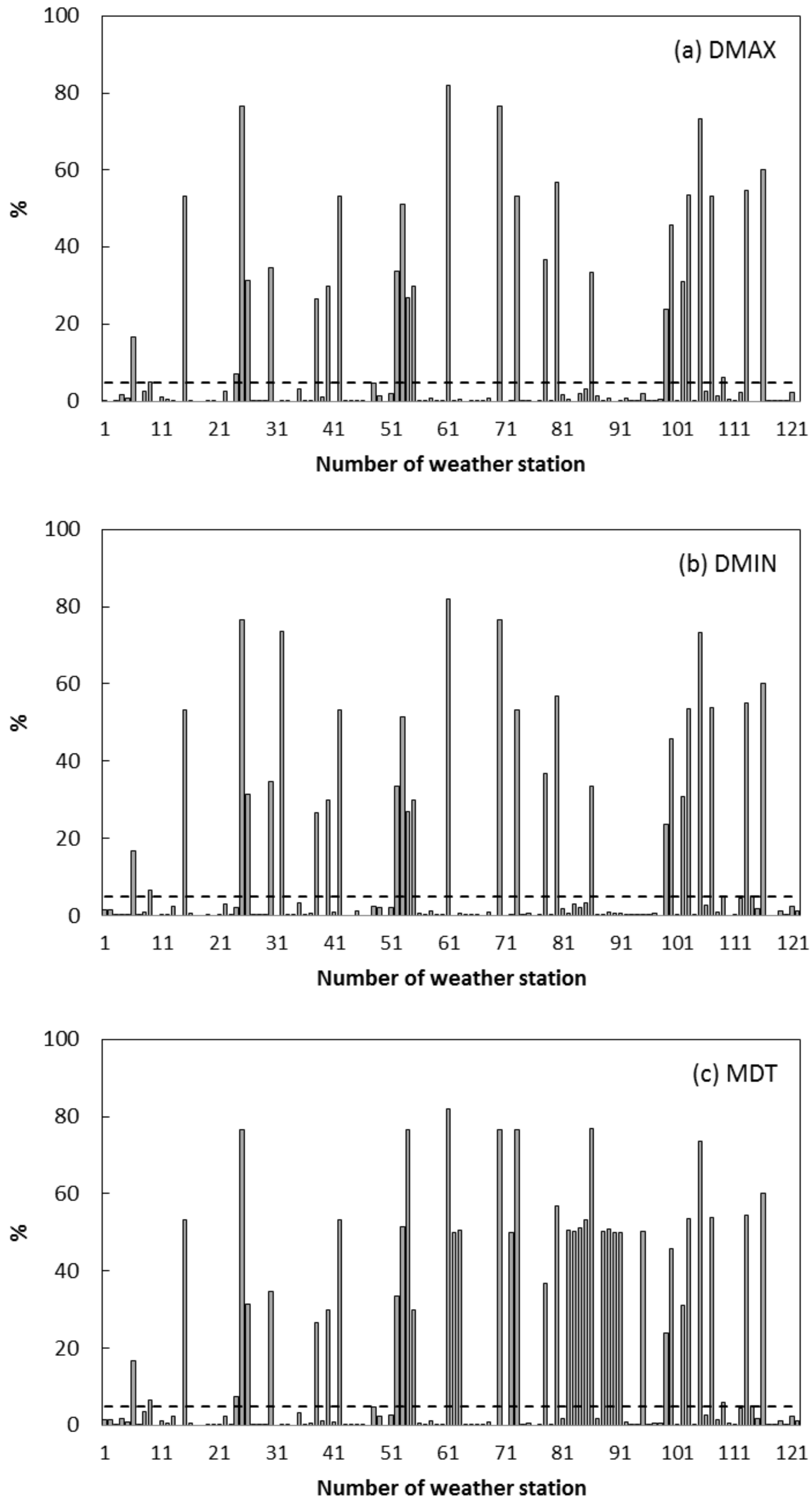
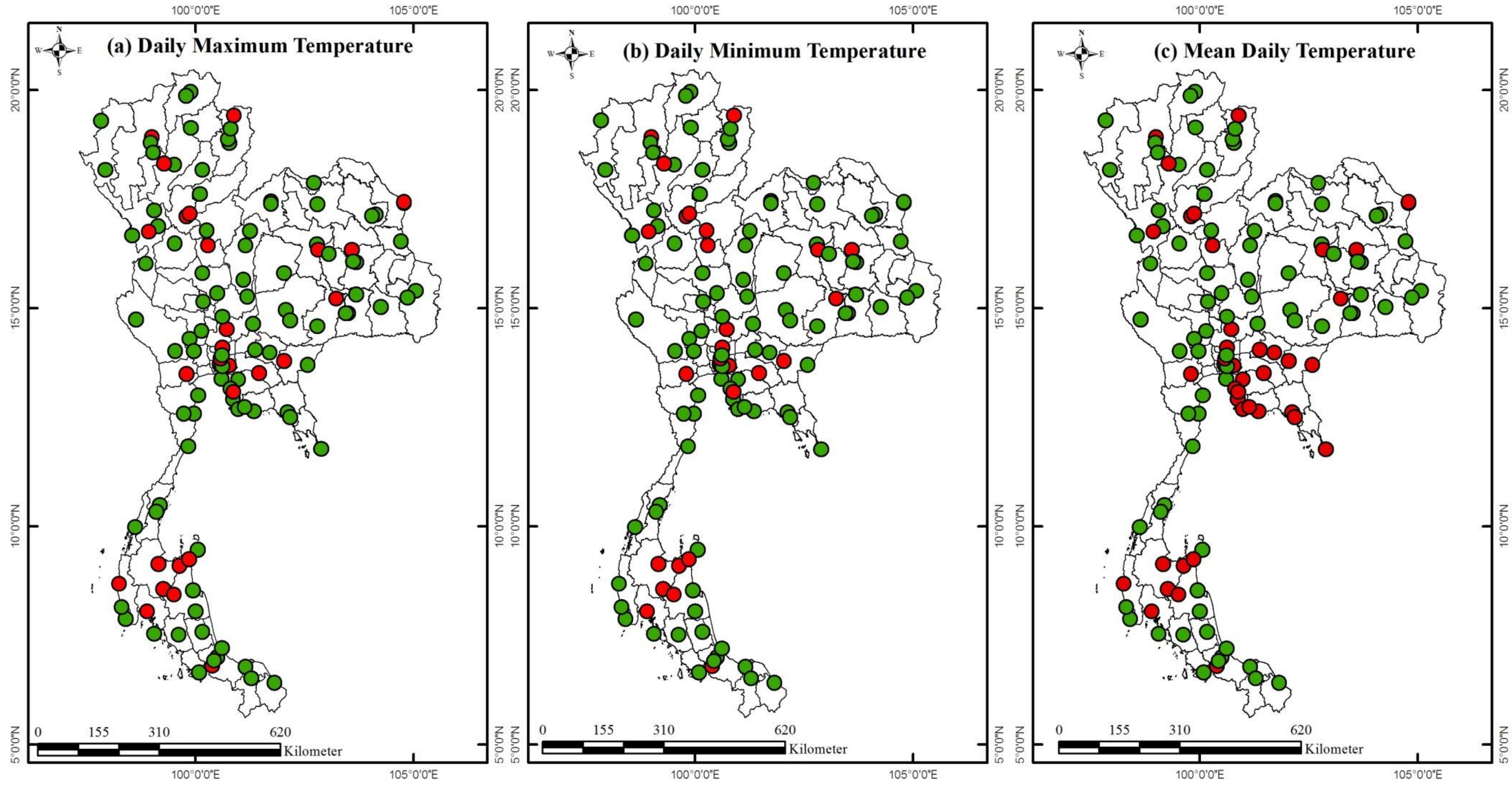


Figure 4.3 Percentage of missing data for each variable: (a) DMAX; (b) DMIN and (c) MDT. The horizontal dashed line indicates the missing 5%, off which the data were included in the analysis.



Legend: Missing data < 5% Missing data > 5%

Figure 4.4 Geographical distributions of the meteorological stations showing the stations where temperature data were used or not used in this study after the missing data tests: (a) DMAX (b) DMIN and (c) MDT.

4.3 Results of Data Quality Checks

4.3.1 Temporal Outlier Check

The Inter-quartile range technique for data with normal distribution patterns was used. The range of variability that has defined the scope outlier value is five times the IQR, which is commonly used to detect outliers and make a database of climate, daily and monthly (Feng *et al.*, 2004) sample to temporal outlier check. (example is given in Figure 4.5). Such techniques can detect outliers that deviate from monthly of the median appeared in serial data quite well. . The effects of outlier check in the all variable are summarized in Table 4.5. In most case, there were only minor data excluded due to outlier checks.

Table 4.5 Results of temporal outlier data checks for each variable.

Variable	Number of Outlier	(%)
1. DMAX	318	0.03
2. MDT	130	0.02
3. DMIN	174	0.02

Note: Outlier of data is $(x_i - q50) > |\pm 5 \times IQR|$

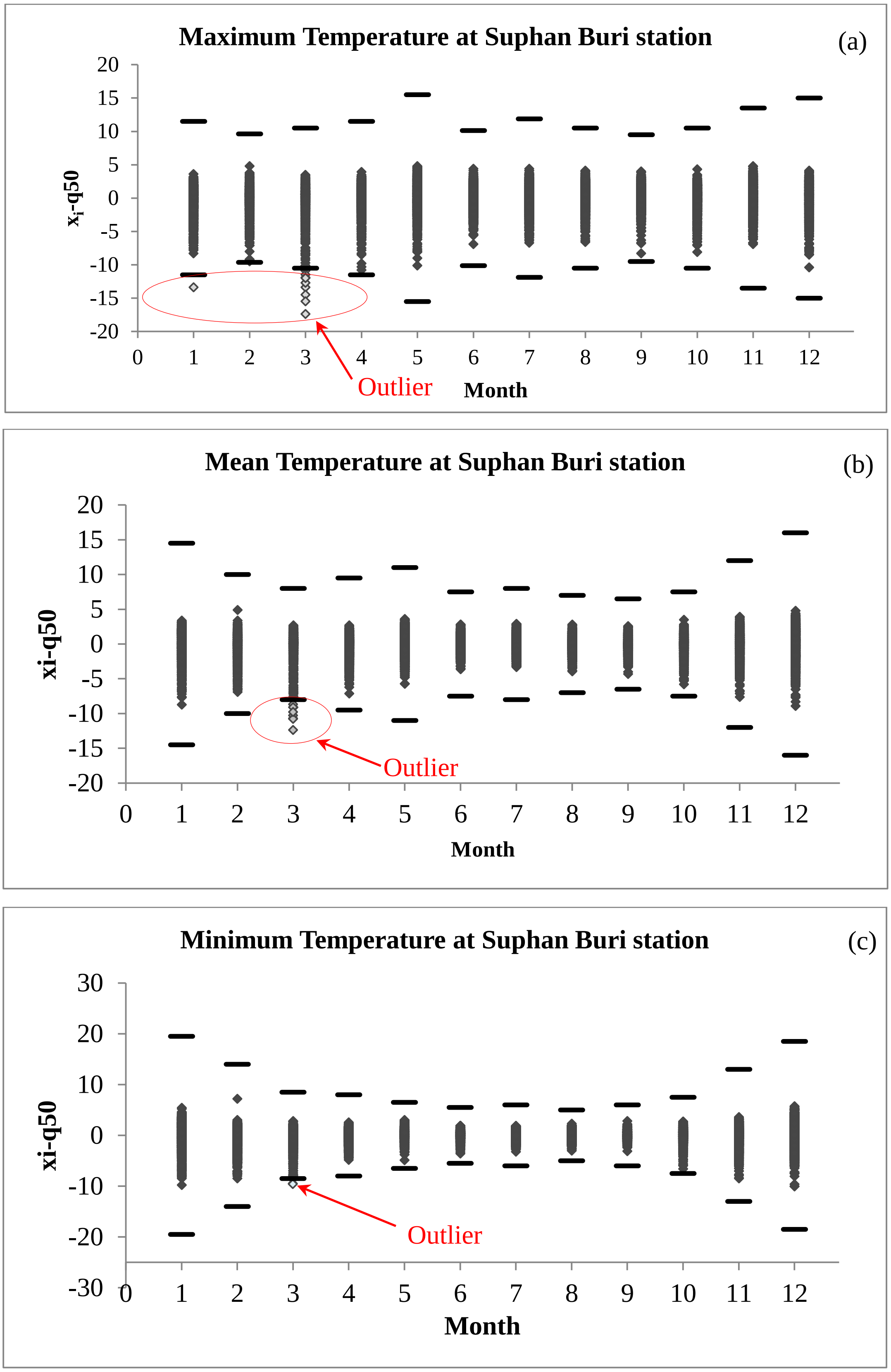


Figure 4.5 An example showing the temporal outlier check for each variable: (a) DMAX; (b) MDT and (c) DMIN at Suphan Buri station with variance range is 5×IQR. The values falling outside the upper and lower horizontal bars for each day indicate outliers.

4.3.2 Spatial Outlier Check

This method detects the outlier by comparing the data of neighboring stations. Correlation coefficients *(r)* were computed for each month using daily data from at least from 3 nearby stations. Stations with statistically significant positive *r* (at the 95% confidence level) were used to create their linear regressions for the same variable between neighboring stations and the candidate station. The effects of spatial outlier check in the all variable are summarized in Table 4.6, showing that only small fraction of data were removed after completing this check.

Table 4.6 Results of the spatial outlier check for each variable.

Variable	Number of Outlier	(%)
1. DMAX	1,481	0.15
2. MDT	563	0.06
3. DMIN	641	0.06

Note : Outlier of data is $XF_{ij} - 5\times RMSE_j < X_i < XF_{ij} + 5\times RMSE_j$

Figure 4.6 shows an example of the spatial outlier check for the relationship between two stations. We assign a daily value of a variable to be suspicious (outlier) if it falls outside the specified confidence intervals. After checking with the third station, if this value still remained outside the confidence range, it was considered as an outlier.

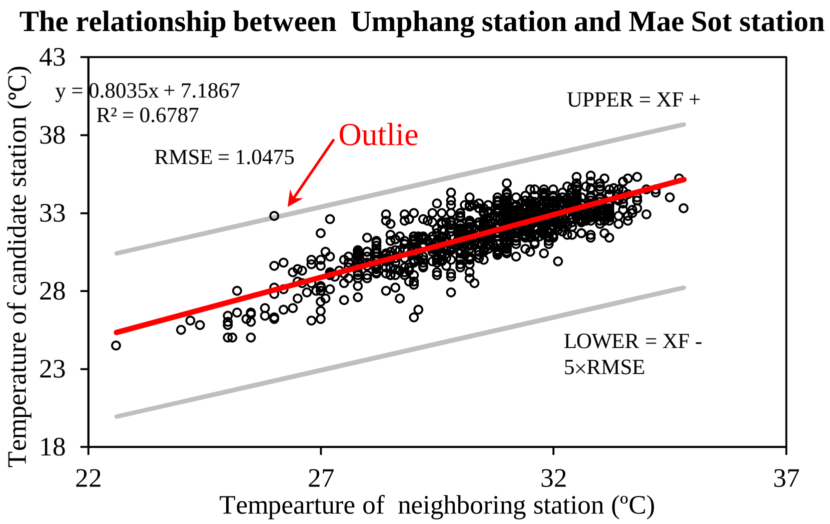


Figure 4.6 The spatial outlier check used linear regression between candidate station and neighboring station.

After performing these quality data checks, if there were any missing data from the data set, the interpolation of the missing data was performed using Equations (5) as described in Chapter 3. An example result is given in Figure 4.8. In sum, the overall fractions of data that were failed during these data quality checks and controls were less than 1% for DMAX, DMIN and MDT (Table 4.7). These were in the similar ranges of those found by (Limjirakan *et al.*, 2008) who reported that the temporal outlier data for DMAX, DMIN and MDT over Thailand for 1961-2005 were usually less than 1%.

Table 4.7 Percentages of erroneous and suspected data by categories.

Variable	Missing data (%)	Temporal outlier (%)	Spatial outlier (%)	Total (%)
DMAX	0.60	0.03	0.15	0.78
MDT	0.85	0.02	0.06	0.93
DMIN	0.78	0.02	0.06	0.86

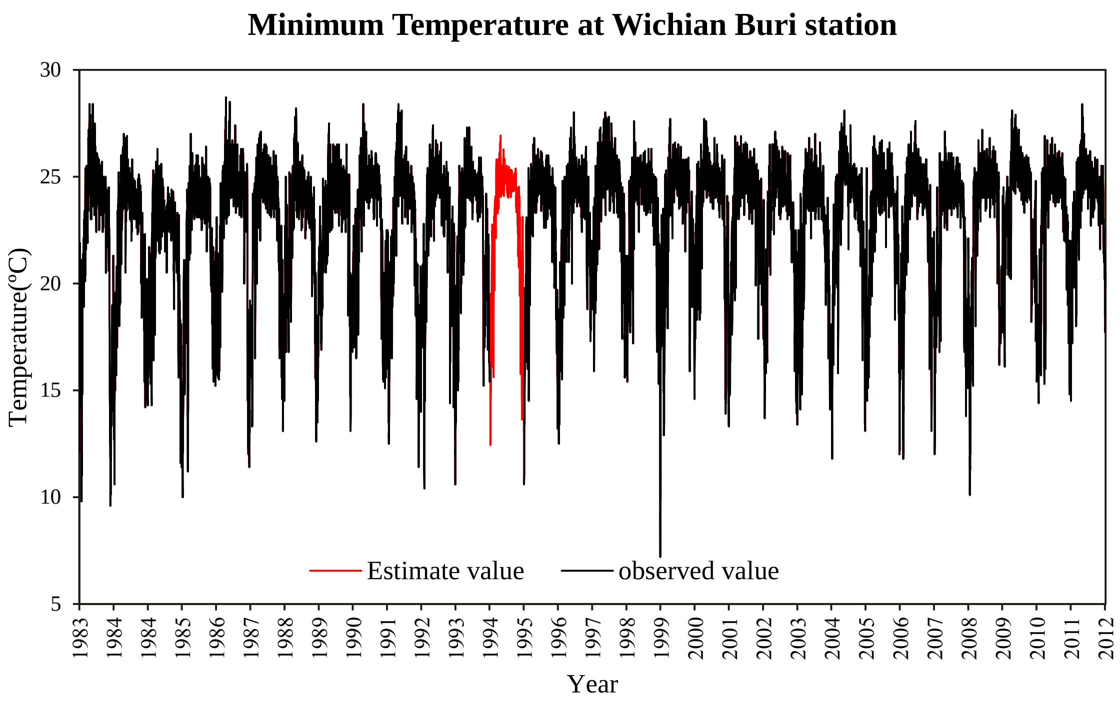


Figure 4.7 An example of gap filling of temperature data for DMIN at Wichian Buri station using the interpolation technique as described in the text.

4.3.4 Homogeneity Check of Data

Penalized Maximal *T* and *F* test (Wang *et al.*, 2007) were used to check the data homogeneity for individual variables. The time series being tested here can be a base series (the true series without a reference series case). To start, the check are identified the type-I change points. If there is no significant change point identified (not the type-I change points), the dataset series being checked can be declared to be homogeneous (Figure 4.8a). If type-I change points were found, re-assessment procedure was repeated by *Stepsize* to the significance and magnitude of the type-I change points. If type-I change points with the corresponding 95% uncertainly range, the dataset series being checked can be declared to be inhomogeneous (Figure 4.8b).

In this study, when a station's data was identified as inhomogeneous, that station's data series was removed from the database. The numbers of stations identified as having inhomogeneity are shown in Table 4.8.

Table 4.8 Number of station with identified inhomogeneity for each variable.

Variable	Number of stations (station)
1. DMAX	2
2. MDT	0
3. DMIN	1

After performing all of these data quality checks, some of the records of temperature data were excluded from the analysis. Overall, the number of stations included in the present study were 78, 80 and 69 stations for DMAX, DMIN and MDT, respectively. The geographical distribution of these meteorological stations is shown in Figure 4.9.

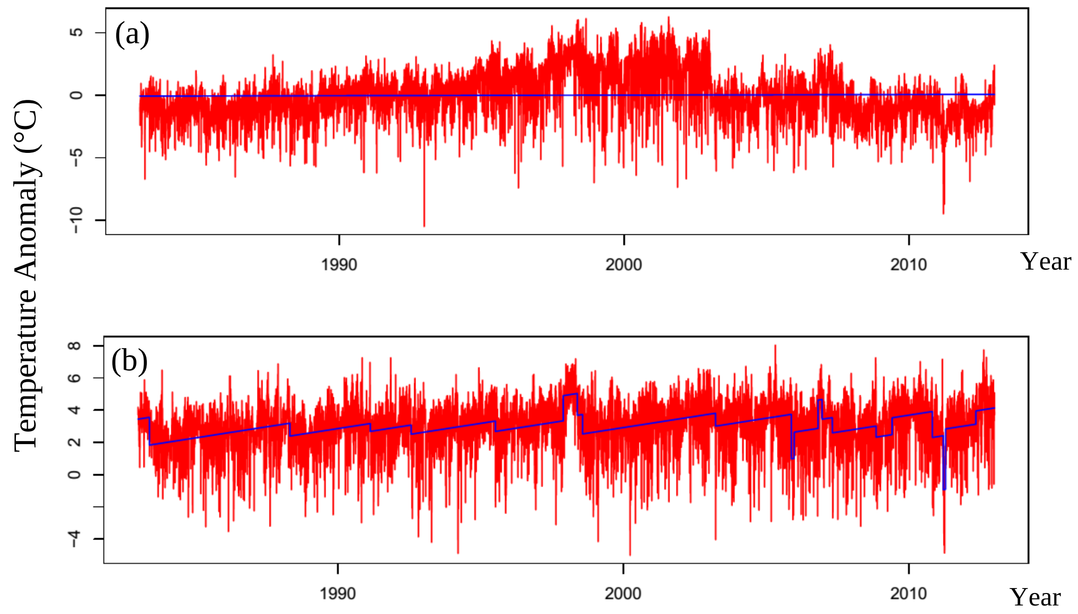


Figure 4.8 (a) An example of a base anomaly series and multi-phase regression fit for homogeneity data check of DMAX at Rayong station, (b) base anomaly series and multi-phase regression fit for inhomogeneity data of DMAX at Nakhorn Sri Thammarat, Agromet station.

4.4 Trends of Daily Maximum Temperature

Changes in daily maximum temperature and its average for each month calculated (linear regression) during 30 years are given in Table 4.9. The data clearly indicated that the temperatures have increased in every region. However, no sigificant change was found on an annual basis over the northern, central and southern parts of Thailand. The magnitude of change on the annual basis over Thailand was 0.40 °C 30 yrs^{-1} period. The magnitude of change in the annual mean DMAX was 0.44, 0.72, 0.28, 0.33 and 0.41 °C 30 yrs^{-1} in the northeastern, eastern, northern, central and southern regions, respectively. The warmest and coolest temperature appeared in the north and northeast parts of country, respectively.

The trends analyzed for each month during this 30-year period indicate that temperatures have increased in January in all regions, except in the central region. The seven months period (February, June, August, September October, November and December) has the increased rate of 0.03 - 1.90°C 30 yrs^{-1}. However, for some months negative trends were noticed in March, April and May. These decreased trends range from

-0.15° to -1.16°C 30 yrs^{-1}. These were found country wide except in eastern region. The monthly mean DMAX in the country was ranged from 30.3 to 35.6 °C, which was higher in the month of April than in other months (35.6°C). On the other hand, In December, the average DMAX was slightly lower (30.3°C).

Spatial variations in the trend of annual mean DMAX were examined at the meteorological stations (Figure 11a). About 80% of the stations showed positive trends. Among these, over 47% of the stations showed significant positive trends. For the eastern region, relatively large fractions of station (70%) showed a positive trend. The northeast region showed both positive and negative trends, with 57.9% of the stations showing significant positive trends and 5.3% showing significant negative trends. Mukdahan, and Thong Pha Phum stations showed largest warming trend with a warming rate of 0.50 – 0.55°C/decade.

Table 4.9 Trends and magnitude (mean) in monthly DMAX in different regions of Thailand. Positive and negative signs indicate increasing and decreasing trends over a 30-year period, respectively.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Thailand													
Trend (°C/30yrs)	0.25	0.28	-0.58	-0.73	-0.28	0.71	0.24	**0.43***	**0.40***	**1.13****	**1.54****	**1.30***	**0.40***
Mean(°C)	31.2	33.1	34.6	35.6	34.2	33.1	32.5	32.2	32.1	31.7	31.1	30.3	32.7
North													
Trend (°C/30yrs)	0.38	0.28	-0.90	-1.15	-1.07	0.62	0.08	0.16	0.24	**1.28****	**1.93****	**1.50***	0.28
Mean(°C)	31.3	33.8	35.9	37.1	34.7	33.1	32.3	31.9	32.2	32.0	31.1	30.1	32.9
Northeast													
Trend (°C/30yrs)	0.36	0.21	-0.66	-1.02	-0.15	**0.92***	0.29	0.28	0.11	**1.34****	**1.89****	1.68	**0.44****
Mean(°C)	30.7	33.1	34.9	36.1	34.3	33.3	36.7	32.1	31.8	31.3	30.7	29.7	32.6
Central													
Trend (°C/30yrs)	-0.06	0.03	-0.67	-0.53	-0.56	0.50	-0.02	0.37	0.55	**1.34****	**1.71****	1.30	0.33
Mean(°C)	32.0	33.6	34.9	36.0	34.7	33.7	33.1	32.9	32.7	32.1	31.6	31.0	32.5
East													
Trend (°C/30yrs)	0.32	0.54	0.14	0.17	0.46	**1.03***	0.58	**0.94****	**0.57***	**1.30****	**1.37***	1.22	**0.72***
Mean(°C)	32.4	33.1	33.9	34.8	33.7	32.9	32.4	32.2	32.0	32.1	32.2	31.9	32.8
South													
Trend (°C/30yrs)	0.14	0.47	-0.41	-0.42	0.36	**0.67***	**0.37***	**0.86****	**0.82****	**0.58***	0.79	0.70	0.41
Mean(°C)	31.3	32.5	33.4	34.1	33.3	32.8	32.5	32.3	32.0	31.4	30.8	30.4	32.2

** Significant at 99% level of confidence, * Significant at 95% level of confidence.

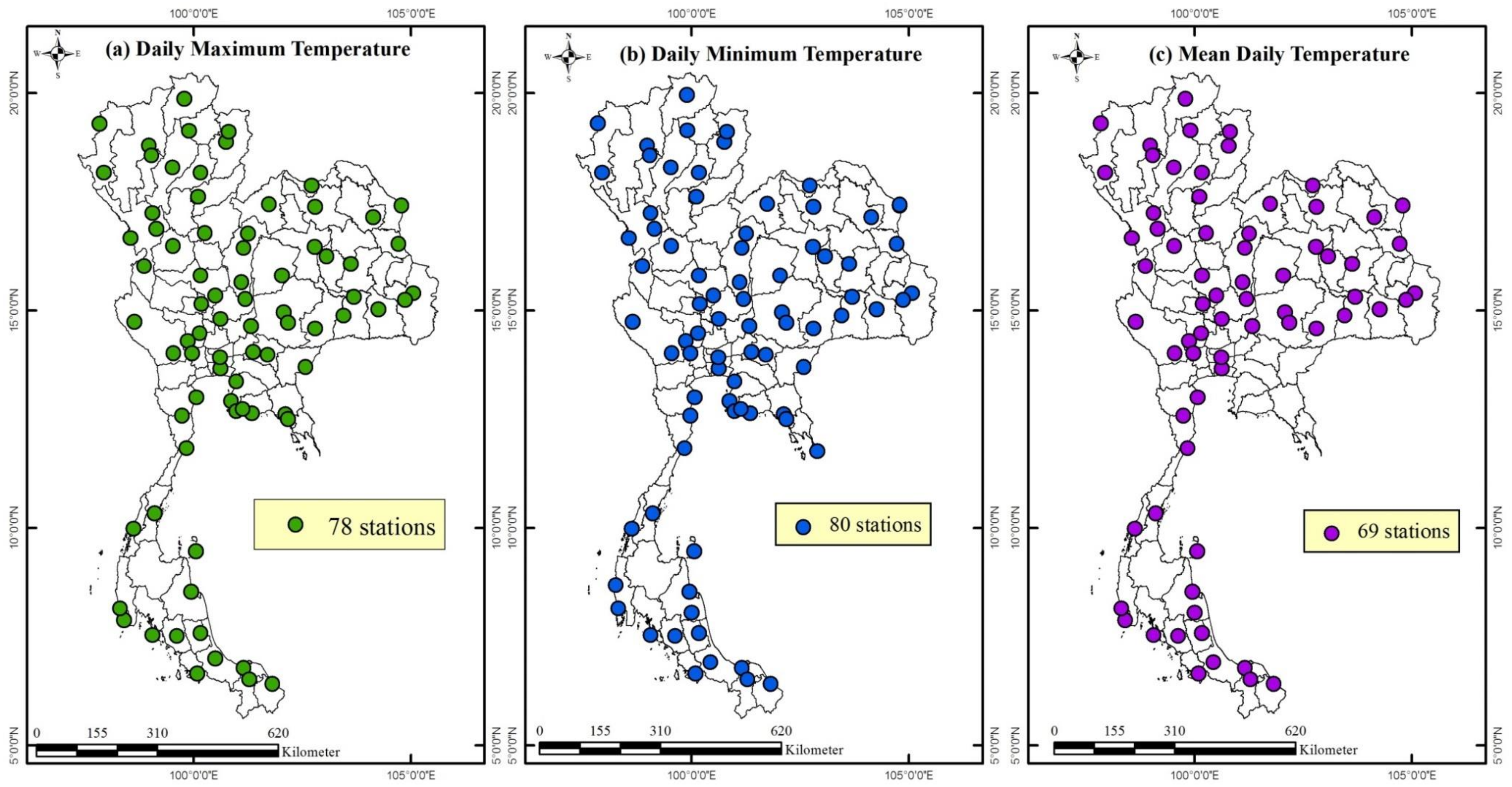


Figure 4.9 Geographical distributions of meteorological stations that were passed through the data quality checks and the temperature records from these stations were included in the present study: (a) DMAX; (b) DMIN and (c) MDT in Thailand.

The spatial changes in mean maximum temperatures during January to December are presented in Figure 4.11. It was indicated that rising trends were evident in October, November and December (over 45% of stations), notably northern, northeastern, central and eastern regions. Country wide, October showed the highest number of the inreased temperature trends (60 stations or 76.9%), except in southern region. In contrast, February, March, and April showed negative trends over 5% of stations, which appeared in some station in central and northern region.

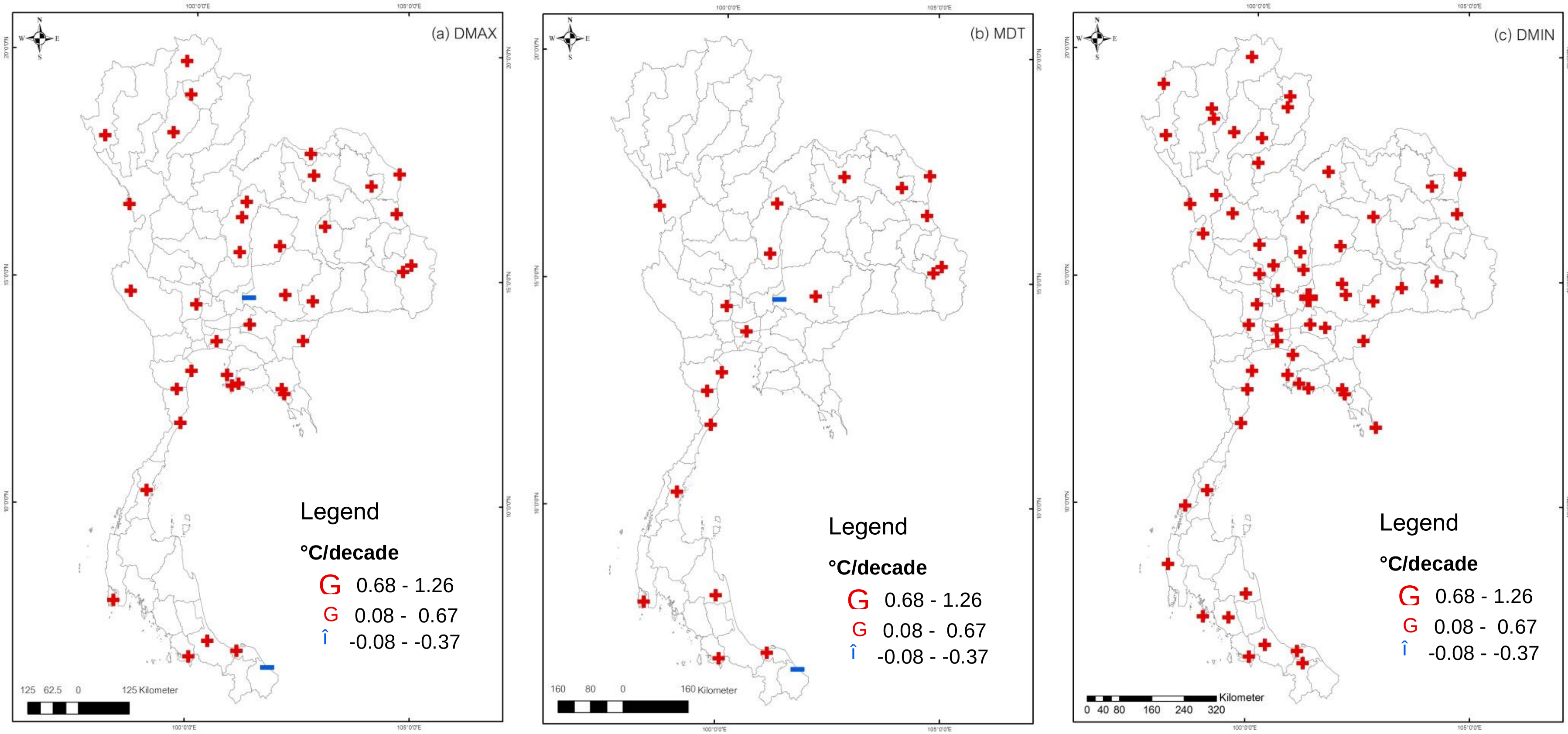


Figure 4.10 Spatial distribution of annual averages for (a) DMAX; (b) MDT and (c) DMIN in Thailand. Positive (+) and negative (-) signs indicate the significant increase and decreases in DMAX, MDT and DMIN, and the rate of change (°C/decade) is indicate by values following the signs.

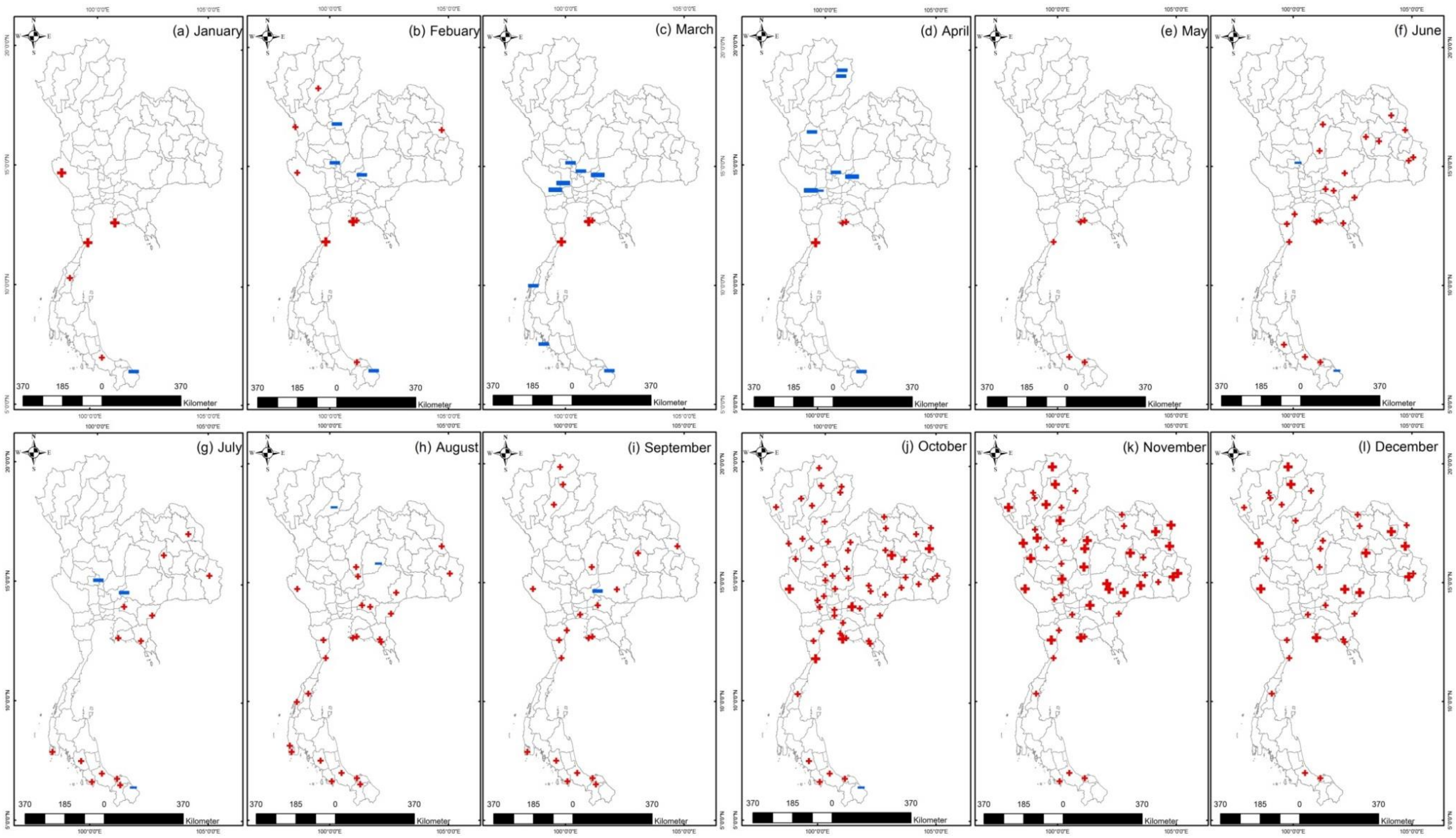


Figure 4.11 Spatial distribution of averages DMAX for (a) January; (b) Febuary; (c) March; (d) April; (e) May; (f) June; (g) July; (h) August; (i) September; (j) October; (k) November and (l) December. Positive (+) and negative (-) signs indicate the significant increases and decreases in DMAX and the rate of change (°C/decade) is indicated by values following the signs.

4.5 Trend of Daily Minimum Temperature Data

The trends in each region of annual mean DMIN during 1983-2012 are presented in Table 4.10. Overall, there was a significant increasing trend in DMIN country wide, with the range of 0.66 – 1.04 °C 30 yrs^{-1}. The annual mean DMIN averaged over the whole country was an increase of 0.89 °C 30 yrs^{-1}. The monthly trends for the months January to December showed positive trends in all region of the country, except during April in northeastern and eastern regions that showed the negative trends but these were not statistically significant. During July, September, October and December the increasing trends were observed with statistical significance of rate of 0.52 - 3.14 °C 30 yrs^{-1}. These were especially obvious in December. The monthly mean of DMIN in the country was ranged from 16.0 to 25.7 °C, which was higher in the month of April (25.7°C) of eastern region. On the other hand, in January, the magnitude of mean DMIN was lower (16.0°C).

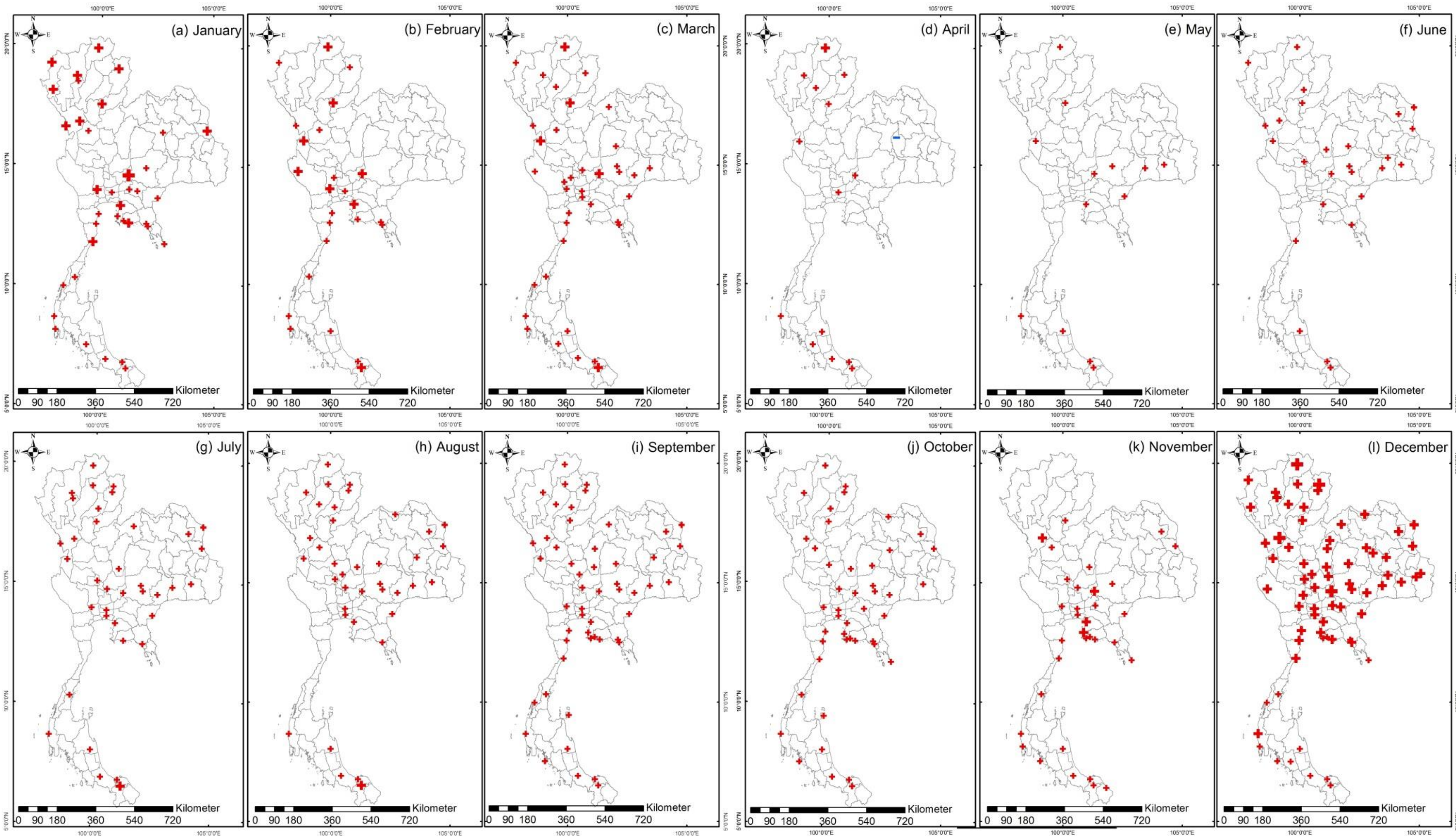
The spatial distributions in the trend of annual mean DMIN are shown in Figure 10c. About 95% of the stations showed the possitve trends. Among these, about 76% of station the mean DMIN have increased with statistical significance. The negative trends appeared in Udon Thani, Bhumibol Dam and Nakhorn Sri Thammarat Agromet stations. The central and eastern regions showed a possitive trends in all stations, with 80% and 90.9% of the station, respectivly, showed the statistically significant possitive trends. The northeastern, northern and southern region showed both positive and negative trends, with 95% of the stations showing positive trends. Majority of stations in the northeastern, northern and southern regions have also shown to have significant positive trend with 65%, 86.4% and 73.7% of the stations, respactively. Chiang Rai, Uttaradit, Pak Chong Agromet, Chon Buri and Yala Agromet stations showed largest increasing trend with the increasing rate ranging between 0.58 and 0.73°C/decade.

The spatial variation of changes in mean DMIN during January to December are shown in Figure 4.12. Majority of the months showed increasing trends, with over 80% of station in each month showing positive trends, except in April with positive trends below 80% of the station. Most of station (88.7%) showed the significant positive trends in December. Northern region showed highly a significant positive trends in the month of July, August, September and December with 57.1%, 66.7%, 76.2% and 95.2% of the stations in this region, respectively.

Table 4.10 Trends and magnitude (mean) in monthly DMIN in different regions of Thailand. Positive and negative signs indicate increasing and decreasing trends over 30 years period, respectively.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Thailand													
Trend (°C/30yrs)	**1.42***	**1.08***	**0.84****	0.26	0.39	**0.48****	**0.61****	**0.45****	**0.66****	**0.76****	**1.04***	**2.33****	**0.86****
Mean(°C)	19.1	20.6	22.6	24.4	24.7	24.7	24.4	24.3	24.0	23.2	21.4	19.2	22.7
North													
Trend (°C/30yrs)	1.80	1.32	1.12	0.57	0.47	**0.58****	**0.59****	**0.46****	**0.76****	**0.83***	**1.00****	**3.14****	**1.04****
Mean(°C)	16.0	17.6	20.6	23.6	24.2	24.3	24.0	23.9	23.6	22.5	19.6	16.3	21.4
Northeast													
Trend (°C/30yrs)	1.39	0.68	0.61	-0.23	0.35	**0.63****	**0.58***	**0.46****	**0.58****	**0.82***	1.33	**2.88****	**0.85****
Mean(°C)	17.0	19.4	22.0	24.3	24.6	24.8	24.5	24.3	23.9	22.6	20.0	17.1	22.0
Central													
Trend (°C/30yrs)	1.48	**1.43***	**1.04****	0.12	0.14	0.32	**0.52***	0.37	**0.52****	**0.64***	**1.01***	**2.62****	**0.85****
Mean(°C)	20.1	22.0	23.9	25.4	25.4	25.2	24.8	24.8	24.5	24.0	22.3	19.8	23.5
East													
Trend (°C/30yrs)	**1.58***	0.92	0.44	-0.20	0.30	**0.40***	**0.57***	**0.50****	**0.70****	**0.99****	**1.39****	**2.28****	**0.83****
Mean(°C)	21.5	23.3	24.7	25.7	25.6	25.5	25.2	25.1	24.6	24.0	22.9	21.2	24.1
South													
Trend (°C/30yrs)	**1.00****	**1.09****	**0.83****	**0.58****	**0.45****	**0.34***	**0.69***	**0.41****	**0.68****	**0.55****	**0.70****	**1.04****	**0.66****
Mean(°C)	22.5	22.6	23.4	24.3	24.6	24.4	24.1	24.1	23.9	23.7	23.4	22.8	23.6

** Significant at 99% level of confidence, * Significant at 95% level of confidence.



Legend G 1.27 - 1.85 G 0.68 - 1.26 G 0.08 - 0.67 î -0.08 - -0.37 î -0.38 - -0.66 î -0.67 - -0.95 **°C/decade**

Figure 4.12 Spatial variations of average of DMIN for (a) January; (b) Febuary; (c) March;(d) April; (e) May; (f) June; (g) July; (h) August; (i) September; (j) October; (k) November and (l) December. Positive (+) and negative (-) signs indicate the significant increase and decrease in DMIN and the rate of change (°C/decade) is indicated by values followed the signs.

4.6 Trend of Mean Daily Temperature Data

The results of the trend analysis of the annual and monthly MDT in each region of Thailand are given in Table 4.11. During 30 year of measurement at all 69 meteorological stations, the mean temperature in Thailand was 27.0 °C. This has increased at the rate of 0.57 and 1.47 °C $30yrs^{-1}$ ($p<0.01$) in October and December, respectively. In the north Thailand, the mean temperature was 26.5 °C. This has increased with statistical significant at the rate of 0.53 and 2.03 °C $30yrs^{-1}$ ($p<0.01$) in October and December, respectively. The northeastern region, the mean temperature was 26.8 °C and this has increased at the rate of 0.34 °C $30yrs^{-1}$ ($p<0.05$). June, October and December have shown a significant increase at a rate of 0.62 ($p<0.05$), 0.82 ($p<0.01$) and 1.69 °C $30yrs^{-1}$($p<0.05$), respectively. For central region, the mean temperature was 27.9 °C, which was highest among regions. The trends during October, Nevember and December hav a significant increase at the rate of 0.64 ($p<0.01$), 1.01 ($p<0.05$) and 1.58 °C $30yrs^{-1}$ ($p<0.05$), respectively. For southern region, the mean temperature was 27.4 °C and this has increased at the rate of 0.22 °C $30yrs^{-1}$ ($p<0.05$). During June, July, August, September, October and December have increased at the rate of 0.35 ($p<0.05$), 0.17($p<0.05$), 0.42 ($p<0.01$), 0.39 ($p<0.01$), 0.27 ($p<0.05$) and 0.41 ($p<0.05$) °C $30yrs^{-1}$, respectively.

The spatial variations of annual mean MDT over Thailand is shown in Figure 4.10b. The figure shows that mean MDT trend has decreased significantly in 2 meterological stations (Pak Chong Agromet and Narathiwat stations) and increased significantly in 20 meterological stations. The spatial change of monthly mean MDT over Thailand is shown in Figure 4.13. The mean MDT of January showed a significant increasing trend at 19 5meterological stations in north, central and south parts of Thailand, and this has a significant decreasing trend at Thong Pha Phum and Narathiwat station (Figure 4.13a). For February, the trend has a significant increase at 8 meteorological stations as well as a deccreasing trends at 8 meterological stations (Figure 4.13b). The trend for March has increased significantly at Thong Pha Phum and Prachuap Khiri Khan station, however the significant decreasing trend showed at 6 meterological stations in central Thailand (Figure 4.13c). For April, this has decreased at 7 meterological stations, and this has increased at 4 meterological stations (Figure 4.13d). As the month of May, June, July, August and September having significant increasing trends at 3, 15, 11, 16 and 18 meterological stations, respectively (Figure 4.13e to i), and these have decreased significantly at 5, 2, 5, 1 and 1 meterological stations, respectively (Figure 4.13f). In contrast of October, November and December during have increased significantly at 50 (72%), 24 (34%) and 40 (58%) meterological stations, respectively. In conclusion, the majority of the months have increasing trends appearing in October, November and December.

Table 4.11 Trends and magnitudes (mean) of monthly MDT in different regions of Thailand. Positive and negative signs indicate increasing and decreasing trends over a 30-year period, respectively.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Thailand													
Trend (°C/30yrs)	0.54	0.16	-0.39	-0.51	-0.19	0.39	0.09	0.18	0.20	**0.57****	0.73	**1.47****	0.29
Mean(°C)	24.3	26.3	28.1	29.4	28.7	28.3	27.8	27.6	27.3	26.9	25.7	24.0	27.0
North													
Trend (°C/30yrs)	0.95	0.09	-0.47	-0.68	-0.60	0.35	0.06	0.08	0.14	**0.53****	0.68	**2.03****	0.27
Mean(°C)	22.7	25.3	27.8	29.7	28.7	28.0	27.5	27.2	27.1	26.6	24.8	22.5	26.5
Northeast													
Trend (°C/30yrs)	0.56	0.23	-0.47	-0.71	-0.06	**0.62***	0.21	0.18	0.10	**0.82****	0.94	**1.69***	**0.34***
Mean(°C)	23.3	25.9	28.0	29.5	28.7	28.4	28.0	27.5	27.2	26.7	25.3	23.1	26.8
Central													
Trend (°C/30yrs)	0.33	0.05	-0.54	-0.43	-0.30	0.16	-0.16	0.03	0.13	**0.64****	**1.01***	**1.58***	0.21
Mean(°C)	25.9	27.7	29.1	30.1	29.3	28.9	28.4	28.2	27.9	27.6	26.7	25.2	27.9
South													
Trend (°C/30yrs)	0.11	0.25	-0.15	-0.16	0.24	**0.35***	**0.17***	**0.42****	**0.39****	**0.27***	0.39	**0.41***	**0.22***
Mean(°C)	26.5	27.3	27.9	28.5	28.2	28.0	27.7	27.6	27.2	26.9	26.6	26.2	27.4

** Significant at 99% level of confidence, * Significant at 95% level of confidence.

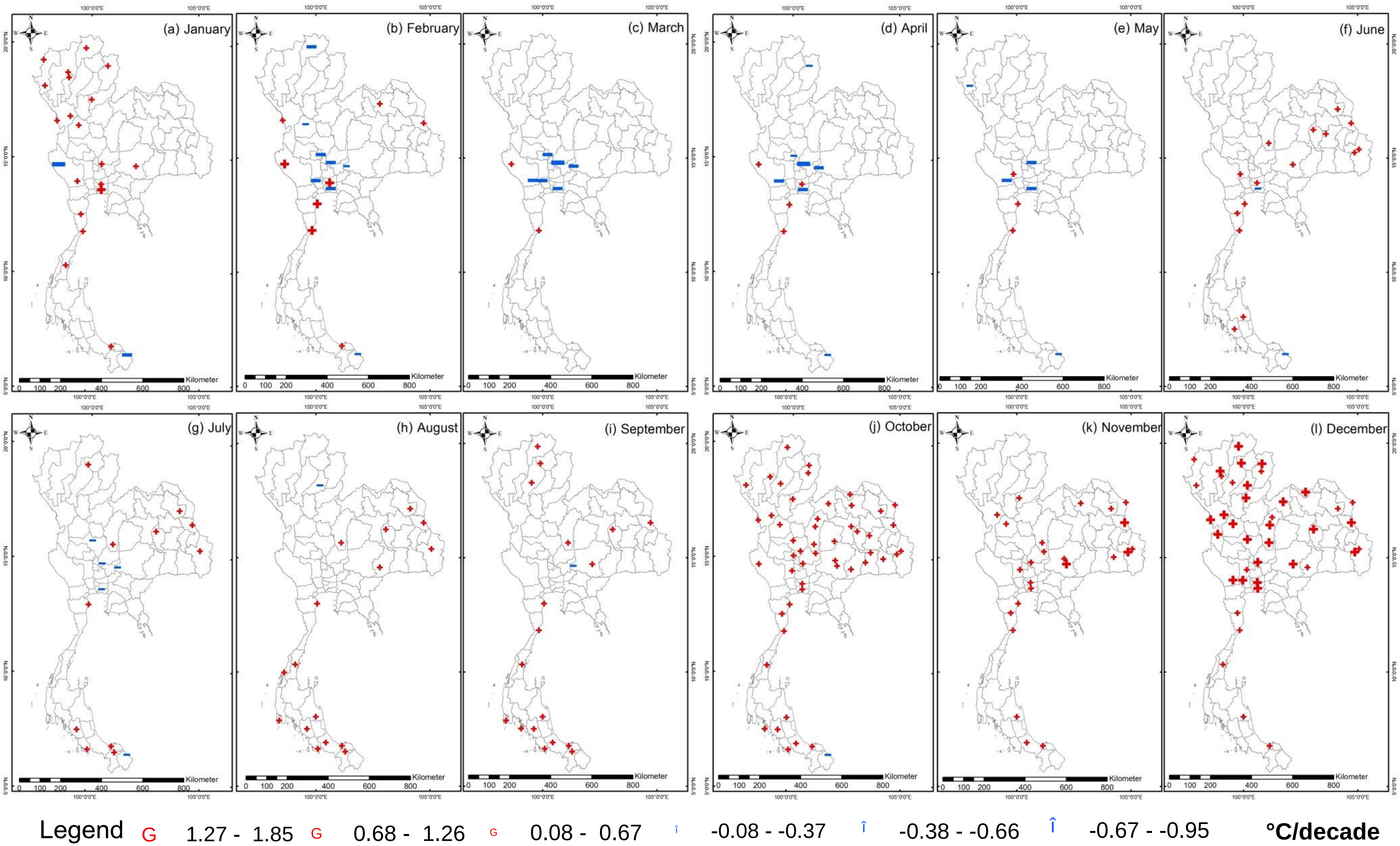


Figure 4.13 Spatial variations of average of MDT for (a) January; (b) Febuary; (c) March;(d) April; (e) May; (f) June; (g) July; (h) August; (i) September; (j) October; (k) November and (l) December. Positive (+) and negative (-) signs indicate the significant increases and decreases in MDT and the rate of change (°C/decade) is indicated by values followed the signs.

4.7 Changes in daily maximum temperature ≥ 35°C

4.7.1 Overview

The threshold of high temperature that exerts damages to rice production has been suggested as a maximum daily temperature of ≥35°C (Yoshida, 1981; Sun and Huang, 2011). Exposing rice plant to this temperature for one hour was sufficient to induce sterility in rice (both indica and japonica genotypes). These temperature indices were then analyzed. Number of days with maximum temperature ≥35°C was found about 19% of total number of DMAX day. The range of maximum temperature ≥35°C was 35- 50 °C, which the highest temperature was found at Naratiwat station in 2006. About 60% of maximum temperature ≥35°C has a range of 35-36 °C (Figure. 4.14).

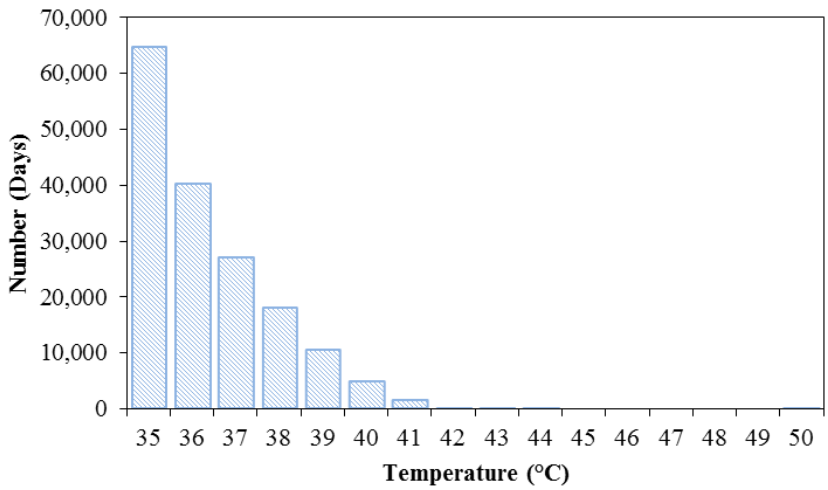


Figure 4.14 Frequency distribution of maximum temperature ≥35°C.

The temporal distribution in the number of days with the maximum temperature ≥35°C is presented in Figure 4.15. This figure, indicates that the highest average number of days with maximum temperature ≥35° are in April, followed by March and May, respectively. There months are the hot season of Thailand.

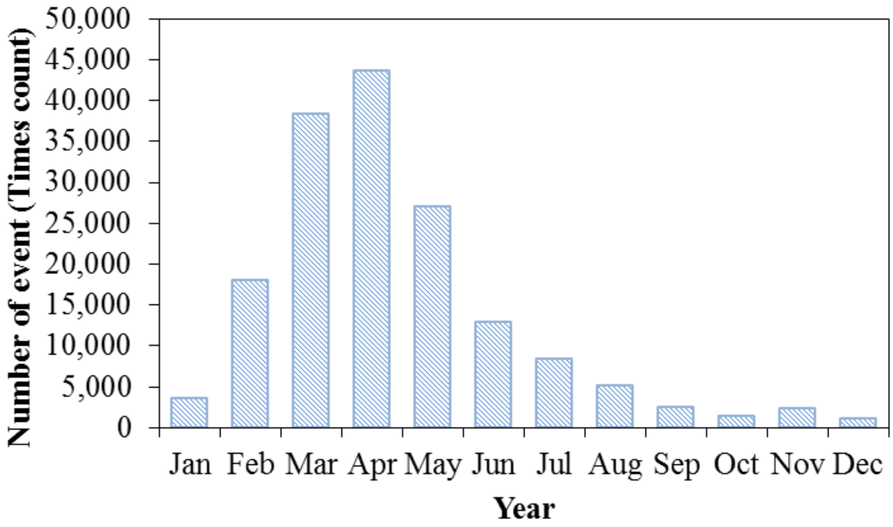


Figure 4.15 The temporal distribution of the number of days with the maximum temperature ≥35°C among the months in a year.

4.7.2 Trend in the number of days with maximum temperature ≥35°C

The trend in the average number of days with maximum temperature ≥35°C are presented in Figure 4.16. The figure indicates that annual average number of days with maximum temperature ≥35°C has slightly increased since 1983, with the largest and smallest years being 1998 and 2011, respectively. These results are consistent ENSO events with over the period 1983, 1987/88, 1991/1992, 1994/1995, 1997/1998, 2002/2003, 2004/2005, 2006/2007 and 2010/2011, which were El Niño events. These periods were found the be associated with the higher number of high temperature day. La Niña events appeared over the period 1983/1984, 1985/1986, 1988/1989, 1995/1996, 1998/2001, 2005/2006, 2007/2008, 2009/2010, 2010/2011 and 2011/2012 with the cold phase (NOAA, 2012). These periods were associated with the number of high temperature day lower than average. The annual average number of high temperature days had an increase by 5.3 days 30 yrs^{-1} but not significant. The magnitude of average number of days with maximum temperature ≥35°C was 70.3 days/year. Similar, Limjirakan *et al.*, (2008) reported that the number of day change for daily maximum temperature above 35°C in Thailand was 21.3 days 42 yrs^{-1}.

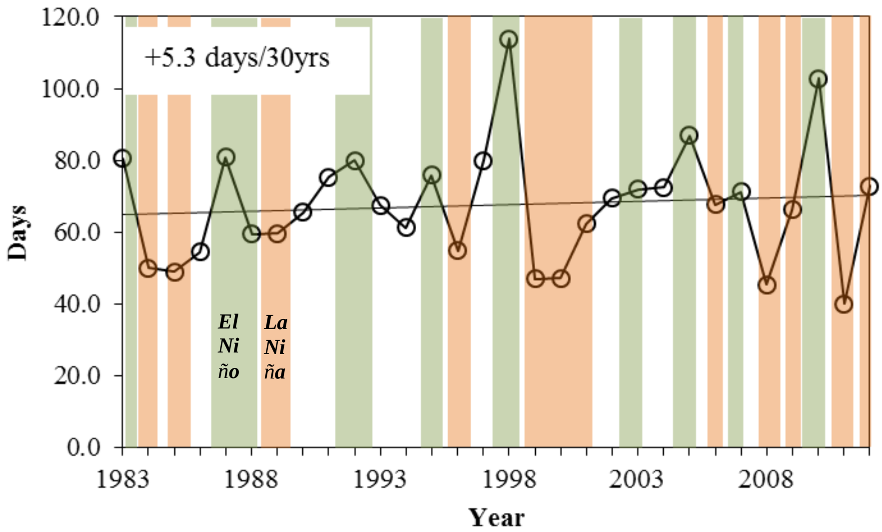


Figure 4.16 Trend in average number of days with maximum temperature ≥35°C. The shading areas indicate the duration of El Niño and La Niña.

The trend in the average number of days with maximum temperature ≥35°C in each month are presented in Figure 4.17. Overall, these were increased in January, February, June, July, August, September, October, November and December with increasing rates ranging from 0.1-2.3 days 30yrs^{-1}. During August to December this has increased significantly (Figure 4.17h to l). August is still during the rice growing season and December is usually during late harvest season. From these data, it can be said that in Thailand the number of days with maximum temperature ≥35°C has overall increasing trends. However, in March, April and May, these have decreasing trends with 1.0 - 2.7 days 30yrs^{-1}.

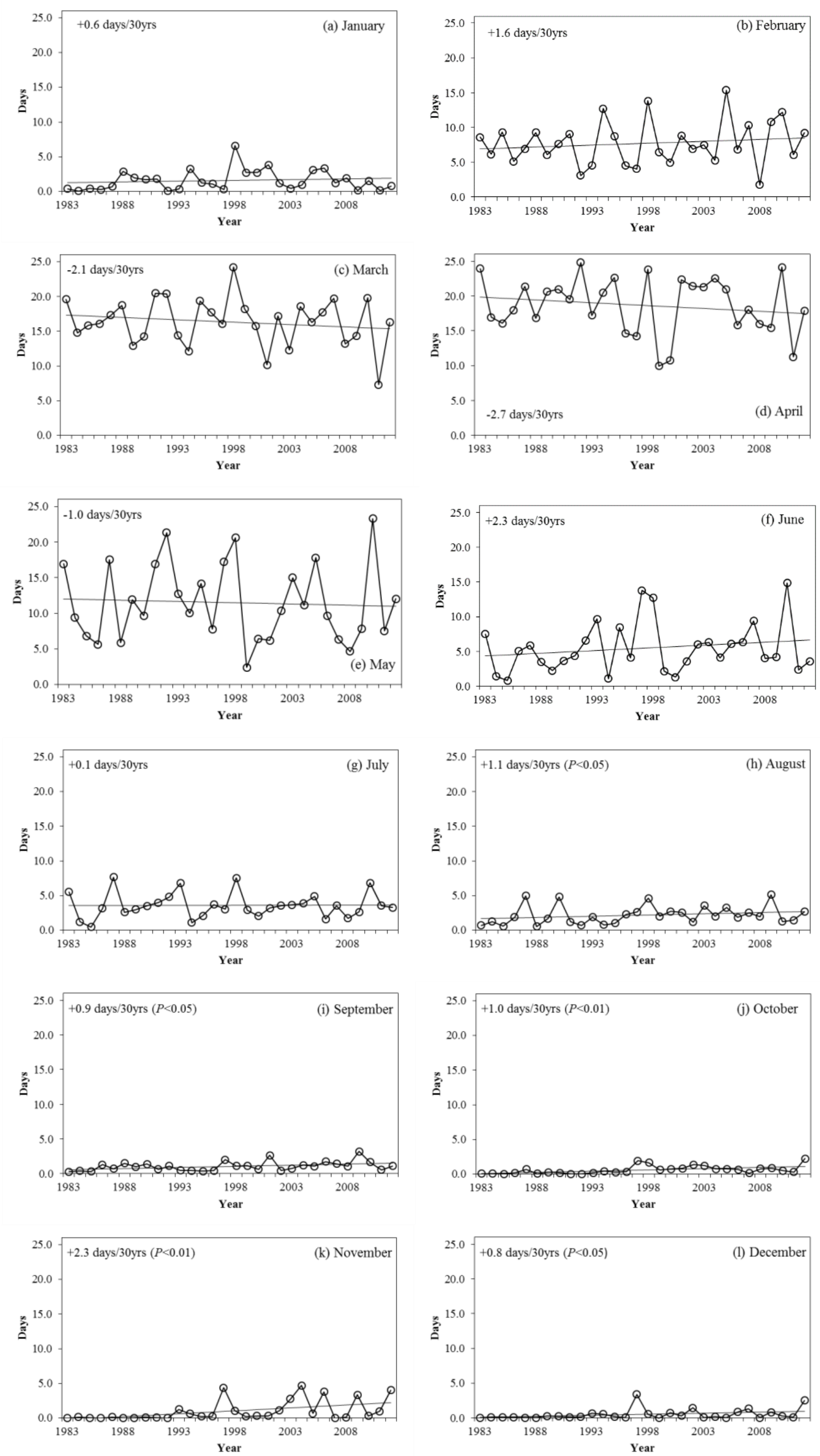


Figure 4.17 Trends in average number of days with maximum temperatures ≥35°C in (a) January; (b) February; (c) March; (d) April; (e) May; (f) June; (g) July; (h) August; (i) September; (j) October; (k) November and (l) December.

The spatial distribution of the average number of days with maximum temperature ≥35°C at the individual station are shown in Figure 4.18. The figure shows that about 55% of the stations have an increasing trend. Out of total stations, the temperature at 12 stations have increased significantly. On the other hand, temperature at some stations have decreased significantly. These were at Chiang Rai Agromet, Pak Chong Agromet and Narathiwat stations.

The spatial changes in the monthly number of days with the maximum temperature ≥35°C are presented in Figure 4.19a to l. The monthly trends indicated that rising trends were noticed in more number of stations during November in northeastern, central and some northern region. The increasing trends could be noticed over 60% of total station with a positive of 0.1 - 10.1 days 30yrs^{-1} (Figire 4.19k). The month of January showed a significant increase at Thang Pha Phum, Sattahip and Nong Phlup Agromet station. February appeared a significant increase account 10 stations and a significant decrease at Chai Nat. In March, April, May June, July, August, September, October, November and December showed a significant increase account 3, 4, 2, 10, 8, 10, 8, 19, 16, 12, 47 and 13 stations, respectively.

The spatial distribution of the cumulated number of days with maximum temperature ≥35°C during 1983-2012 is shown in Figure 4.20. About 56% of station showed number of days with maximum temperature ≥35°C above 2,000 days 30yrs^{-1}. The majority of stations appeared in northeastern, central and northern region. In southern region showed number of days with maximum temperature ≥35°C below 2,000 days 30 yrs^{-1}. In addtion, the highest number of days with maximum temperature ≥35°C appeared at Kanchanaburi station with 4,310 days 30yrs^{-1}.

The monthly cumulated number of days with maximum temperature ≥35°C is shown in Figures 4.21a to l. Overall, the majority of the stations in each month showed the cumulated number of days with maximum temperature ≥35°C below 300 days 30 yrs^{-1}. However, during Febraury to July these were above 300 days 30yrs^{-1} in many stations. The highest of number of days with maximum temperature ≥35°C was found at Mae Hong Son, Mae Sariang, Lampang, Uttaradit and Nakhon Sawan station in April with over 800 days 30yrs^{-1}. The number of days with maximum temperature ≥35°C with 700-800 days 30yrs^{-1} was noticed in central and northern region, accounting for 20 and 23 stations for March and April, respectively. The months of September to December showed the number of days with maximum temperature ≥35°C below 200 day 30yrs^{-1}.

The numbers of consecutive days with temperature ≥35° are presented in Figures 4.22a to f. Majority of station showed number of times with temperature of ≥35° that last for 1 day until 3 consecutive days. Figure 4.22a shows a time with temperature of ≥35° that last for 1 day. Majority of them showed a number above 1,320 times in the northeastern, northern and central region. About 70% of total stations showed a value between 1,321-3,960 times 30yrs^{-1}, with the highest at Kanchanaburi stations followed by Nakhon Sawan, Bua Chum, Uttaradit and Suphan Buri station, respectively (red color). In eastern and southern region showed a number of times below 1,980 times. For 2 consecutive days with temperature of ≥35° are showed in Figure 4.22b. This Figure showed a value of 1-181 times 30 yrs^{-1}, which the highest at Thong Pha Phum stations with 181 times 30 yrs^{-1}. About 67% of total station showed a number of times above 60 times 30 yrs^{-1}, which appeared in central, northern and northeastern region. In the southern and eastern regions, there have appeared a number of times below 90 times 30yrs^{-1}.

For 3 consecutive days with temperatures of ≥35°, the results are given in Figure 4.22c. This indicates that about 88% of the total stations were noticed, of which about 50 stations were noticed for a number of times below 6 times 30 yrs^{-1}. The highest of number appeared at Thong Pha Phum stations with 17 times 30 yrs^{-1}. About 30% of total stations were noticed with 4 consecutive days (Figure 4.22d), which appeared a number of times below 2 times 30 yrs^{-1}. The highest stations were noticed at Bhumibol Dam, Lom Sak, Kosum Phisai, Chai Nat and Donmuang station. Wichian Buri station were found for the ≥35° temperature episode which last for 5 consecutive days (Figure 4.22e). Finally, for 6 consecutive days with maximum temperature of ≥35° were noticed at Rayong and Huai Pong Agromet station in the eastern region.

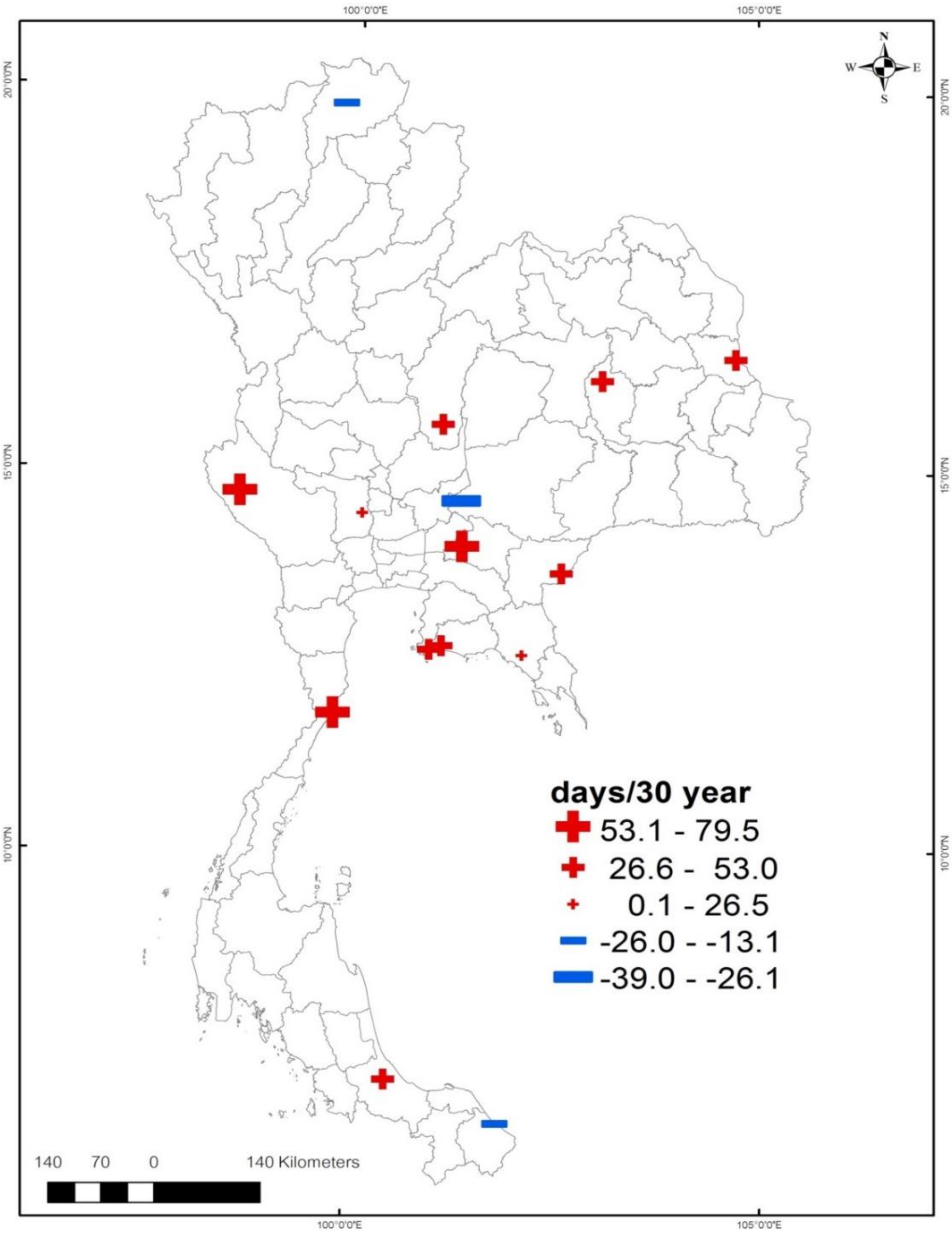


Figure 4.18 Spatial variations in the average number of days with maximum temperature ≥35°C at individual stations over Thailand, showing only those exhibiting a statistical significance. Positive (+) and negative (-) signs indicate the significant increase and decrease of DMAX ≥ 35°C, and the rate of change (days/30 year) is indicated by values following the signs.

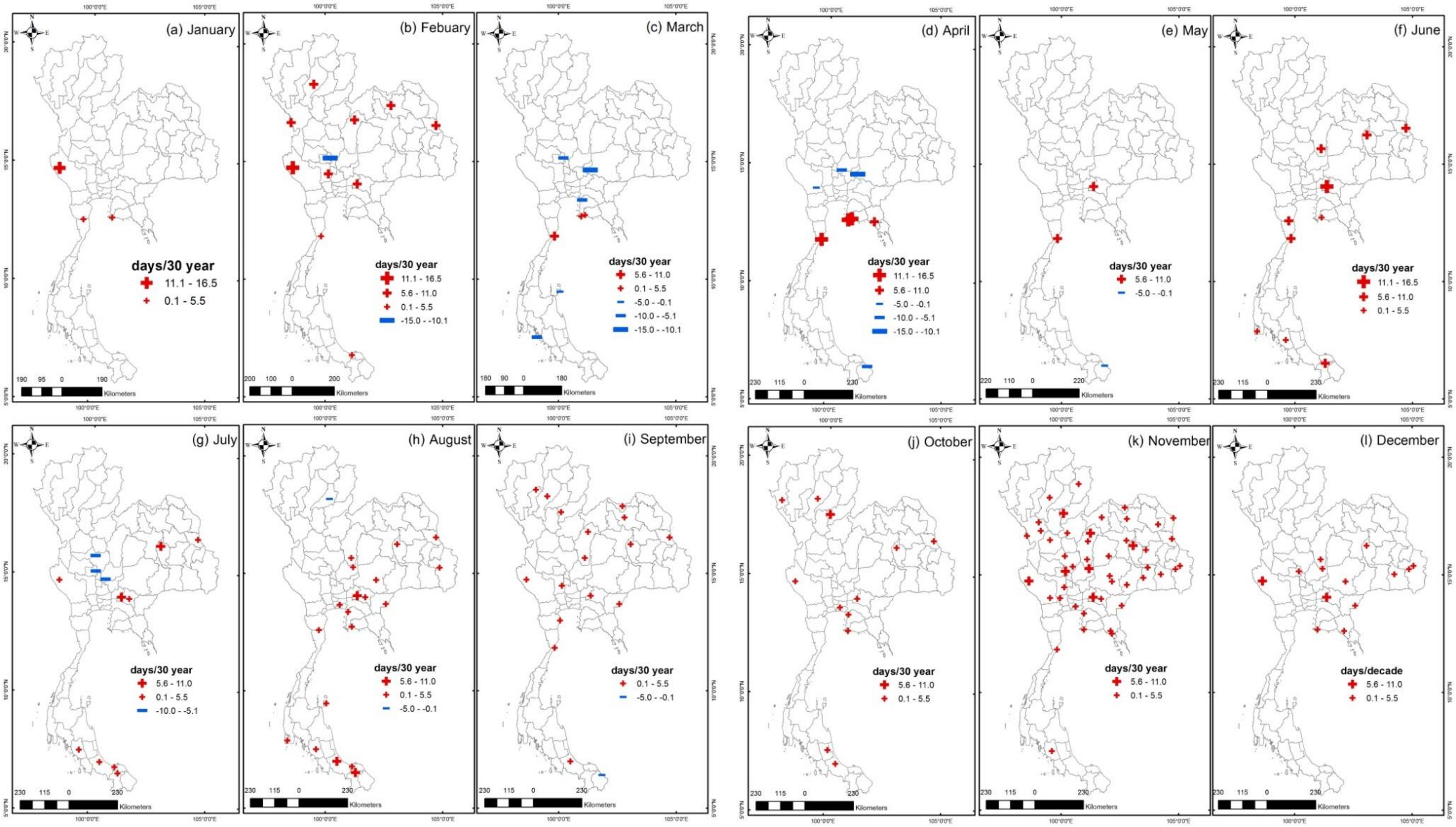


Figure 4.19 Spatial distribution in the number of days with maximum temperature ≥35°C for (a) January; (b) February; (c) March; (d) April; (e) May; (f) June; (g) July; (h) August; (i) September; (j) October; (k) November and (l) December. Positive (+) and negative (-) signs indicate the significant increase and decrease of DMAX ≥ 35°C and the rate of change (days/30 year) is indicated by values followed the signs.

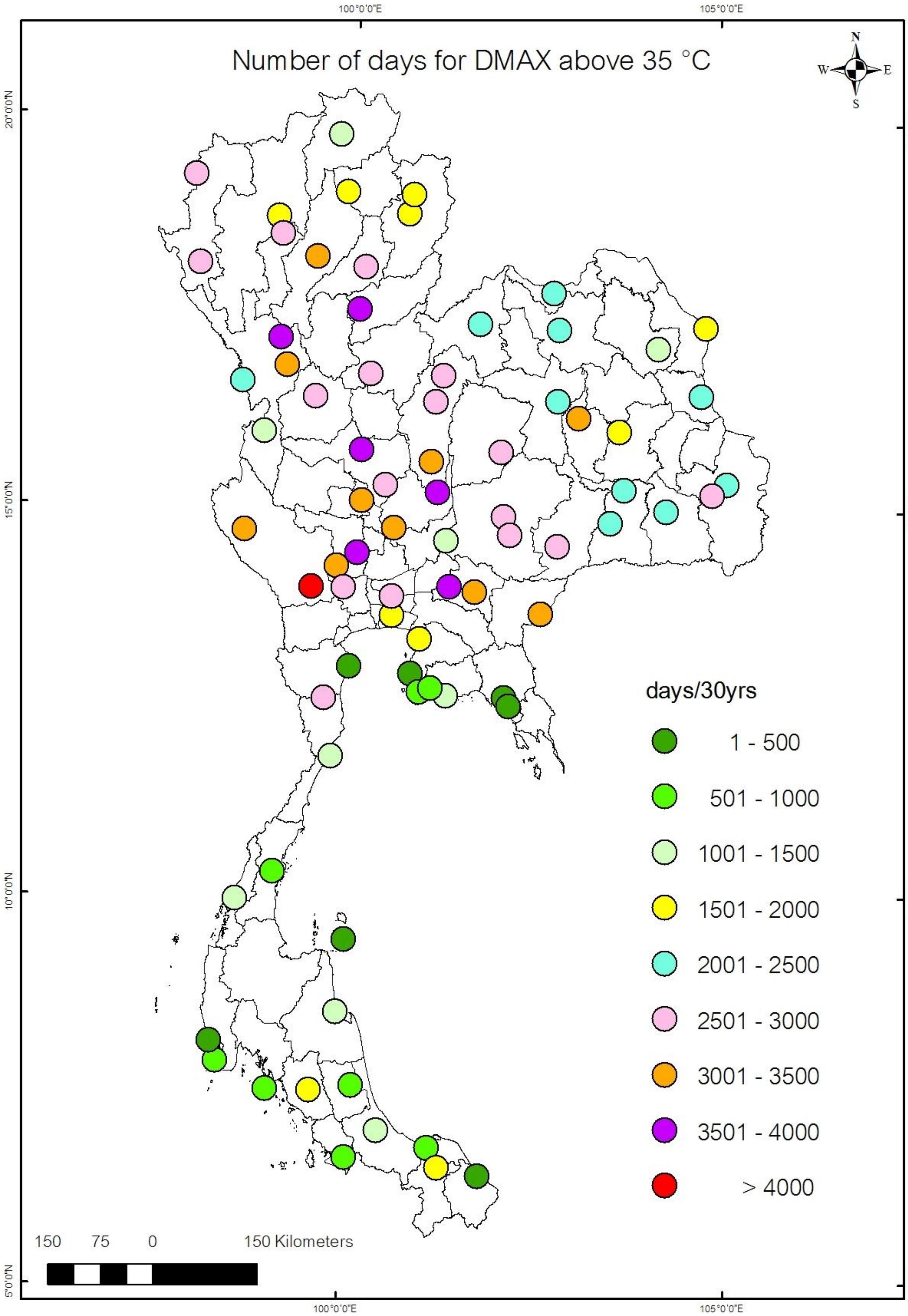


Figure 4.20 Spatial distribution of cumulated number of days with maximum temperature ≥35°C during 1983-2012.

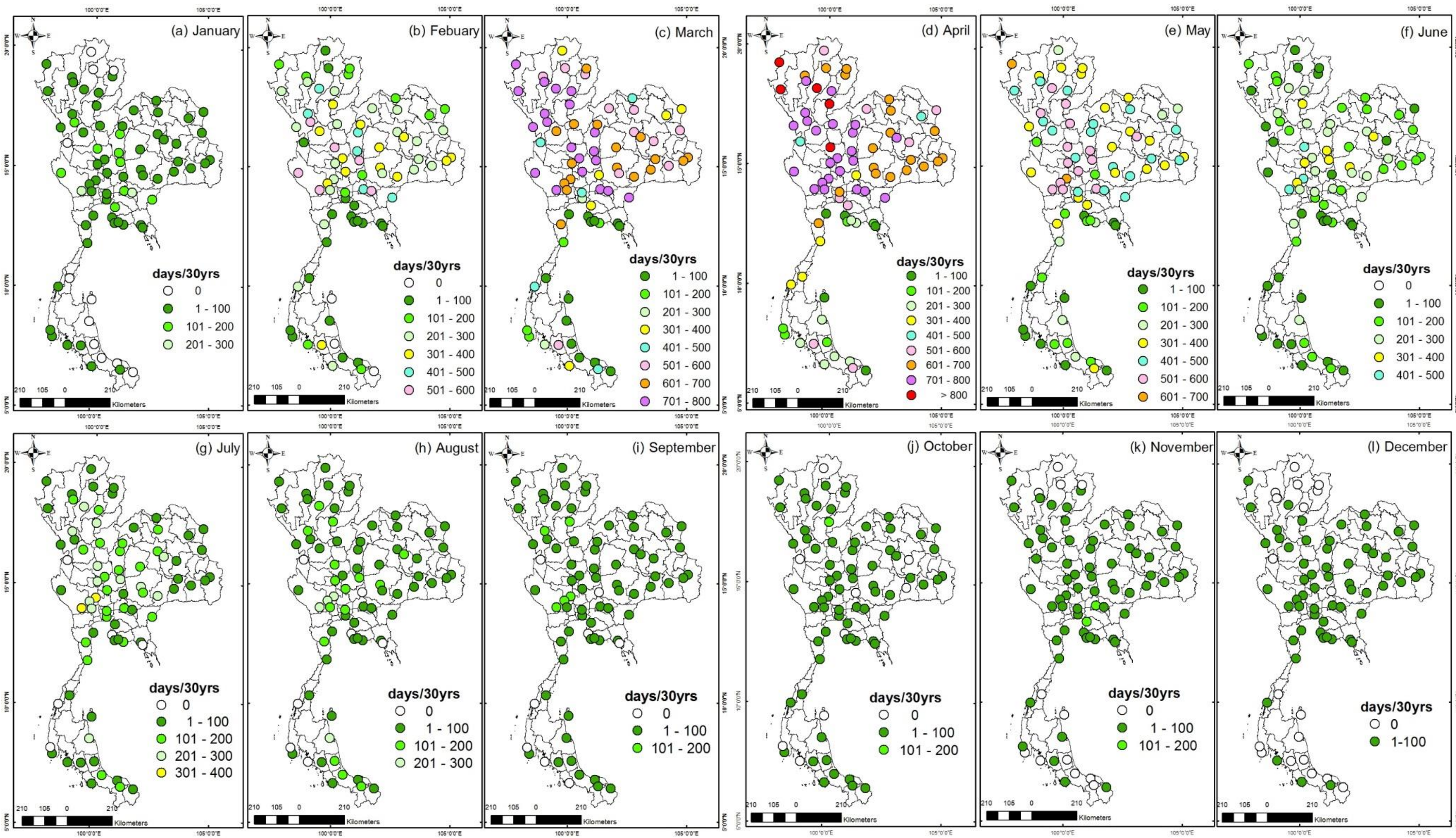


Figure 4.21 Spatial distribution of cumulated number of days with maximum temperature ≥35°C for (a) January; (b) February; (c) March; (d) April; (e) May; (f) June; (g) July; (h) August; (i) September; (j) October; (k) November and (l) December.

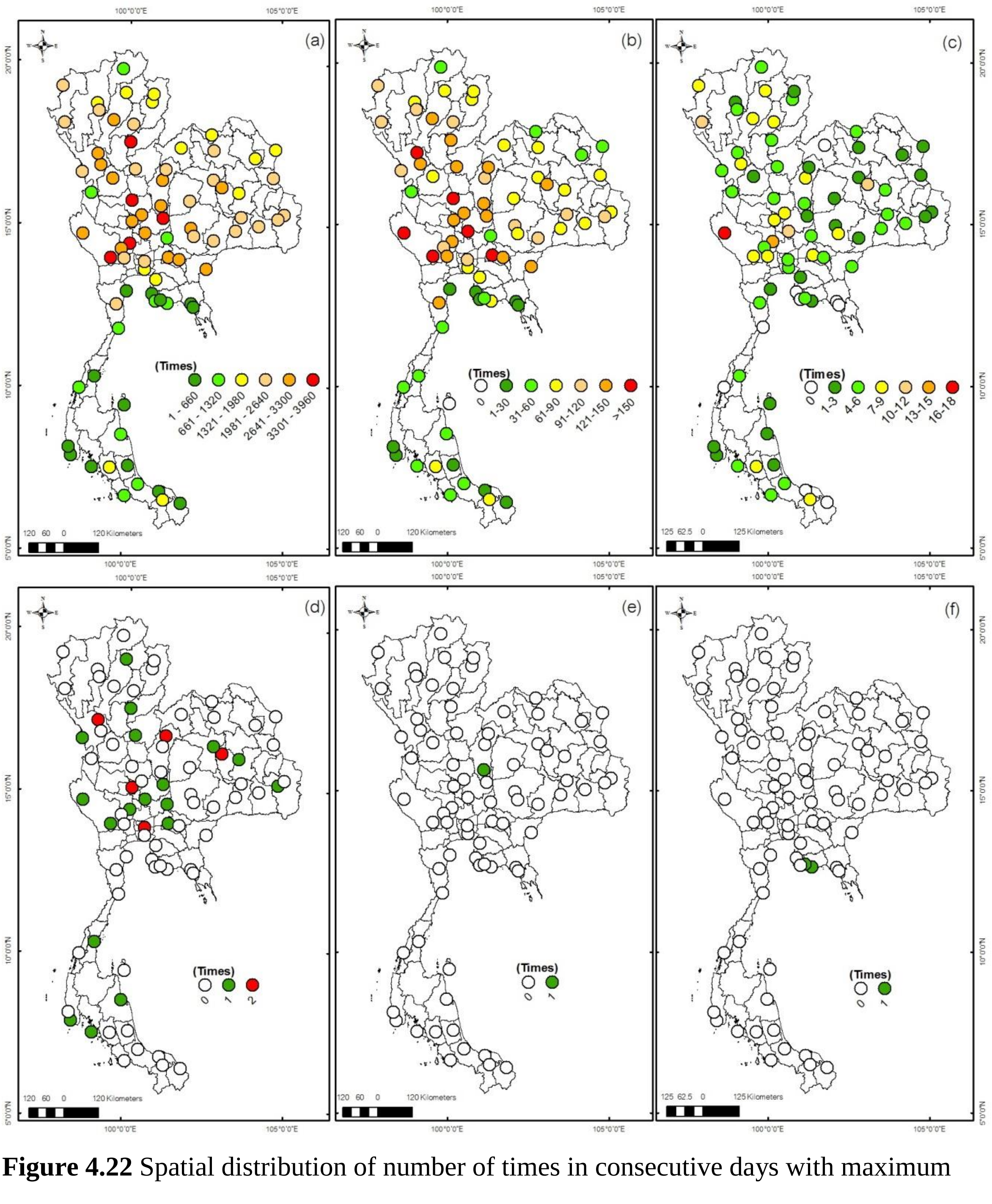


Figure 4.22 Spatial distribution of number of times in consecutive days with maximum temperature ≥35°C in Thailand for (a) 1 day; (b) 2 consecutive days; (c) 3 consecutive days; (d) 4 consecutive days; (e) 5 consecutive days and (f) 6 consecutive days.

4.7.3 Potential impacts of high temperature on rice production

Rice, like other cultivated crops, has a variable temperature optimal more or less specific for each growth stage. Deviation from the stage-dependent optimum temperature will alter the physiological activities or lead to a different developmental pathway

(Wassmann *et al.*, 2009). In addition, the response of rice to temperature stress depends on the duration, intensity, and period of its occurrence (day or night), and the rate of temperature change (Das *et al.*, 2014).

The discussion that follows after this is based on the analysis results of high temperature threshold analysis (≥35°C), temperature indices (numbers of day with temperature ≥35°C, trends of number of day with maximum temperature ≥35°C, and the number of ≥3 days with temperature of ≥35°C described above). These were combined with rice cultivation calendars in different regions of Thailand. If the period with lasting temperature indices overlapped with the rice growing calendar for specific growth stage, it is assumed that rice cultivation will have a likelihood to be affected by high temperature stress. In reality, rice production may or may be not affected by this high temperature. The impacts of high temperature will depend on other factors. However, the analysis here at least could provide a general view how likely plant would be likely affected, based on the temperature records in the past and from what we have known about rice responds to high temperature.

Combining the temperature indices mentioned above with the potential impacts indicator, the potential impacts resulting from high temperature occurrences were analysed (Figures. 4.23-4.24). Generally, the high impact is appeared in four months only (February, March, April and June), which are displayed at Prachin Buri, Mae Sot station and Thong Pha Phum station for February; Mae Sariang station for March; Huai Pong Agromet station for April and Prachin Buri station for June. In January, about 80% of total station are appeared a low impact with an exception being at Sattahip, Nong Phlup Agromet and Thong Pha Phum station, where a moderate impact were found. However, about 15% of total stations showed no potential impacts from high temperature stress (east coast of south, some station in northeast and some station in north). In March, April, May and November the most of station in these months are appeared a moderate impact which accounted for 69%, 75%, 51% and 58% of total stations, respectively. For the rest, majority of station fell within a low impact. In addition, the fraction of station considered as no potential impacts from high temperature accounted for 26%, 16%, 11%, 9%, 10%, 6%, 3% and 3% of total station in December, November, October, September, August, July, February and June, respectively.

4.7.3.1 Potential impacts of high temperature during the vegetative phase

The vegetative phase begins with seed germination until panicle initiation (Smith *et al.,* 2002). For the impact of high temperature stress on rice growth, Yoshida (1981) reported that the germination percentage decreased when rice seed was exposed to temperatures between 15-37°C for 2 days. Ali *et al.,* (2014) also found that the high temperature decreased germination about 40%. However, high temperature stress caused good seedling growth, but over 40°C seedling may die. Elongation of the radicle stops above 40°C. Basically, higher temperatures increase the rate of leaf emergence, and provide more tiller buds (Yoshida, 1981). Therefore, the high temperature stress has an influence in both the development and damage to early-rice growing.

The temperature analysis results showed that in the northern region, the sowing and transplanting stages were mainly during mid- May to late- September for the main rice-growing season (Figure 3.5a). Temperature records from this region indicate that 10 stations were appeared to fall within the potential impact category "moderate" in May, after that these were appeared to be within "low" impacts. The numbers of 5 stations were considered to experience low impacts in every month on this stage. Wichian Buri station for 4 consecutive months (June-September), Tak Fa Agromet station for 3 consecutive months (May-July), and Uttaradit and Tak station for 2 consecutive months were fallen within the moderate impacts.

For the northeastern region, the sowing and transplanting stages were mainly during mid- April to mid- September for the main rice-growing season (Figure 3.5b). The majority of the stations appeared to have a moderate impact in April. So, planting in April may expose rice plant to high temperature stress. Delaying date of sowing and transplanting dates is a general recommendation to avoid these potential impacts. Mukdahan and Kosum Phisai station showed 6 consecutive months (April-September) with moderate impacts. The numbers of 4 stations were appeared to fall within the potential impact category "moderate" in April, after that these were appeared to be within "low" impacts. Nakhon Ratchasima and Chok Chai station for 3 consecutive months (April-June), and Nong Khai, Nakhon Phanom, Roi Et Agromet, Ubon Ratchathani Agromet, Tha Tum and Nang Rong station for 2 consecutive months (April-May) were fallen within the moderate impacts. Udon Thani station was considered to experience low impacts in every month on this stage (except in August). Surin Agromet station was appeared to fall within the potential impact category "low" in May.

In the central and eastern regions, the planting date is usually around May until mid- September (Figure 3.5c). The Prachin Buri station was subject to the highest temperature stress as the temperature indices were highest, especially during May to August. The numbers of 5 stations were appeared to fall within the moderate impacts in May, after that these were appeared to be within "low" impacts. Phatthaya and Phriu Agromet station appeared a smallest severity. Kabin Buri station for 4 consecutive months (May-August), and Aranyaprathet station for 2 consecutive months (May-June) were fallen within the moderate impacts.

For the southern region, the sowing and transplanting stages were mainly during August to early January for the main rice-growing season on the east coast (Figure 3.5d) and during June to early November on the west coast (Figure 3.5e). In the east part, Kho Hong Agromet station showed 3 consecutive months (August - October) with moderate impacts, after that this was showed no potential impacts from high temperature stress. Nong Phlup Agromet, Ko Samui, Pattani Airport and Yala Agromet station appeared a moderate impacts in August, after that these were appeared to be within the low impacts. Nakhon Si Thammarat and Narathiwat station were considered to experience low impacts in every month on this stage. In west part, Trang Airport station showed 3 consecutive months (June- August) with moderate impacts, after that this was showed no potential impacts from high temperature stress. The Phuket station was appeared to have a moderate impact in June, August and September.

4.7.3.2 The potential impacts of high temperature at heading stage

The heading stage is one part of the reproductive phase in rice, which has been found to be more sensitive to high temperature stresses than was the vegetative phase (Yoshida, 1981; Wassmann *et al.,* 2009). The date of heading is the same as the date of anthesis or flowering (Yoshida, 1981). Yoshida (1981) reported that rice is most sensitive to high temperature at heading and next most sensitive at about 9 days before heading. One or two hours of high temperature at anthesis has a decisive effect on the incidence of sterility. In addition, high temperature (35°C) during microsporogenesis and anthesis resulted in 34% and 80% decline in spikelet fertility, respectively. High temperatures induce sterility, if the sensitive physiological processes (anther dehiscence, pollination, pollen germination on the stigma, pollen tube growth or the early events of fertilization) are affected. Anthesis in rice is extremely sensitive to high temperatures, and spikelets opening on any flowering day during the flowering period (5-7 days) could be affected differently depending on the duration of exposure (Yoshida, 1981; Wassmann *et al.*, 2009).

In this study, for the northern region, the heading stage of the main rice-growing season was mainly from late September to December (Figure 3.5a). Usually, the heading date was in November. Lampang and Uttaradit station for 3 consecutive months (September-November), and Lamphun station in September were fallen within the moderate impacts. The total of 7 stations were appeared a light temperature impacts in every month on this stage. Chiang Rai Agromet station in October to December, Phayao, Chiang Mai and Tha Wang Pha station in November and December, and Lamphun, Phrae, Nan Agromet and Lom Sak station were found no potential impacts from high temperature stress.

For the northeastern region, the heading stage of the main rice-growing season was mainly from mid-August until November (Figure 3.5b). Kosum Phisai and Mukdaham station were considered to experience moderate impacts in every month on this stage. Most of station was appeared a moderate temperature impacts in November. Pak Chong Agromet station showed a low impact in every month on this stage.

In the central and eastern regions, the rice growth stage was mainly from late-September to December, as in the northern region. Prachin Buri station showed a moderate impact in every month on this stage. Thong Pha Phum station was appeared to fall within the potential impact category “low” in August, after that these were appeared to be within “moderate” impacts. The total of 4 stations appeared a light condition in every month. Phathaya station was found no potential impacts from high temperature stress.

For the southern region, this stage was mainly from October to February. On the east coast, Nong Phlup Agromet station appeared a moderate impact in January and February but with a low impact in October to December. Prachuap Khiri Khan station showed a moderate impact in November and February. Phathalung and Kho Hong Agromet station showed a moderate in October, after that these were appeared to be within the potential impact category “light”. On the west coast, majority of station appeared a light condition in this stage. Ranong and Satun station showed a light condition in every month (October to February). Trang Airport station was appeared a low impact in October, November and January, after that this was appeared a moderate impact in February.

4.7.3.3 The potential impacts of high temperature at harvesting stage

High temperatures at the harvesting stage can affect cellular and developmental processes leading to reduced fertility and grain quality (Barnabas *et al.*, 2008; Wassmann *et al.*, 2009). Decreased grain weight, reduced grain filling, higher percentage of white chalk rice and milky white rice are common effects of high temperature exposure during ripening stage (Yoshida, 1981; Wassmann *et al.*, 2009). The model studies suggested a decline in yield of 33.89% for KDML 105 and 19.83% for RD6, with a 5°C increase in temperature (Babel *et al.*, 2011). This loss yield may be caused by heat-induced spikelet sterility or increased crop respiration loss during grain filling, which reduces the grain-filling capacity and thus reduces the grain yield (Wassmann, 2007).

The analysis results on the northern region with the harvesting stage of the main rice-growing season being mainly from mid-November to early February showed that a total number of 8 stations had been subject to the light temperature impacts during this growth stage. Mae Sot station showed a high impact in last-harvesting season (February). The number of 6 stations showed a moderate impact in November and February. Nan, Phisannulok, Phetchabun, Wichian Buri, Kamphaeng Phet and Nakhon Sawan station were appeared to fall within the potential impact category “moderate” in November, after that these were appeared to be within “low” impacts. Chiang Rai Agromet, Phayao and Tha Wang Pha station showed a low impact in February.

For the northeastern region, this stage was mainly from October to December. The Kosum Phisai station appeared to have a moderate impact in this stage. Mukdahan station showed 2 consecutive months (October and November) with a moderate impact, and Ubon Ratchathani Agromet, Ubon Ratchathani, Chok Chai and Si Sa Ket Agromet station showed 2 consecutive months (November-December) with a moderate impact. Pak Chong Agromet station was considered to experience low impacts in every month on this stage.

In the central and eastern regions, this stage was mainly from December to January. The Thong Pha Phum and Sattahip stations were appeared to have a moderate impact at this stage. The number of 14 stations appeared a low impact in this stage. Chai Nat, Prachin Buri, Bua Chum and Aranyaprathet station were appeared to fall within the potential impact category “moderate” in December, after that these were appeared to be within “low” impacts.

For the southern region, this stage was mainly from December to March. In the east coast, Prachuap Khiri Khan and Yala Agromet station showed a moderate impact in

February. The Nong Phlup Agromet stations showed 2 consecutive months (January-February) with a moderate impact. On the west coast, the Trang Airport station showed a moderate impact in February. Most of the stations showed light temperature impact levels.

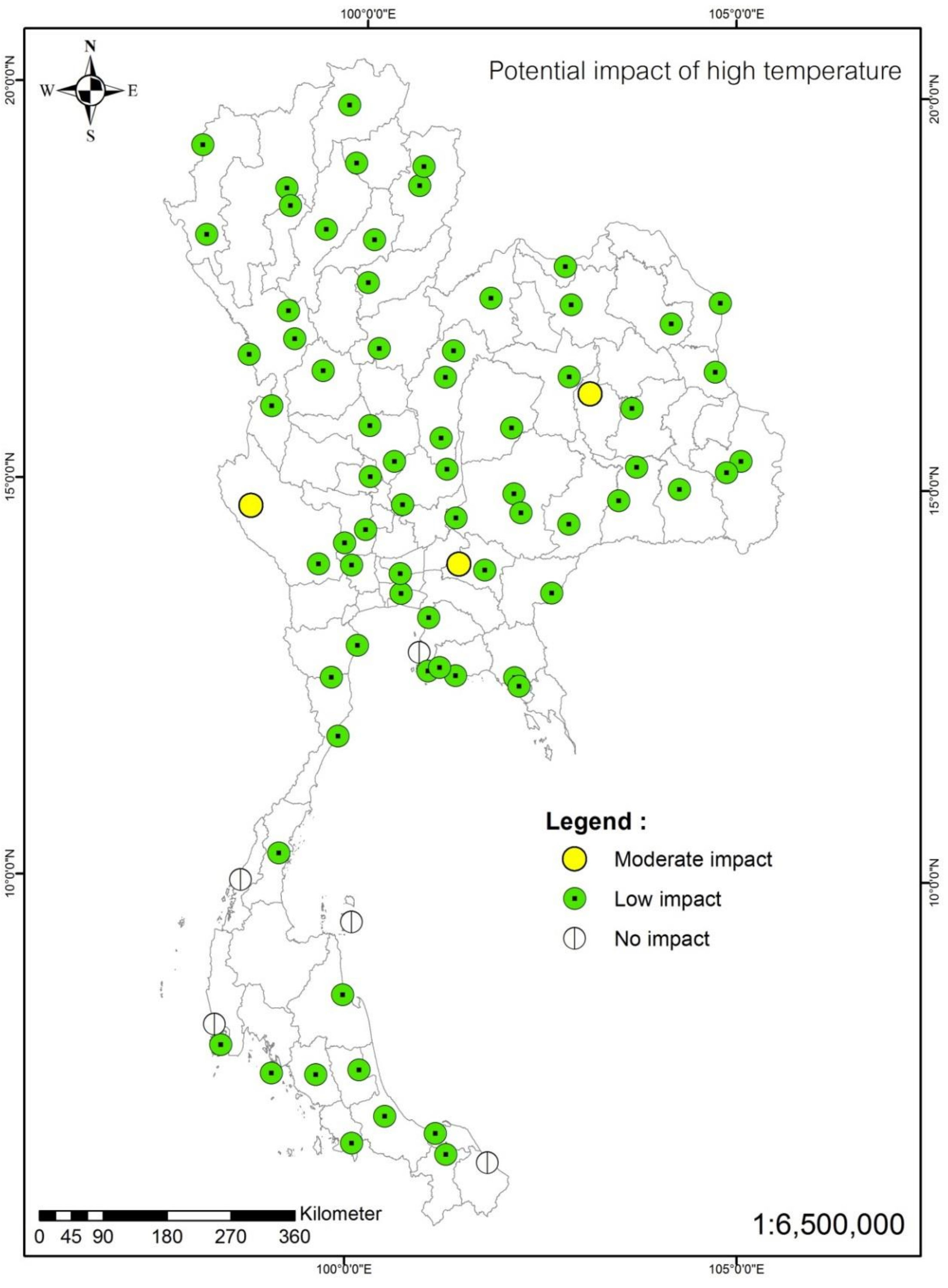


Figure 4.23 Potential impacts of daily maximum temperature (≥35°C) on rice production in Thailand, calculated from temperature records during 1983-2012.

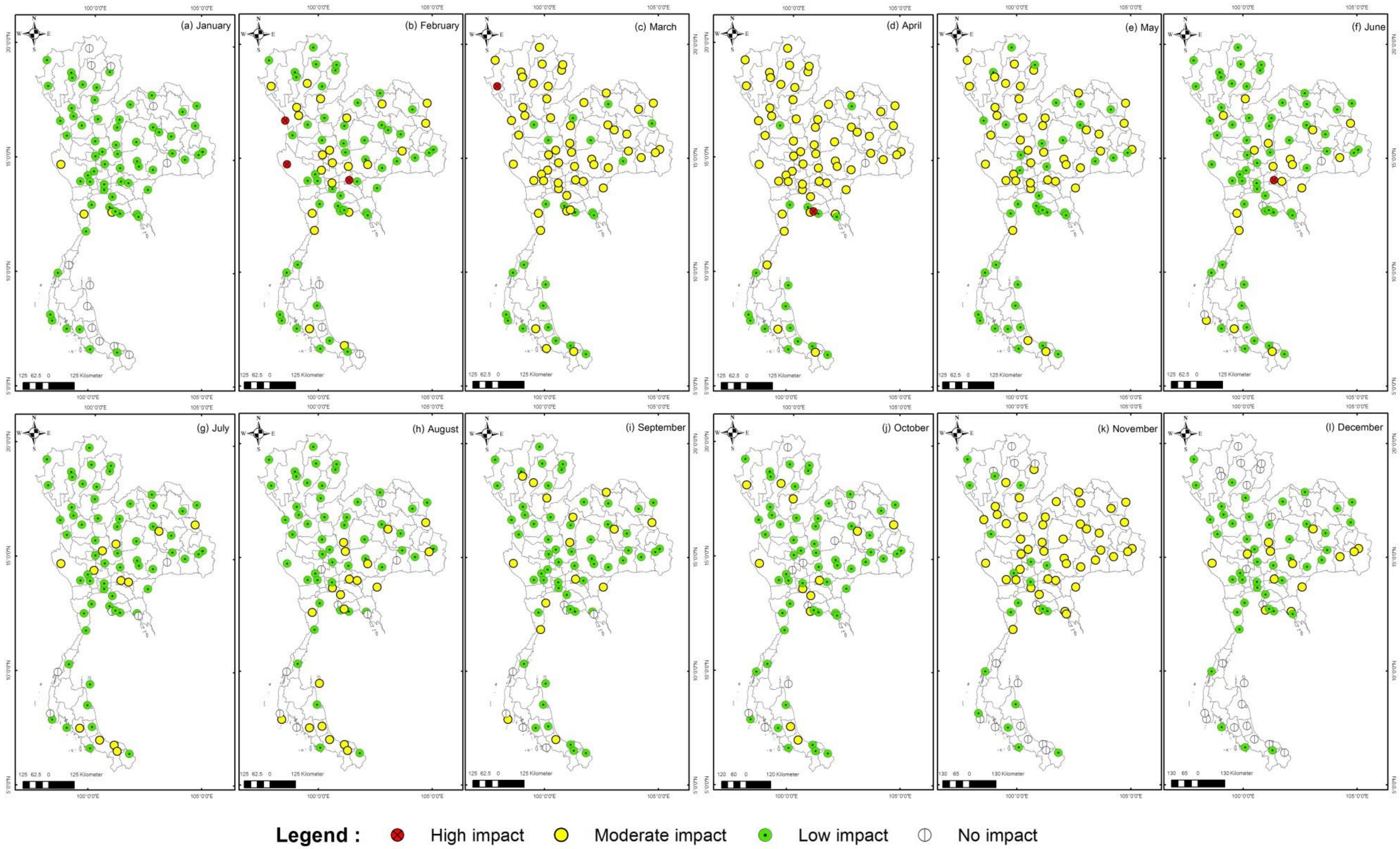


Figure 4.24 Monthly distribution of potential impacts of daily maximum temperatures among all meteorological stations, calculated using 30-year temperature records from each station.

4.8 Change in mean daily temperature ≤ 22° C

4.8.1 Overview

The number of days with mean daily temperature ≤ 22° C made up about 4.8% of the total MDT days. The ranges of low temperature that could induce stress in rice was 9.4 – 22 °C, which the lowest temperature of 9.4 °C appeared at the Sakon Nakhon Agromet station during December, 1991. About 65% of the temperature ≤ 22° C ranged between 21 and 22°C (Figure 4.25). Temporal variations in cumulative numbers of days with mean daily temperature ≤ 22° C are presented in Figure 4.27. Majority of mean temperature ≤ 22°C appeared during 5 months (January, February, March, November and December), or during the cool season in Thailand. During such period, rice was rarely planted accepted in the central part of Thailand where the irrigation facility was available.

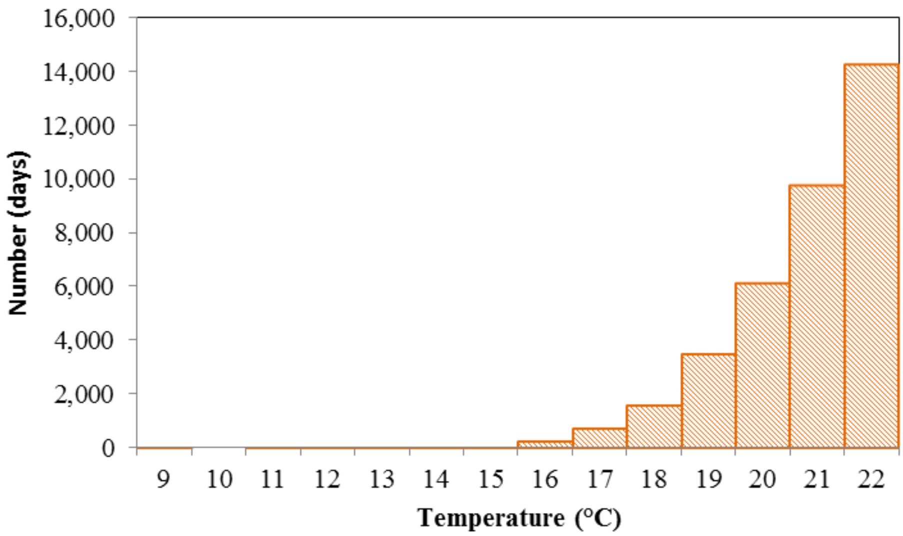


Figure 4.25 Frequency distribution of mean daily temperature ≤ 22° C.

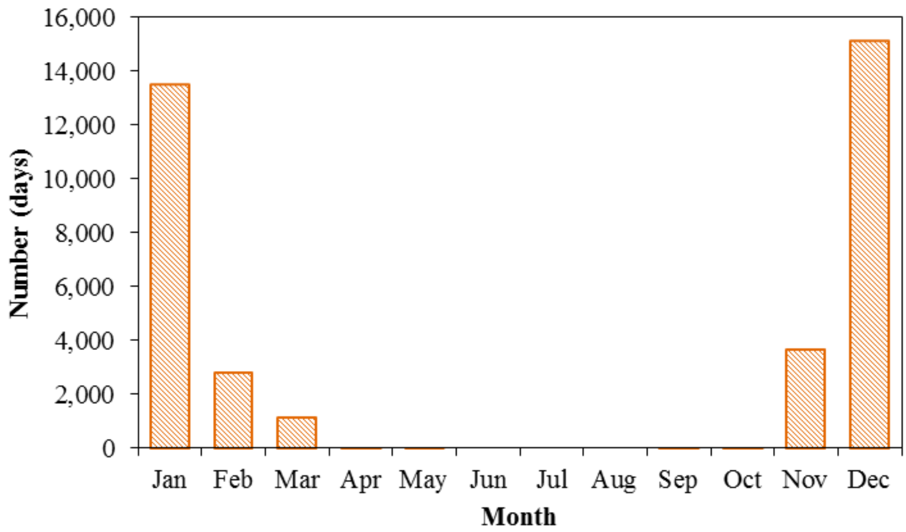


Figure 4.26 Monthly variations in cumulative numbers of days with mean daily temperature ≤ 22°C in Thailand during 1983-2012.

4.8.2 Trend in mean daily temperature ≤ 22° C

The trend in avarege number of days with mean daily temperature ≤ 22° C is presented in Figure 4.27. The figure indicated that annual average number of days with mean temperature ≤ 22° C has decreased since 1983, with the largest and smallest numbers being 2008 and 2012, respectively. During this period, the annual average number of days with mean daily temperature ≤ 22° C had decreased by 4.3 days. However, this decrease is not statistically significant.

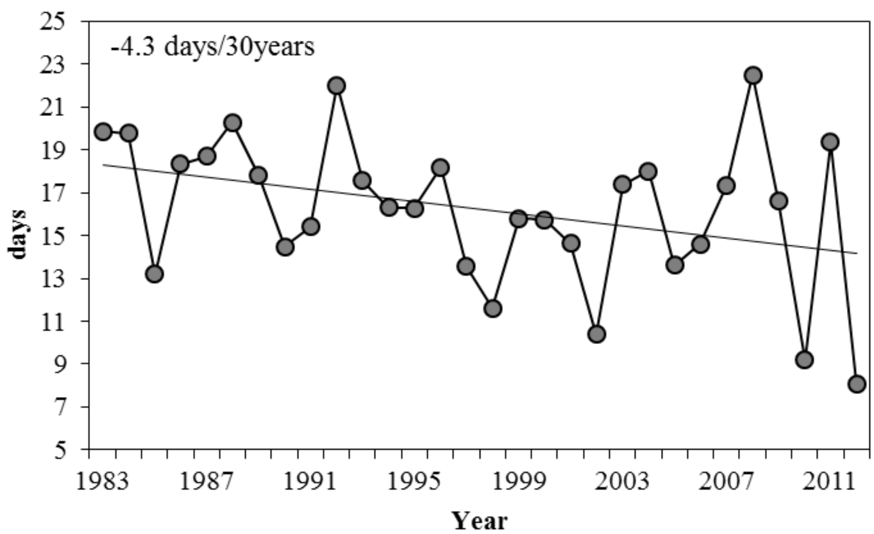


Figure 4.27 Trend in average number of days with mean daily temperature ≤ 22° C.

The spatial distribution of the average number of days with mean daily temperatures ≤ 22° C at the individual stations are shown in Figure 4.28a. The temperature records at 13 meterological stations have decreased significantly and at 2 meterological stations have increased significantly (Phitsanulok and Thong Pha Phum).

The spatial changes of the monthly number of days with mean daily temperatures ≤ 22° C are displayed in Figure 4.28b. The monthly trends indicated that the number of days in December of about 34% of total meterological station has decreased. During April to September, there were no significance trends.

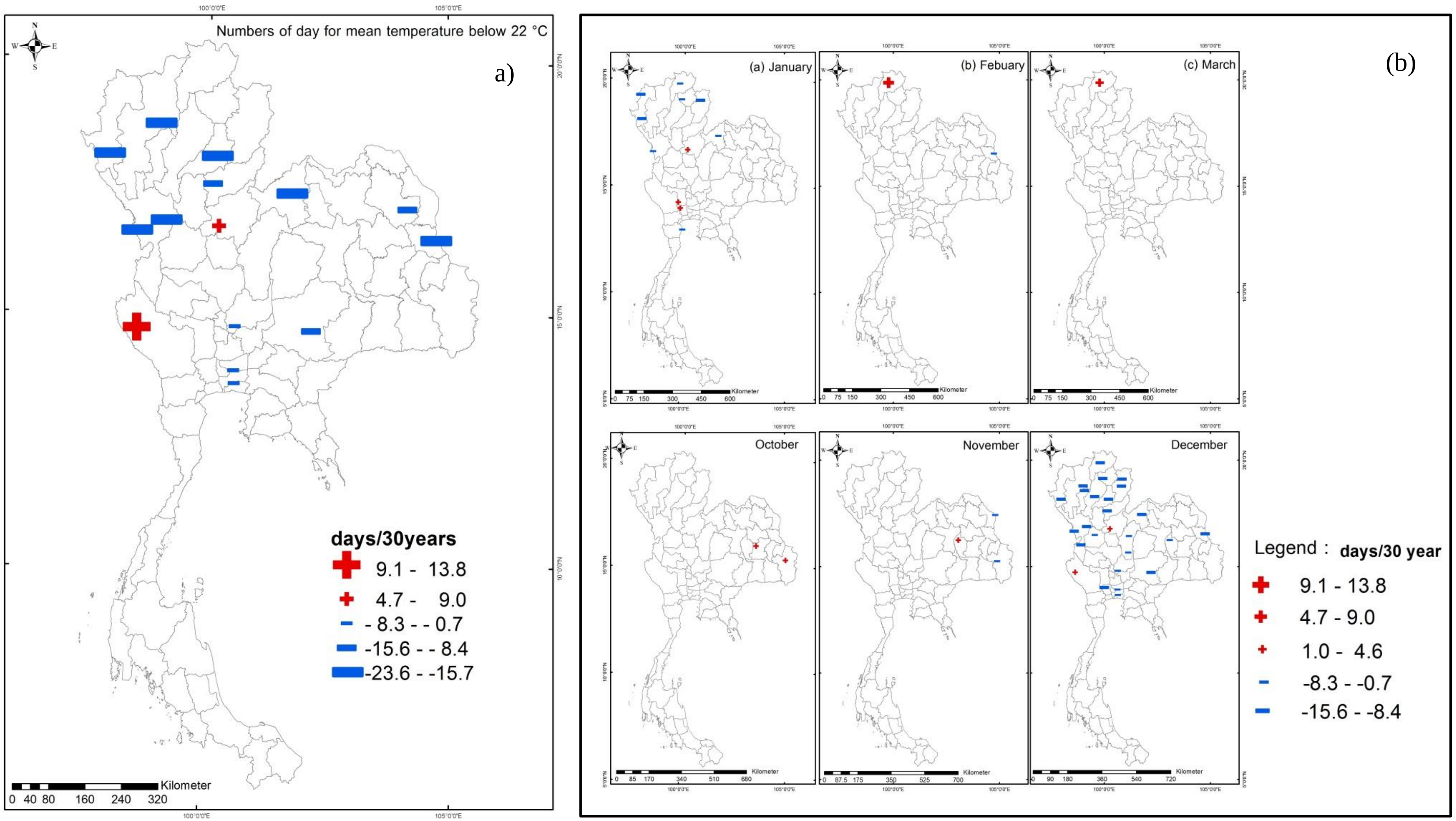


Figure 4.28 (a) Spatial distributions in average number of days with mean daily temperature ≤ 22° C at individual stations over Thailand.(b) spatial distribution among the months (it shows significant trends only).

The spatial distribution of the cumulative numbers of days with mean daily temperatures ≤ 22° C during 1983-2012 are shown in Figure 4.29. It indicates that about 35% of total station was subject to low temperature of ≤350 days 30 yrs^{-1}. These majority of stations appeared in central and southern region. In northern region, the most of station show the number of low temperature stress day above 1,050 day 30yrs^{-1}. The highest number of low temperature stress day appeared at Chiang Rai Agromet station with 2,430 days 30 yrs^{-1}. In addition, majority of stations in the southern region have not experience the temperature below 22 °C.

The monthly cumulative number of days with mean daily temperatures ≤ 22° C are given in Figure 4.30. Overall, the low temperature stress day is appeared during January to May and October to December in all regions (except in southern region). The highest cumulative number of days with mean daily temperature ≤ 22° C appeared at Chiang Rai Agromet station in January and December with over 805 day 30 yrs^{-1}.

The number of times in consecutive days with temperatures ≤ 22° C are presented in Figures 4.31a to d. Majority of station have 1 and 2 consecutive days with that temperature range (except in southern region, where isn't appeared a mean daily temperature ≤ 22° C in some station). For 3 consecutive days, these appeared in northern, central and northeastern region with below 4 times 30 yrs^{-1}. In addition, Nan, Phrae and Mae sot station shows a 4 consecutive day with mean daily temperature ≤ 22° C.

4.8.4 Potential impacts of low temperature on rice production in Thailand

Combining the temperature indices mentioned above with the potential impact indicates, the potential impacts resulting from low temparature occurrences were analysed (Figures 4.32-4.33). The low temperature were likely to cause stress to rice cultivation during January to May and October to December. The majority of stations for January, February, March, April, May, October, November and December fell within low impact with 62% (43 stations), 72% (50 stations), 79% (55 stations), 33% (23 stations), 18% (13 stations), 42% (29 stations), 74% (51 stations) and 54% (37 stations) of total station, respectively. This appear in all regions (except a southern region, where the most of station do not show a low temperature stress). In addition, in January, the Phayao station showed a high impact.

4.8.4.1 The potential impacts of low temperature at vegetative phase

The damage of low temperature stress to the vegetative phase was reported by Yoshida (1981) who indicated that the low temperature extended the seed germination of rice. The elongation of the radicle stops when temperature is below 15°C. Therefore, low temperature stress can cause failure to germinate, delayed seedling emergence, stunting, a reduction in plant height, leaf yellowing and inhibited tillering. Lee (2001) also reported that the temperature below 15 °C decreases plant height, tillering, root growth and dry weight of the rice plant.

This stage was during April until January in different regions of Thailand (see Figures 3.5a to e). For northern region, the low temperature stress appeared at 9 stations in May. In northeastern region, 11 stations were found with a low impact. For southern region, the number of 3 stations appeared a low impact on some month in east part of southern region. For example, Prachuap Khiri Khan station appeared a low impact in November. Nong Phlup Agromet station appeared a low impact in November to March. In central region, there were found no potential impacts from low temperature stress.

4.8.4.2 The potential impacts of low temperature at heading stage

The heading stage was during August to February in different regions of Thailand. In the northern region, it was during September to December for the heading stage of the main rice-growing season. Chiang Rai Agromet station appeared a low temperature impact during September to December). In addition, 10 stations showed a low temperature stress during October to December. For rest of station, the potential impacts from low temperature stress from November to December. The heading stage of main rice-growing season in northeastern region was during August to November. Kosum Phisai station showed a moderate impact in November. 11 stations showed 2 consecutive months (October-November) with a low impact. For the central region, this was during mid-September to December for the heading stage. Lop Buri station and Kanchanaburi station showed 3 consecutive months (October-December). The number of 7 stations appeared to have a low impact in November and December. Thong Pha Phum appeared a moderate impact in December. In southern region, the heading stage of main rice-growing season was during October to February. Nong Phlup Agromet, Prachuap Khiri Khan, Sawi Agromet and Narathiwat station showed a low impact.

4.8.4.3 The potential impacts of low temperature at harvesting stage

In the northern region, the harvesting stage of the main rice-growing season was during November to February. The majority of stations appeared to have a moderate impact in December and January. In addition, Phayao appeared a high impact in January. For northeastern region, this stage was mainly from October to December. Majority of station appeared a low impact in harvesting stage. Kosum Phisai station showed a moderate impact in November. In central region, this stage was mainly from December to January. The most of station appeared a low impact in this stage. Thong Pha Phum appeared a moderate impact in December. U Thong Agromet and Kamphaeng Saen Agromet station showed a moderate impact in January. This stage was mainly from December to March in southern region. The number of 5 stations appeared a severity of low temperature stress. At this stage, the low temperatures induce poor grain filling, high spiketlet sterility, irregular maturity and rapid leaf senescence (Yoshida, 1981).

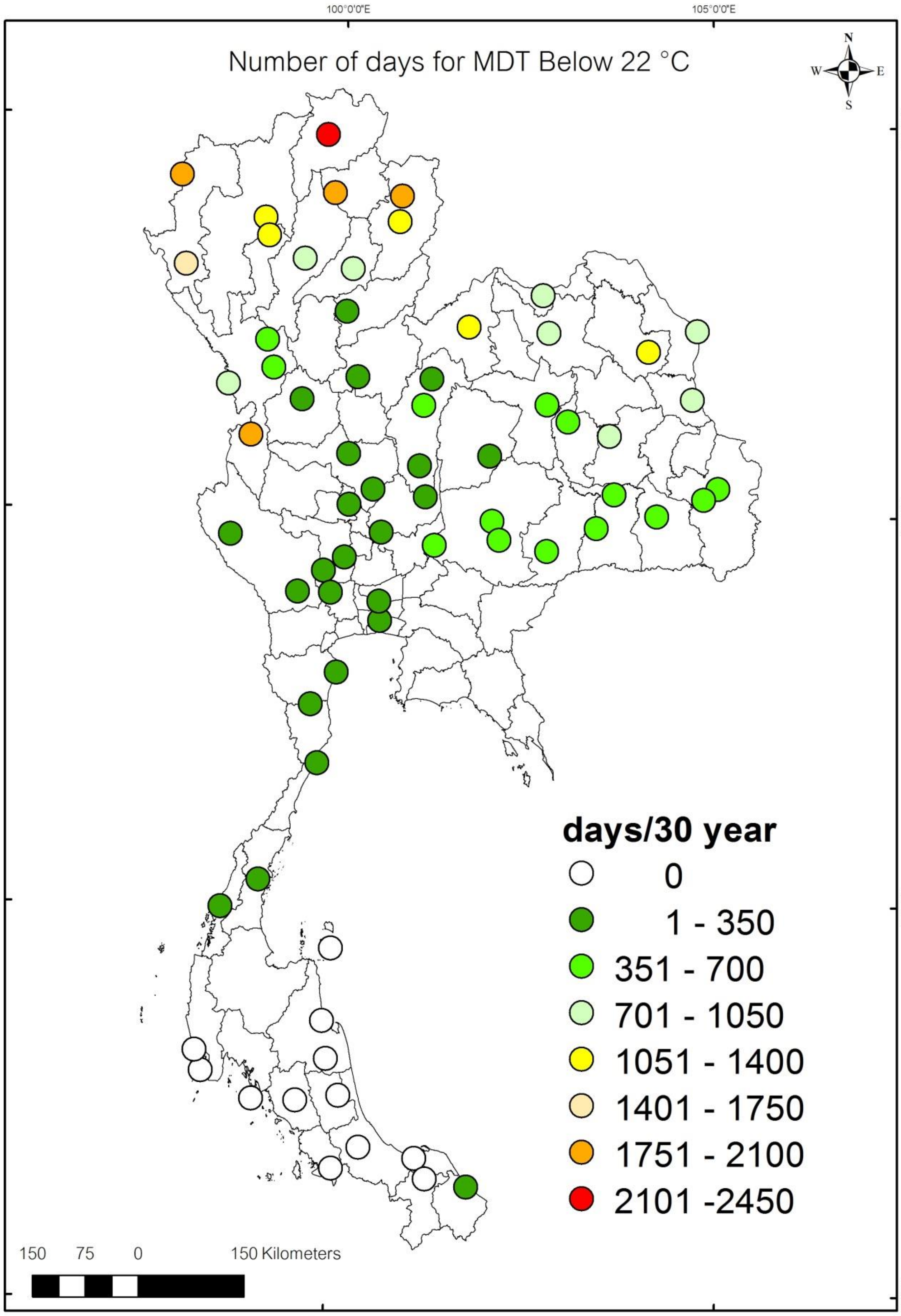


Figure 4.29 Spatial distribution of cumulative number of days with mean daily temperatures ≤ 22° C during 1983-2012.

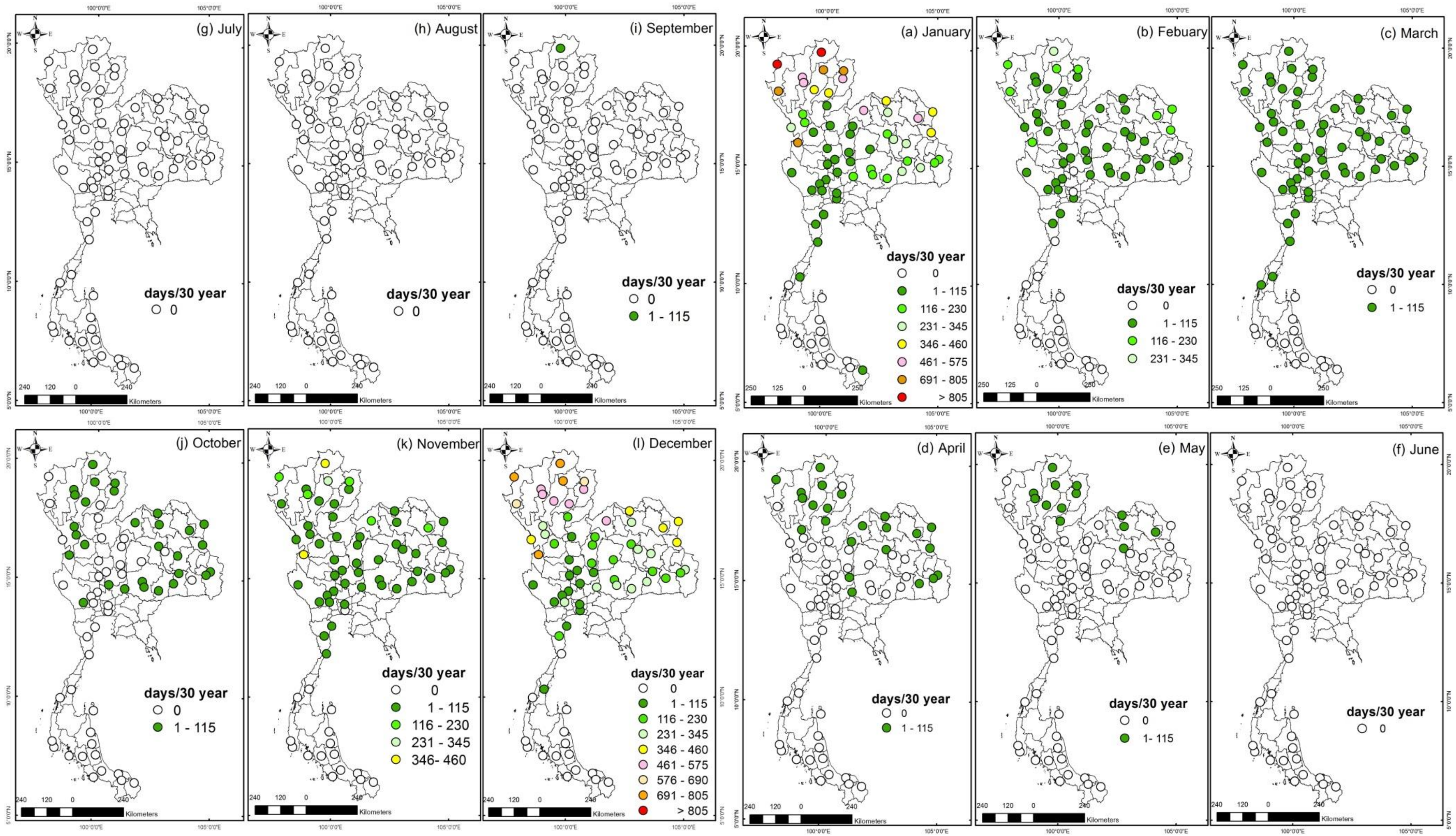


Figure 4.30 Spatial distribution of cumulative number of days with mean daily temperature ≤ 22° C for (a) January; (b) February; (c) March; (d) April; (e) May; (f) June; (g) July; (h) August; (i) September; (j) October; (k) November and (l) December.

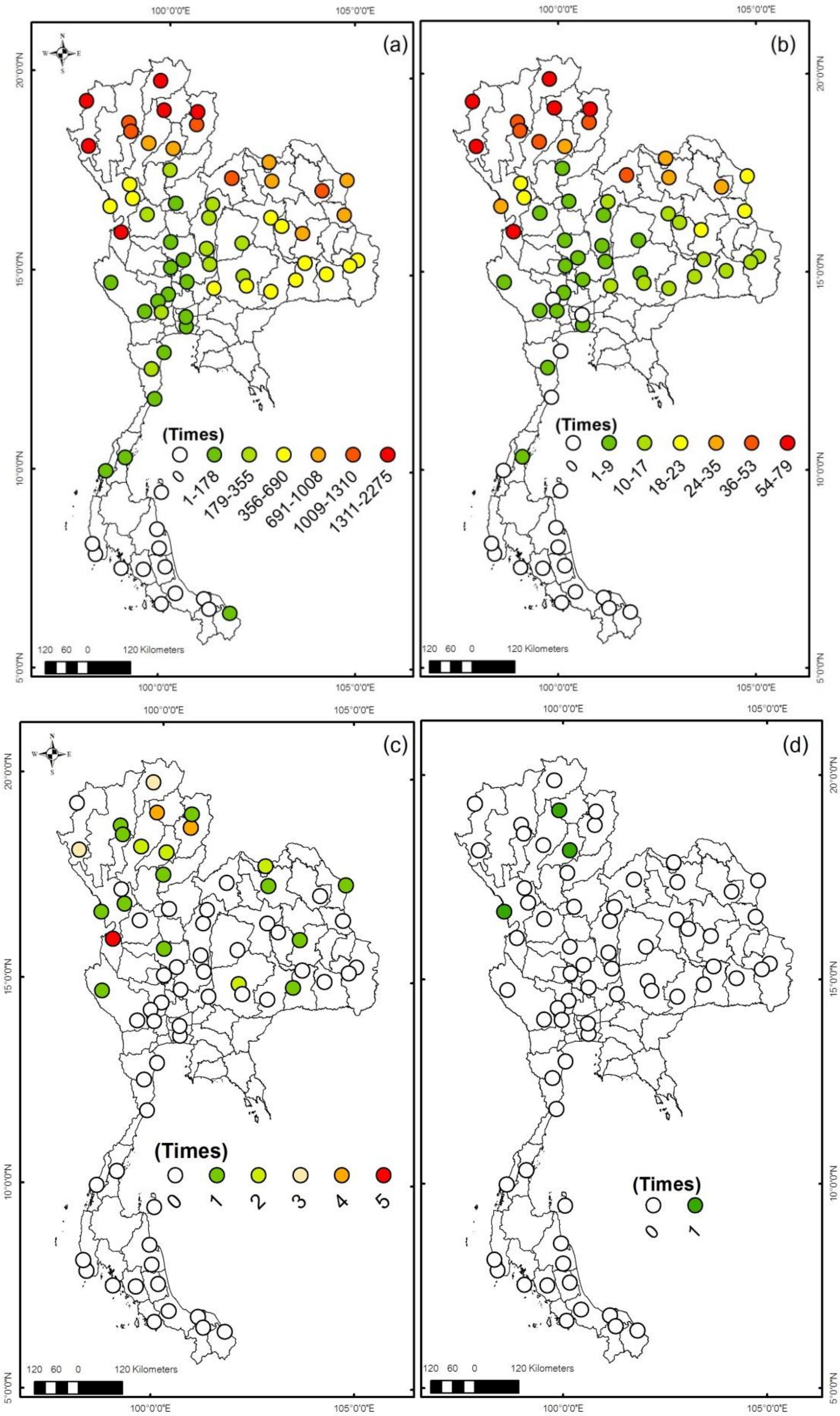


Figure 4.31 Spatial distribution of number of times in consecutive days with mean daily temperatures ≤ 22° C over Thailand for (a) 1 day; (b) 2 consecutive days; (c) 3 consecutive days and (d) 4 consecutive days.

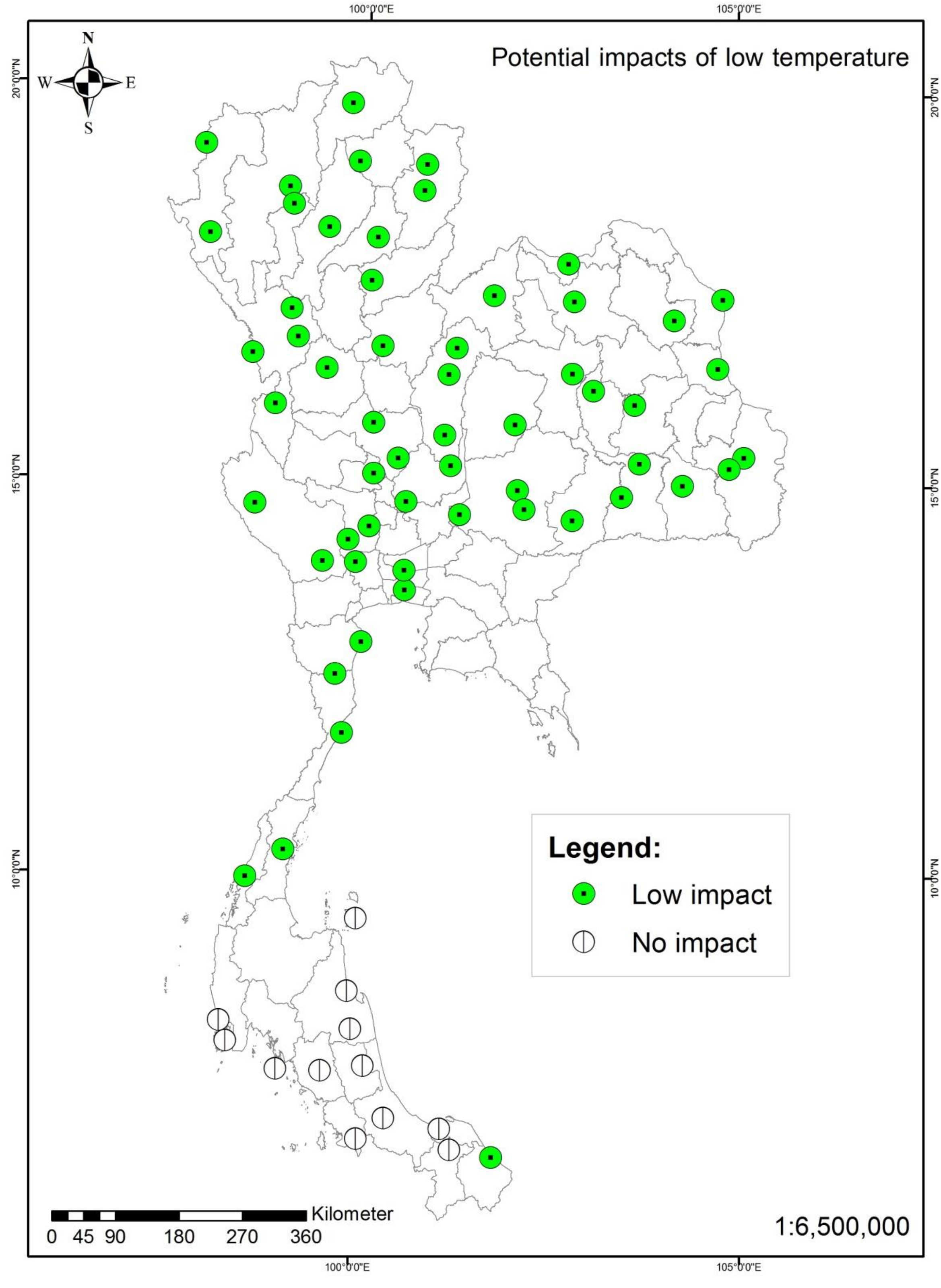


Figure 4.32 Potential impacts of mean daily temperatures (≤22°C) on rice production in Thailand, calculated from temperature records during 1983-2012.

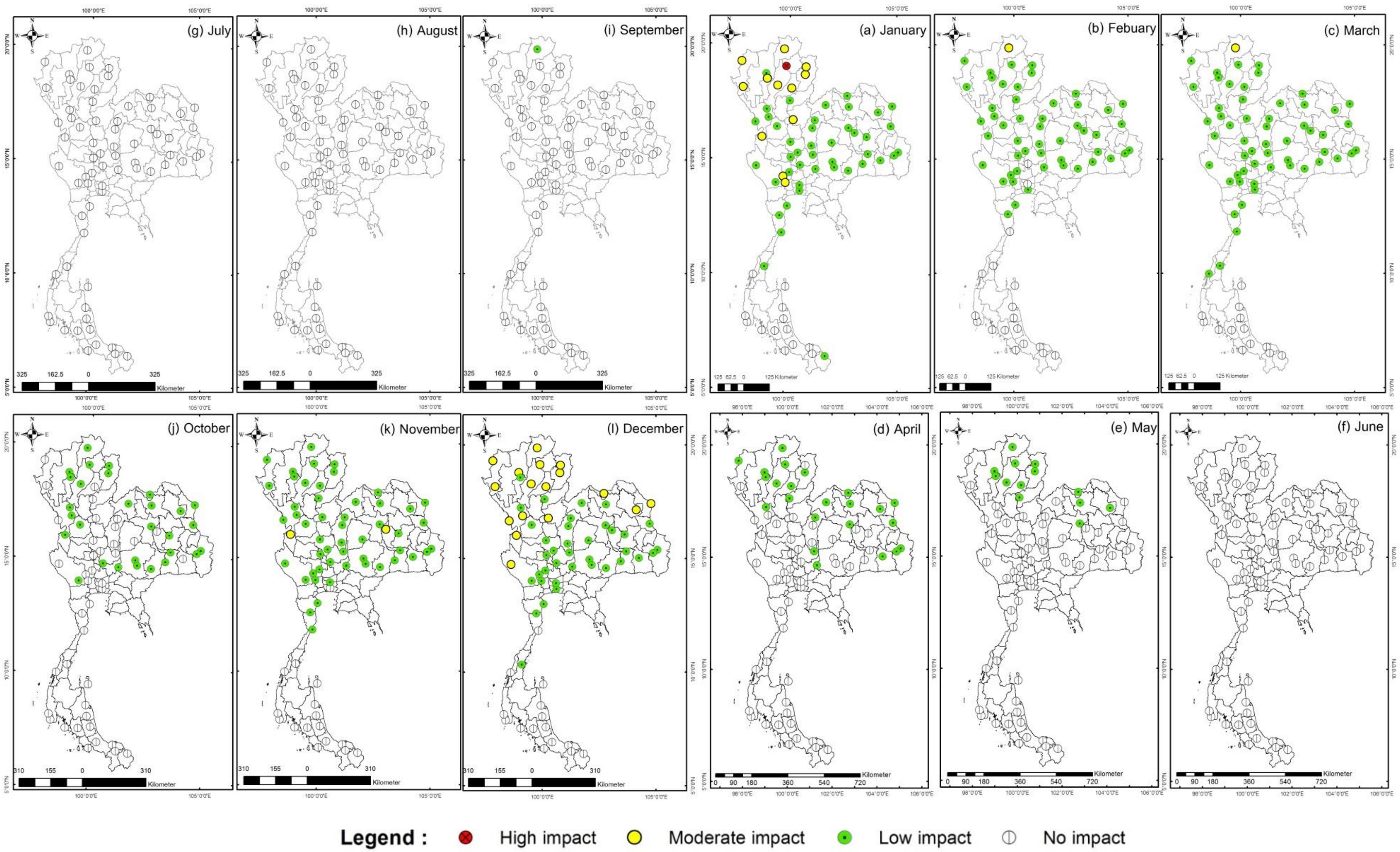


Figure 4.33 Distribution of monthly potential impacts of mean daily temperature among all meteorological stations, calculated using 30-year temperature records from each station.

CHAPTER 5
CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study attempts to evaluate the potential impacts of temperature variations on rice production in Thailand, as global greenhouse gas emissions have increased. As the consequence, global temperature and climate change have occurred. The increase in temperature extremes will have the adverse impacts on rice production and high quality temperature records are available in Thailand. The temeperature data covered the period between 1983 and 2012 from Thai Meteorological Department (TMD). Those were passed through these quality control checks were then used to determine the temperature indices (high and low temperature) for evaluating the potential impacts on rice production.

This study starts from the data quality control and checks. It is the check for missing data for this case. It was found that there were 29 stations with missing data above 5% for daily maximum temperature data, 28 stations for daily minimum temperature data and 41 stations for mean daily temperatures. These stations were distributed all around Thailand as indicated here in different regions. So these were removed from dataset. After the removing these meteorological station, the data missing fraction is below 1%. This 1% of missing data were then gap-filled based on the relationship with the nearby stations. Thus, the number of station with high quality data were; daily maximum temparature data was 78 stations, mean temparature data was 69 stations and minimum temperature data was 80 stations.

The analysis results indicate that the overall daily maximum, mean and minimum temperatures in Thailand have increased by 0.13, 0.10 and 0.29°C ($p<0.01$), respectively. However, the increase magnitude and rate with regards to temperature component varied among regions. For the Northeast Thailand all temperature component analyzed; maximum, mean and minimum temperatures have significantly increased. In the Eastern Thailand the statistically signficant increases were found in daily maximum and minimum temperatures. In the Southern and North region, minimum temperatures have significantly increased. The average values of maximum, mean and minimum temperature in the whole country were 32.7, 27.0 and 22.7°C, respectively. The distributions of annual maximum and minimum temperatures changes for meteorological station have increased in all regions. On the other hand, mean temperatures have increased in some northeastern, some central and some southern regions. The change in maximum and mean temperatures rate for each month was found that in October, November and December, the maximum and mean temperatures have increased siginificantly and this occurred all over Thailand. In contrast, maximum and mean temperatures in February, March and April have the decreasing trends in some meteorological station of central regions. The monthly minimum temperature changes differ the case of maximum temperature is that the increase was found in all month and all over Thailand. However, the majority of the meteorological stations have the temperature increase in January - March and in June – December.

After analyzing the general characteristics of temperature records, the potential impacts of extreme temperature wuth regards to critical or threshold temperatures for rice production were considered. The first case is maximum temperature ≥35°C. Analyzing three aspects; rate of change in number of days with temperature ≥35°C, cumulative numbers of days with temperature ≥35°C, and numbers of ≥ 3 consecutive days with temperature ≥35°C revealed that one average these were 5,511 days per years over Thailand and this varied according to different regions. The number of days with temperature ≥35°C has increased at 4.5 days per 30 year. In most cases, this last only 1 day. However, there was 0.29% for those lasing more than 3 days. The potential impact of these high temperatures to rice production in Thailand is considered low to moderate. An except at Prachin Buri, Kosum Phisai and Thong Pha Phum station ranked highest and thus has subject to impacts of high temperature during the 30 years period. With a year and for all station, the months of February-April and June appeared to be most vulnerable to high temperature, while the months of November was also moderately vulnerable. The most cases these were not during rice cultivation period in Thailand. During cultivation period, the impacts were generally low.

The second case is the mean temperature ≤22°C. Analyzing three aspects, the rate of change in number of days with temperature ≤22°C, the cumulative numbers of days with temperature ≤22°C, and the numbers of ≥ 3 consecutive days with temperature ≤22°C indicated that on average there were 1,105 days per year over Thailand, and this varied according to region. The number of days with temperature ≤22°C has deccreased at 5.3 days per 30 years. In most cases, this last only 1 days. However, there was 0.13% for those lasting more than 3 days. The potential impact of these low temperatures on rice production in Thailand is considered low level with a decreasing trend.

5.2 Recommendations and Limitations

- For the data during 1983-2005, the mean daily temperatures were calculated from the daily maximum and daily minimum temperatures. These data are different from 2006-2012, which data was the measured data.
- The duration, and the starting and ending dates of data used for temperature analysis may also affect the calculations of the temperature index.
- Air, but not field or canopy temperatures were used in this study. The location of meteorological station may not be located in rice growing areas (e.g urban area). Thus the results may be considered as preliminary, details study is needed to improve this.
- To provide a more accurate assessment, canopy temperatures should be used (usually 1-2 °C lower than air temperature).
- The data of plants were also limited. Information on response to temperature, detailed rice calendars and other related parameters are needed.

5.3 Future work

Further in-depth analysis with sufficient observational data will further improve our understanding of potential impacts as well as provide guidance for counter measures in the future.

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APPENDIXES

A : Location of Thai Department of Meteorology's stations in Thailand**.**

B : Monthly rate of change with daily maximum temperatures during 1983-2012.

C : Monthly rate of change with daily minimum temperatures during 1983-2012.

D : Monthly rate of change with mean daily temperatures during 1983-2012.

E : The monthly cumulated number of days with maximum temperatures ≥35°C**.**

F : Monthly rate of change for numbers of days with daily maximum temperatures ≥35ºC during 1983-2012**.**

G : Monthly numbers of ≥ 3 consecutive days with daily maximum temperatures ≥35°C during 1983-2012.

H : The monthly cumulated number of days with mean temperatures ≤22°C**.**

I : Monthly rate of change for numbers of days with mean daily temperatures ≤22ºC during 1983-2012**.**

J : Monthly numbers of ≥ 3 consecutive days with mean daily temperatures ≤22°C during 1983-2012**.**

APPENDIX A: Location of Thai Department of Meteorology's stations in Thailand**.**

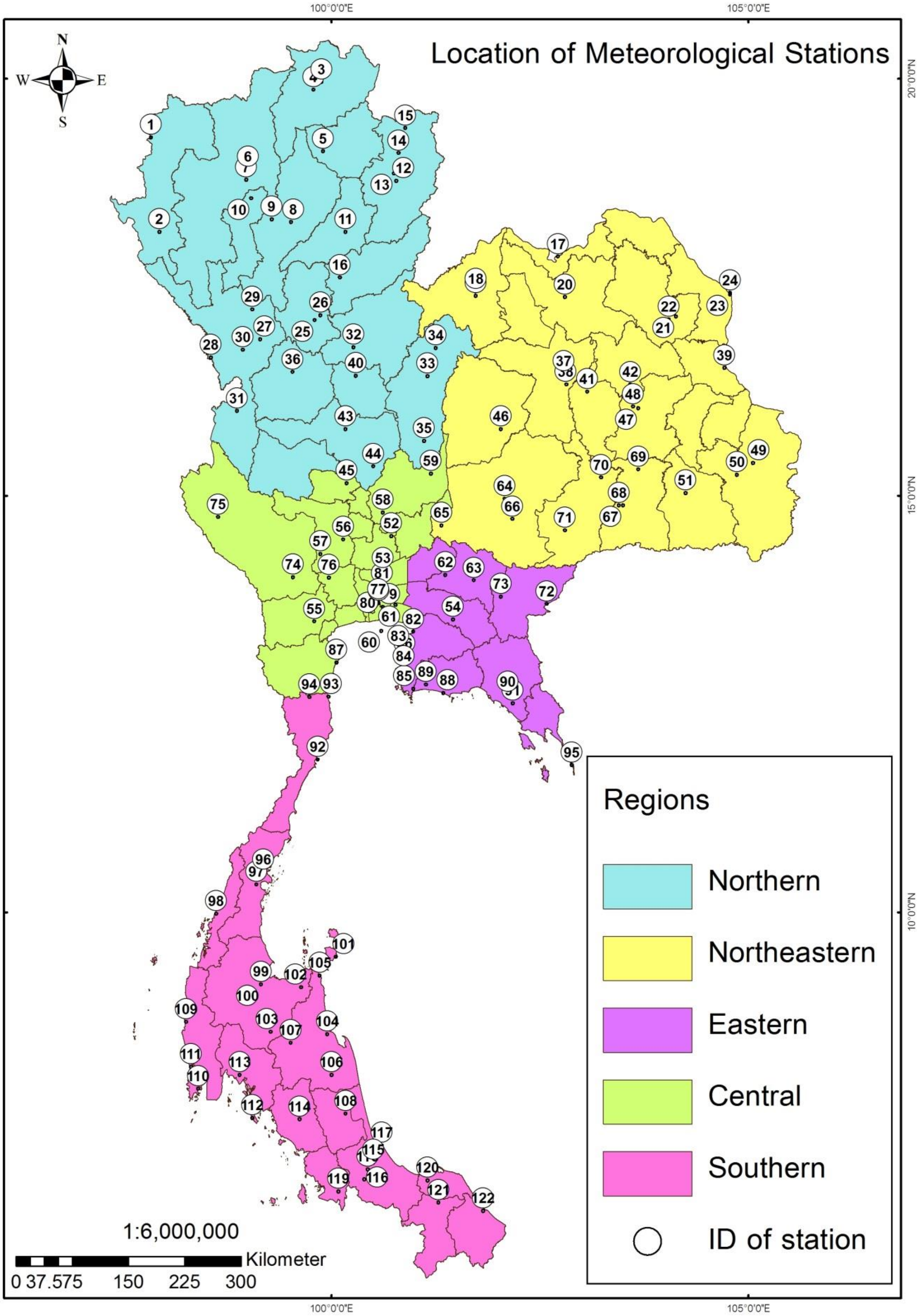

Table A-1 Lists of meteorological stations in Thailand from which the temperature records were used in this study

ID	StationName	Latitude	Longitude	Address	Region	TMD station code	WMO station code
1	Mae Hong Son	19.3000	97.8333	Chong Kham Sub-district, Mueang district, Mea Hong Son province	NORTHERN	300201	48300
2	Mae Sariang	18.1667	97.9333	Ban Kat Sub-district, Mae Sariang district, Mea Hong Son province	NORTHERN	300202	48325
3	Chiang Rai	19.9614	99.8814	Ban Du Sub-district, Mueang district, Chiang Rai province	NORTHERN	303201	48303
4	Chiang Rai Agromet	19.8708	99.7828	Rop Wiang Sub-district, Mueang district, Chiang Rai province	NORTHERN	303301	48304
5	Phayao	19.1333	99.9000	Ban Tom Sub-district, Mueang district, Phayao province	NORTHERN	310201	48310
6	Mae Jo	18.9167	99.0000	Suthep Sub-district, Mueang district, Chiang Mai province	NORTHERN	327301	48326
7	Chiang Mai	18.7900	98.9769	Suthep Sub-district, Mueang district, Chiang Mai province	NORTHERN	327501	48327
8	Lampang	18.2833	99.5167	Phra Bat Sub-district, Mueang district, Lampang province	NORTHERN	328201	48328
9	Lampang Agromet	18.3167	99.2833	Wiang Tan Sub-district, Hang Chat district, Lampang province	NORTHERN	328301	48334
10	Lamphun	18.5667	99.0333	Ban Klang Sub-district, Mueang district, Lamphun province	NORTHERN	329201	48329
11	Phrae	18.1667	100.1667	Na Chak Sub-district, Mueang district, Phrae province	NORTHERN	330201	48330
12	Nan	18.7797	100.7778	Du Tai Sub-district, Mueang district, Nan province	NORTHERN	331201	48331
13	Nan Agromet	18.8667	100.7500	Pha Sing Sub-district, Mueang district, Nan province	NORTHERN	331301	48333
14	Tha Wang Pha	19.1106	100.8025	Tha Wang Pha Sub-district, Tha Wang Pha district, Nan province	NORTHERN	331401	48315
15	Thung Chang	19.4119	100.8853	Lae Sub-district, Thung Chang district, Nan province	NORTHERN	331402	48307
16	Uttaradit	17.6167	100.1000	Tha It Sub-district, Mueang district, Uttaradit province	NORTHERN	351201	48351
17	Nong Khai	17.8667	102.7167	Pho Chai Sub-district, Mueang district, Nong Khai province	NORTHEASTERN	352201	48352
18	Loei	17.4500	101.7333	Na An Sub-district, Mueang district, Loei province	NORTHEASTERN	353201	48353
19	Loei Agromet	17.4000	101.7333	Na Pong Sub-district, Mueang district, Loei province	NORTHEASTERN	353301	48350
20	Udon Thani	17.3833	102.8000	Mak Khaeng Sub-district, Mueang district, Udon Thani province	NORTHEASTERN	354201	48354
21	Sakon Nakhon	17.1500	104.1333	That Choeng Chum Sub-district, Mueang district, Sakon Nakhon province	NORTHEASTERN	356201	48356
22	Sakon Nakhon Agromet	17.1167	104.0500	Huai Yang Sub-district, Mueang district, Sakon Nakhon province	NORTHEASTERN	356301	48355
23	Nakhon Phanom	17.4167	104.7833	Nai Mueang Sub-district, Mueang district, Nakhon Phanom province	NORTHEASTERN	357201	48357
24	Nakhon Phanom Agromet	17.4333	104.7833	Kham Thao Sub-district, Mueang district, Nakhon Phanom province	NORTHEASTERN	357301	48358
25	Sukhothai	17.1061	99.8000	Thap Phueng Sub-district, Si Samrong district, Sukhothai province	NORTHERN	373201	48372
26	Si Samrong Agromet	17.1667	99.8667	Khlong Tan Sub-district Si Samrong district, Sukhothai province	NORTHERN	373301	48373
27	Tak	16.8783	99.1433	Nam Ruem Sub-district, Mueang district, Tak province	NORTHERN	376201	48376
28	Mae Sot	16.6592	98.5508	Tha Sai Luat Sub-district, Mae Sot district,Tak province	NORTHERN	376202	48375
29	Bhumibol Dam	17.2333	99.0500	Sam Ngao Sub-district, Sam Ngao district,Tak province	NORTHERN	376203	48377
30	Doi Muser Agromet Stn.	16.7500	98.9333	Mae Tho Sub-district, Mueang district, Tak province	NORTHERN	376301	48387
31	Umphang	16.0158	98.8656	Umphang Sub-district, Umphang district, Tak province	NORTHERN	376401	48385

Table A-1 Lists of meteorological stations in Thailand from which the temperature records were used in this study (con't)

ID	StationName	Latitude	Longitude	Address	Region	TMD station code	WMO station code
32	Phitsanulok	16.7833	100.2667	Aranyik Sub-district, Mueang district, Phitsanulok province	NORTHERN	378201	48378
33	Phetchabun	16.4333	101.1500	Nai Mueang Sub-district, Mueang district, Phetchabun province	NORTHERN	379201	48379
34	Lom Sak	16.7736	101.2494	Lom Sak Sub-district, Lom Sak district, Phetchabun province	NORTHERN	379401	48374
35	Wichian Buri	15.6569	101.1083	Tha Rong Sub-district, Wichian Buri district, Phetchabun province	NORTHERN	379402	48413
36	Kamphaeng Phet	16.4833	99.5333	Nai Mueang Sub-district, Mueang district, Kamphaeng Phet province	NORTHERN	380201	48380
37	Khon Kaen	16.4633	102.7867	Ban Pet Sub-district, Mueang district, Khon Kaen province	NORTHEASTERN	381201	48381
38	Tha Phra Agromet	16.3333	102.8167	Tha Phra Sub-district, Mueang district, Khon Kaen province	NORTHEASTERN	381301	48384
39	Mukdahan	16.5333	104.7167	Mukdahan Sub-district, Mueang district, Mukdahan province	NORTHEASTERN	383201	48383
40	Pichit Agromet	16.4381	100.2925	Rong Chang Sub-district, Mueang district, Phichit province	NORTHERN	386301	48386
41	Kosum Phisai	16.2472	103.0681	Hua Khwang Sub-district, Kosum Phisai district, Maha Sarakham province	NORTHEASTERN	387401	48382
42	Kamalasai	16.3325	103.5883	Lak Mueang Sub-districtKamalasai district, Kalasin province	NORTHEASTERN	388401	48390
43	Nakhon Sawan	15.8000	100.1667	Nakhon Sawan Ok Sub-district, Mueang district, Nakhon Sawan province	NORTHERN	400201	48400
44	Tak Fa Agromet	15.3500	100.5000	Suk Samran Sub-district, Tak Fa district, Nakhon Sawan province	NORTHERN	400301	48401
45	Chai Nat	15.1500	100.1833	Bang Luang Sub-district, Sapphaya district, Chai Nat province	CENTRAL	402301	48402
46	Chaiyaphum	15.8000	102.0333	Nai Mueang Sub-district, Mueang district, Chaiyaphum province	NORTHEASTERN	403201	48403
47	Roi Et	16.0500	103.6833	Nai Mueang Sub-district, Mueang district, Roi Et province	NORTHEASTERN	405201	48405
48	Roi Et Agromet	16.0667	103.6167	Nuea Mueang Sub-district, Mueang district, Roi Et province	NORTHEASTERN	405301	48404
49	Ubon Ratchathani Agromet	15.3925	105.0592	Tha Chang Sub-district, Sawang Wirawong district,Ubon Ratchathani province	NORTHEASTERN	407301	48408
50	Ubon Ratchathani	15.2500	104.8667	Pathum Sub-district, Mueang district, Ubon Ratchathani province	NORTHEASTERN	407501	48407
51	Si Sa Ket Agromet	15.0333	104.2500	Nong Khrok Sub-district, Mueang district, Si Sa Ket province	NORTHEASTERN	409301	48409
52	Ayuttaya Agromet	14.5167	100.7167	Tha Chao Sanuk Sub-district, Tha Ruea district, Phra Nakhon Si Ayutthaya province	CENTRAL	415301	48415
53	Pathumthani Agromet	14.1000	100.6167	Khlong Nueng Sub-district, Khlong Luang district, Pathum Thani province	CENTRAL	419301	48419
54	Chacherngsao Agromet	13.5156	101.4583	Lat Krathing Sub-district, Sanam Chai Khet district, Chachoengsao province	EASTERN	423301	48458
55	Ratchaburi	13.4897	99.7922	Ang Thong Sub-district, Mueang district, Ratchaburi province	CENTRAL	424301	48464
56	Suphan Buri	14.4744	100.1389	Rua Yai Sub-district, Mueang district, Suphan Buri province	CENTRAL	425201	48425
57	U Thong Agromet	14.3000	99.8667	Chorakhe Sam Phan Sub-district, U Thong district, Suphan Buri province	CENTRAL	425301	48427
58	Lop Buri	14.8000	100.6167	Thale Chup Son Sub-district, Mueang district, Lop Buri province	CENTRAL	426201	48426
59	Bua Chum	15.2639	101.1917	Bua Chum Sub-district, Chai Badan district, Lop Buri province	CENTRAL	426401	48418
60	Pilot Station	13.3772	100.5994	Pak Nam Sub-district, Mueang district, Samut Prakan province	CENTRAL	429201	48457
61	Suvarnabhumi Airport	13.6864	100.7675	Racha Thewa Sub-district, Bang Phli district, Samut Prakan province	CENTRAL	429601	48429
62	Prachin Buri	14.0500	101.3667	Na Mueang Sub-district, Mueang district, Prachin Buri province	EASTERN	430201	48430

Table A-1 Lists of meteorological stations in Thailand from which the temperature records were used in this study (con't)

ID	StationName	Latitude	Longitude	Address	Region	TMD station code	WMO station code
63	Kabin Buri	13.9833	101.7072	Kabin Sub-district, Kabin Buri district, Prachin Buri province	EASTERN	430401	48439
64	Nakhon Ratchasima	14.9628	102.0767	Nai Mueang Sub-district, Mueang district, Nakhon Ratchasima province	NORTHEASTERN	431201	48431
65	Pak Chong Agromet	14.6439	101.3208	Klang Dong Sub-district, Pak Chong district, Nakhon Ratchasima province	NORTHEASTERN	431301	48435
66	Chok Chai	14.7189	102.1686	Chok Chai Sub-district, Chok Chai district, Nakhon Ratchasima province	NORTHEASTERN	431401	48434
67	Surin	14.8833	103.5000	Nok Mueang Sub-district, Mueang district, Surin province	NORTHEASTERN	432201	48432
68	Surin Agromet	14.8833	103.4500	Kho Kho Sub-district, Mueang district, Surin province	NORTHEASTERN	432301	48433
69	Tha Tum	15.3167	103.6833	Tha Tum Sub-district, Tha Tum district, Surin province	NORTHEASTERN	432401	48416
70	Bu Ri Rum	15.2167	103.2333	Ron Thong Sub-district, Satuek district, Buri Ram province	NORTHEASTERN	436201	48437
71	Nang Rong	14.5833	102.8000	Nong Bot Sub-district, Nang Rong district, Buri Ram province	NORTHEASTERN	436401	48436
72	Aranyaprathet	13.7000	102.5833	Aranyaprathet Sub-district, Aranyaprathet district, Sa Kaeo province	EASTERN	440201	48462
73	Sa Kaew	13.7889	102.0347	Sa Khwan Sub-district, Mueang district, Sa Kaeo province	EASTERN	440401	48440
74	Kanchanaburi	14.0225	99.5358	Ban Nuea Sub-district, Mueang district, Kanchanaburi province	CENTRAL	450201	48450
75	Thong Pha Phum	14.7422	98.6364	Tha Khanun Sub-district, Thong Pha Phum district, Kanchanaburi province	CENTRAL	450401	48421
76	Kamphaeng Saen Agromet	14.0167	99.9667	Kamphaeng Saen Sub-district, Kamphaeng Saen district, Nakhon Pathom province	CENTRAL	451301	48451
77	Bangkok Metropolis	13.6663	100.6069	Khwaeng Khlong Toei Khet Khlong Toei Bangkok	CENTRAL	455201	48455
78	Klong Toey	13.7069	100.5681	Khwaeng Khlong Toei Khet Khlong Toei Bangkok	CENTRAL	455203	48454
79	Bang Na	13.6663	100.6060	Khwaeng Bang Na Khet Bang Na Bangkok	CENTRAL	455301	48453
80	Bang Khen	13.8500	100.5833	NULL	CENTRAL	455302	NULL
81	Donmuang	13.9192	100.6050	Khwaeng Si Kan Khet Don Mueang Bangkok	CENTRAL	455601	48456
82	Chon Buri	13.3667	100.9833	Ban Suan Sub-district, Mueang district, Chon Buri province	EASTERN	459201	48459
83	Ko Sichang	13.1617	100.8019	Tha Thewawong Sub-district, Ko Sichang district, Chon Buri province	EASTERN	459202	48460
84	Phatthaya	12.9200	100.8694	Nong Prue Sub-district, Bang Lamung district, Chon Buri province	EASTERN	459203	48461
85	Sattahip	12.6833	100.9833	Phlu Ta Luang Sub-district, Sattahip district, Chon Buri province	EASTERN	459204	48477
86	Lam Chabang	13.0769	100.8758	Thung Sukhla Sub-district, Si Racha district, Chon Buri province	EASTERN	459205	48463
87	Phetchaburi	12.9994	100.0606	Hat Chao Samran Sub-district, Mueang district, Phetchaburi province	CENTRAL	465201	48465
88	Rayong	12.6322	101.3436	Taphong Sub-district, Mueang district, Rayong province	EASTERN	478201	48478
89	Huai Pong Agromet	12.7333	101.1333	Huai Pong Sub-district, Mueang district, Rayong province	EASTERN	478301	48479
90	Chanthaburi	12.6167	102.1133	Wat Mai Sub-district, Mueang district, Chanthaburi province	EASTERN	480201	48480
91	Phriu Agromet	12.5086	102.1731	Tapon Sub-district, Khlung district, Chanthaburi province	EASTERN	480301	48481
92	Prachuap Khiri Khan	11.8333	99.8333	Ko Lak Sub-district, Mueang district, Prachuap Khiri Khan province	SOUTHERN	500201	48500
93	Hua Hin	12.5861	99.9625	Hua Hin Sub-district, Hua Hin district, Prachuap Khiri Khan province	SOUTHERN	500202	48475

Table A-1 Lists of meteorological stations in Thailand from which the temperature records were used in this study (con't)

ID	StationName	Latitude	Longitude	Address	Region	TMD station code	WMO station code
94	Nong Phlup Agromet	12.5833	99.7333	Nong Phlap Sub-district, Hua Hin district, Prachuap Khiri Khan province	SOUTHERN	500301	48474
95	Khlong Yai	11.7667	102.8833	Khlong Yai Sub-district, Khlong Yai district, Trat province	EASTERN	501201	48501
96	Chumphon	10.4833	99.1833	Tha Taphao Sub-district, Mueang district, Chumphon province	SOUTHERN	517201	48517
97	Sawi Agromet	10.3333	99.1000	Wisai Tai Sub-district, Sawi district, Chumphon province	SOUTHERN	517301	48520
98	Ranong	9.9833	98.6167	Bang Rin Sub-district, Mueang district, Ranong province	SOUTHERN	532201	48532
99	Surat Thani	9.1356	99.1519	Hua Toei Sub-district, Phunphin district,Surat Thani province	SOUTHERN	551201	48551
100	Phunphin Airport	9.1356	99.1519	NULL	SOUTHERN	551202	NULL
101	Ko Samui	9.4667	100.0500	Maret Sub-district, Ko Samui district,Surat Thani province	SOUTHERN	551203	48550
102	Surat Thani Agromet	9.1000	99.6333	Tha U-thae Sub-district, Kanchanadit district,Surat Thani province	SOUTHERN	551301	48555
103	Phra Sang	8.5667	99.2667	I-pan Sub-district, Phrasaeng district,Surat Thani province	SOUTHERN	551401	48556
104	Nakhon Si Thammarat	8.5378	99.9472	Pak Phun Sub-district, Mueang district, Nakhon Si Thammarat province	SOUTHERN	552201	48552
105	Khanom	9.2431	99.8575	NULL	SOUTHERN	552202	48553
106	Nakhorn Sri Thammarat Agromet	8.0500	100.0000	Bang Chak Sub-district, Mueang district, Nakhon Si Thammarat province	SOUTHERN	552301	48554
107	Chawang	8.4319	99.5119	Chawang Sub-district, Chawang district, Nakhon Si Thammarat province	SOUTHERN	552401	48557
108	Phatthalung Agromet	7.5833	100.1667	Lampam Sub-district, Mueang district, Phatthalung province	SOUTHERN	560301	48560
109	Takua Pa	8.6842	98.2522	Khuekkhak Sub-district, Takua Pa district, Phang–nga province	SOUTHERN	561201	48561
110	Phuket	7.8833	98.4000	Talat Yai Sub-district, Mueang district, Phuket province	SOUTHERN	564201	48564
111	Phuket Airport	8.1450	98.3144	Mai Khao Sub-district, Thalang district, Phuket province	SOUTHERN	564202	48565
112	Ko Lanta	7.5333	99.0500	Ko Lanta Sub-district, Ko Lanta district, Krabi province	SOUTHERN	566201	48566
113	Krabi	8.0500	98.9000	Nuea Khlong Sub-district, Nuea Khlong district, Krabi province	SOUTHERN	566202	48563
114	Trang Airport	7.5167	99.6167	Khok Lo Sub-district, Mueang district, Trang province	SOUTHERN	567201	48567
115	Kho Hong Agromet	7.0000	100.5000	Kho Hong Sub-district, Hat Yai district, Songkhla province	SOUTHERN	568301	48571
116	Sa Dao	6.7981	100.3906	Tha Pho Sub-district, Sadao district, Songkhla province	SOUTHERN	568401	48574
117	Songkhla	7.2039	100.6047	Bo Yang Sub-district, Mueang district, Songkhla province	SOUTHERN	568501	48568
118	Hat Yai Airport	6.9167	100.4333	Khlong Hoi Khong Sub-district, Khlong Hoi Khong district, Songkhla province	SOUTHERN	568502	48569
119	Satun	6.6500	100.0833	Khlong Khut Sub-district, Mueang district, Satun province	SOUTHERN	570201	48570
120	Pattani Airport	6.7833	101.1500	Bo Thong Sub-district, Nong Chik district,Pattani province	SOUTHERN	580201	48580
121	Yala Agromet	6.5167	101.2833	SatengSub-district, Mueang district, Yala province	SOUTHERN	581301	48581
122	Narathiwat	6.4167	101.8167	Bang Nak Sub-district, Mueang district, Narathiwat province	SOUTHERN	583201	48583

APPENDIX B: Monthly rate of change with daily maximum temperatures during 1983-2012. Bold values indicate the rates of change that are statistically significant at p<0.05 by Kendall'tau non-parametric test.

ID	Rate of change with daily maximum temperature (ºC/decade)												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
1	-0.19	-0.03	-0.29	-0.20	-0.47	0.19	0.04	0.10	0.05	0.21	0.16	-0.12	-0.04
2	0.40	0.31	-0.03	-0.25	-0.52	0.13	0.13	0.04	0.09	**0.49**	**0.71**	**0.54**	**0.17**
4	0.24	0.21	-0.56	-0.65	-0.25	0.13	0.17	0.09	**0.26**	**0.62**	**0.82**	**0.74**	**0.15**
5	0.37	0.21	-0.49	-0.55	-0.15	0.33	0.30	0.17	**0.34**	**0.67**	**0.88**	**0.75**	**0.24**
7	0.24	0.21	-0.31	-0.21	-0.48	0.07	-0.06	-0.16	0.01	0.29	**0.57**	**0.53**	0.06
8	0.44	**0.42**	-0.16	-0.16	-0.33	0.31	0.17	0.13	**0.27**	**0.44**	**0.74**	**0.65**	**0.24**
10	0.19	0.20	-0.48	-0.48	-0.64	0.14	0.01	0.04	0.11	**0.43**	**0.62**	**0.48**	0.05
11	-0.04	0.00	-0.44	-0.55	-0.58	-0.04	-0.24	**-0.29**	-0.06	0.22	**0.48**	0.39	-0.10
13	0.18	0.26	-0.36	**-0.52**	-0.29	0.08	0.00	-0.07	-0.01	**0.45**	**0.60**	**0.60**	0.08
14	-0.02	0.15	-0.33	**-0.50**	-0.11	0.35	0.33	0.14	0.04	**0.31**	0.34	0.35	0.09
16	0.17	-0.07	-0.46	-0.53	-0.29	0.34	0.11	0.04	0.13	**0.56**	**0.84**	**0.61**	0.12
17	0.19	0.14	-0.27	-0.46	0.01	0.29	0.21	0.09	0.12	**0.62**	**0.62**	**0.59**	**0.18**
18	0.06	-0.02	-0.33	-0.43	-0.18	0.11	-0.01	-0.13	-0.15	0.34	0.57	0.35	0.01
20	0.30	0.32	0.01	-0.16	0.17	0.33	0.21	0.20	0.17	**0.60**	**0.66**	**0.61**	**0.29**
21	0.23	0.22	-0.15	-0.36	0.22	**0.55**	**0.31**	0.25	0.20	**0.63**	**0.78**	**0.70**	**0.30**
23	0.21	0.36	0.02	-0.38	-0.01	0.23	0.01	-0.06	-0.03	**0.42**	**0.71**	**0.64**	**0.18**
27	0.11	0.13	-0.32	-0.49	-0.68	0.28	-0.12	0.04	0.06	**0.34**	**0.78**	0.58	0.06
28	0.45	**0.46**	0.08	-0.08	-0.33	0.35	0.16	0.19	0.12	**0.51**	**0.85**	**0.77**	**0.29**
29	0.11	0.13	-0.36	-0.49	-0.57	0.24	-0.11	-0.07	-0.05	0.31	**0.64**	0.54	0.03
31	0.16	0.08	-0.35	-0.45	-0.35	0.39	0.07	0.18	-0.02	**0.43**	**0.69**	**0.53**	0.11
32	-0.34	**-0.42**	-0.46	-0.52	-0.55	0.09	-0.14	-0.04	-0.08	**0.31**	**0.51**	0.13	-0.13
33	0.13	-0.03	-0.15	-0.25	-0.27	0.32	0.02	0.06	0.01	**0.53**	**0.79**	**0.61**	**0.15**
34	0.24	0.22	0.05	-0.02	-0.02	**0.50**	0.09	0.12	0.11	**0.50**	**0.76**	**0.62**	**0.26**
35	0.21	0.26	0.02	-0.10	0.15	**0.56**	0.29	**0.42**	**0.27**	**0.62**	**0.72**	**0.54**	**0.33**
36	-0.22	-0.39	-0.51	**-0.64**	-0.56	-0.02	-0.25	-0.08	0.00	**0.29**	**0.60**	0.33	-0.12
37	-0.02	-0.18	-0.44	-0.61	-0.15	0.30	0.02	0.00	-0.03	**0.39**	0.38	0.32	0.00
39	0.61	**0.58**	0.28	-0.06	0.27	**0.66**	0.35	**0.31**	**0.31**	**0.70**	**0.94**	**1.00**	**0.50**
41	0.26	0.07	-0.20	-0.38	0.12	**0.57**	**0.37**	0.21	**0.30**	**0.73**	**0.88**	**0.80**	**0.31**
43	-0.15	-0.27	-0.47	-0.50	-0.34	-0.21	-0.27	0.01	0.02	**0.42**	**0.55**	0.41	-0.07
44	0.07	0.03	-0.25	-0.28	-0.25	0.01	-0.10	0.10	0.12	**0.44**	0.49	0.46	0.07
45	-0.29	**-0.66**	**-0.65**	-0.37	-0.44	**-0.31**	**-0.46**	-0.19	0.20	**0.57**	**0.75**	0.50	-0.11
46	0.25	0.15	-0.29	-0.37	-0.17	0.22	-0.03	**-0.08**	-0.15	0.34	0.58	0.55	**0.08**
48	-0.01	-0.07	-0.20	-0.42	-0.12	**0.36**	0.06	0.05	-0.01	**0.37**	**0.49**	0.47	0.08
49	0.17	0.17	-0.02	0.01	0.12	**0.55**	**0.27**	**0.30**	0.06	**0.51**	**0.74**	**0.67**	**0.30**
50	0.33	0.18	-0.08	-0.15	0.02	**0.50**	0.20	0.24	0.16	**0.65**	**0.87**	**0.79**	**0.31**
51	-0.05	0.06	-0.16	-0.13	-0.10	0.38	0.13	0.12	-0.02	**0.36**	**0.57**	0.46	0.13
56	-0.20	0.12	-0.04	0.07	-0.13	0.16	-0.01	0.11	0.25	**0.46**	**0.64**	0.39	**0.15**
57	-0.19	-0.31	**-0.71**	-0.54	-0.30	-0.08	-0.25	-0.04	0.17	**0.55**	**0.64**	0.46	-0.05
58	-0.13	-0.34	**-0.63**	**-0.64**	-0.48	-0.03	-0.17	-0.01	0.04	**0.37**	0.44	0.33	-0.10

APPENDIX B: Monthly rate of change with daily maximum temperatures during 1983-2012. Bold values indicate the rates of change that are statistically significant at $p<0.05$ by Kendall'tau non-parametric test. (con't)

ID	Rate of change with daily maximum temperature (°C/decade)												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
59	0.02	-0.10	-0.43	-0.40	-0.26	0.19	-0.02	**0.31**	0.09	**0.43**	0.56	0.52	0.08
62	0.15	0.31	0.09	0.13	0.40	**0.64**	**0.40**	**0.53**	**0.44**	**0.72**	**0.72**	**0.53**	**0.42**
63	-0.18	-0.16	-0.38	-0.34	-0.01	**0.50**	0.18	**0.27**	0.10	**0.35**	0.30	0.13	0.06
64	0.04	-0.07	-0.37	-0.47	-0.12	0.30	0.06	0.13	0.01	**0.40**	**0.69**	0.57	0.10
65	-0.40	**-0.49**	**-0.88**	**-0.81**	-0.55	-0.18	**-0.44**	-0.29	**-0.48**	0.01	0.23	0.14	**-0.34**
66	0.31	0.15	-0.20	-0.21	0.08	**0.43**	0.14	0.25	**0.21**	**0.61**	**0.89**	**0.87**	**0.29**
67	-0.01	0.05	-0.28	-0.37	-0.09	0.32	0.07	0.14	0.03	**0.48**	**0.74**	0.54	0.13
69	-0.03	-0.10	-0.44	-0.52	-0.14	0.36	0.16	0.21	0.16	**0.52**	**0.63**	0.54	0.11
71	0.18	0.06	-0.22	-0.30	-0.11	0.19	0.08	**0.18**	0.08	**0.41**	**0.70**	**0.68**	**0.16**
72	0.11	0.03	-0.15	-0.21	0.06	**0.39**	**0.26**	**0.31**	0.13	**0.43**	**0.57**	**0.57**	**0.21**
74	-0.18	-0.32	**-0.93**	**-0.90**	-0.64	0.14	-0.21	-0.08	-0.03	0.21	0.44	0.26	-0.19
75	**0.68**	**0.66**	0.25	0.25	-0.15	0.71	0.44	**0.58**	**0.42**	**0.83**	**1.01**	**0.91**	**0.55**
76	-0.21	-0.02	-0.41	**-0.35**	-0.29	0.15	-0.07	0.01	0.09	**0.33**	0.56	0.43	0.02
79	0.16	0.17	0.06	-0.02	-0.03	0.22	0.04	0.17	**0.26**	**0.54**	**0.64**	**0.46**	**0.22**
81	-0.17	0.11	-0.05	-0.12	-0.13	0.23	0.13	0.23	0.26	**0.53**	0.57	0.46	0.17
82	-0.06	-0.03	-0.31	-0.30	0.00	0.15	0.04	0.11	0.13	**0.41**	0.42	0.23	0.07
84	-0.03	0.18	0.00	0.06	0.08	0.18	0.11	0.20	0.11	**0.29**	0.18	0.22	**0.13**
85	**0.74**	**0.73**	**0.68**	**0.62**	**0.45**	**0.38**	0.27	**0.44**	**0.48**	**0.75**	**0.85**	**0.91**	**0.61**
87	-0.03	0.23	0.08	0.26	0.16	**0.34**	0.22	0.20	**0.35**	**0.34**	**0.45**	0.26	**0.24**
88	0.07	0.03	0.03	0.02	-0.06	-0.03	-0.08	-0.02	-0.05	0.22	0.22	0.19	0.05
89	0.24	**0.56**	**0.46**	**0.51**	**0.38**	**0.56**	**0.34**	**0.56**	**0.37**	**0.45**	**0.41**	0.38	**0.44**
90	0.05	0.14	0.10	0.16	0.24	**0.43**	**0.28**	**0.43**	0.17	**0.40**	0.51	**0.52**	**0.29**
91	-0.01	0.02	-0.03	-0.07	-0.01	0.22	0.13	**0.30**	0.00	**0.30**	0.38	**0.40**	**0.13**
92	**0.69**	**1.11**	**0.93**	**0.84**	**0.52**	**0.67**	0.08	**0.32**	**0.56**	**0.69**	**0.66**	**0.55**	**0.63**
94	0.21	0.25	-0.19	-0.13	-0.08	**0.60**	0.24	**0.33**	**0.28**	**0.35**	**0.70**	**0.54**	**0.26**
97	**0.29**	0.21	-0.07	-0.16	0.06	0.43	0.13	**0.43**	0.34	**0.22**	**0.38**	**0.48**	**0.23**
98	-0.28	-0.24	**-0.55**	-0.23	-0.17	0.14	0.00	**0.29**	0.20	0.07	0.06	-0.07	-0.07
101	0.01	0.06	-0.14	-0.26	0.03	0.11	-0.03	0.24	0.15	0.03	0.02	0.14	0.03
104	-0.01	0.18	-0.17	-0.32	0.21	0.20	0.11	0.21	0.13	-0.04	0.11	0.25	0.07
108	0.03	0.19	-0.03	-0.18	0.22	0.20	0.10	0.27	0.18	0.18	0.19	0.24	0.13
110	0.05	0.18	-0.09	-0.16	0.21	0.17	**0.13**	**0.32**	**0.37**	0.22	0.27	0.10	**0.15**
111	0.00	0.08	-0.31	-0.12	0.03	0.03	0.04	**0.16**	0.21	0.09	0.25	0.17	0.05
112	-0.22	-0.17	**-0.54**	-0.45	-0.15	-0.15	-0.05	0.09	0.14	0.06	0.16	0.01	-0.11
114	-0.11	-0.08	-0.35	-0.21	0.28	**0.34**	**0.38**	**0.54**	**0.56**	**0.34**	0.21	0.10	0.17
115	**0.22**	0.36	0.17	0.07	**0.33**	**0.28**	**0.31**	**0.47**	**0.37**	**0.26**	**0.26**	**0.36**	**0.29**
119	0.05	0.18	-0.18	-0.14	0.23	0.16	**0.19**	**0.27**	**0.35**	**0.32**	**0.34**	0.25	**0.17**
120	0.30	**0.53**	0.13	0.03	**0.29**	**0.36**	**0.38**	**0.44**	**0.47**	**0.45**	**0.57**	**0.55**	**0.38**
121	0.11	0.26	-0.22	-0.21	0.15	0.26	**0.21**	**0.35**	**0.21**	0.14	0.30	0.32	0.16
122	**-0.63**	**-0.60**	**-0.58**	**-0.60**	-0.28	**-0.24**	**-0.27**	-0.15	-0.12	**-0.31**	-0.23	-0.13	**-0.35**

APPENDIX C: Monthly rate of change with daily minimum temperatures during 1983-2012. Bold values indicate the rates of change that are statistically significant at $p<0.05$ by Kendall'tau non-parametric test.

ID	Rate of change with daily minimum temperature (°C/decade)												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
1	**0.95**	**0.59**	**0.60**	0.41	0.34	**0.27**	0.15	0.09	0.20	0.22	0.19	**0.80**	**0.40**
2	**0.78**	0.22	0.35	-0.01	-0.10	-0.02	0.12	0.02	0.13	0.09	0.07	**0.76**	**0.20**
3	**1.00**	**0.88**	**0.84**	**0.72**	**0.43**	**0.41**	**0.45**	**0.38**	**0.49**	**0.60**	0.37	**1.27**	**0.65**
5	0.54	0.24	-0.15	-0.02	0.01	0.12	**0.17**	**0.13**	**0.20**	0.22	0.09	**1.13**	0.22
7	**0.77**	0.41	**0.45**	**0.42**	0.06	0.22	**0.23**	**0.16**	**0.31**	**0.39**	0.39	**1.12**	**0.41**
8	0.54	0.51	**0.41**	**0.36**	0.15	0.15	0.09	**0.11**	**0.17**	0.19	0.19	**1.00**	**0.32**
10	**0.57**	0.39	0.37	0.32	0.26	0.16	**0.21**	0.13	0.15	0.10	0.12	**0.88**	**0.31**
11	0.66	0.55	0.36	0.22	0.22	**0.33**	**0.40**	**0.25**	**0.35**	**0.41**	0.41	**1.17**	**0.45**
13	0.45	0.51	**0.49**	**0.34**	0.20	0.11	**0.26**	**0.15**	**0.31**	**0.36**	0.12	**1.10**	**0.37**
14	**0.76**	**0.61**	0.27	0.24	0.22	0.27	**0.39**	**0.31**	**0.30**	**0.44**	0.29	**1.35**	**0.45**
16	**0.77**	**0.83**	**0.75**	**0.56**	**0.38**	**0.38**	**0.34**	**0.30**	**0.40**	**0.47**	**0.61**	**1.22**	**0.58**
17	0.26	0.22	0.27	0.01	0.08	0.08	0.15	**0.12**	0.17	**0.36**	0.42	**0.97**	0.26
18	0.57	0.44	**0.46**	0.07	0.13	0.10	**0.18**	0.10	**0.24**	0.27	0.46	**1.26**	**0.36**
20	-0.09	-0.14	-0.02	-0.16	-0.07	-0.01	0.00	-0.08	-0.02	0.05	0.01	0.51	0.00
21	0.48	0.19	0.15	-0.05	0.24	**0.32**	**0.31**	**0.21**	**0.24**	**0.34**	**0.61**	**1.08**	**0.34**
23	0.41	0.25	0.34	-0.04	0.12	**0.25**	**0.20**	**0.18**	**0.26**	0.27	0.58	**1.03**	**0.32**
24	0.13	-0.05	0.14	-0.19	0.07	**0.30**	**0.35**	**0.33**	**0.29**	0.09	0.27	**0.83**	**0.21**
27	**0.90**	0.44	0.16	0.07	0.28	**0.46**	**0.37**	**0.42**	**0.60**	**0.62**	**0.73**	**1.42**	**0.54**
28	**0.70**	**0.58**	**0.56**	0.22	0.12	**0.24**	**0.14**	0.09	**0.20**	0.17	0.40	**1.23**	**0.39**
29	0.09	-0.26	-0.24	-0.38	-0.13	0.01	-0.12	-0.17	0.00	0.02	0.09	0.56	-0.04
31	0.45	**0.96**	**1.05**	**0.52**	**0.37**	**0.21**	**0.28**	**0.21**	**0.44**	0.20	0.42	**1.00**	**0.51**
33	0.55	0.38	0.34	-0.02	0.10	0.13	0.11	0.08	**0.15**	0.19	0.45	**1.13**	**0.30**
34	0.37	0.33	0.33	-0.02	0.04	0.02	-0.08	-0.15	0.00	0.04	0.25	**0.98**	0.18
35	0.54	0.20	0.20	-0.03	0.17	**0.24**	**0.23**	**0.28**	**0.32**	**0.34**	**0.56**	**1.17**	**0.35**
36	**0.63**	**0.59**	**0.41**	0.13	0.08	0.15	0.13	**0.12**	**0.17**	**0.27**	**0.49**	**1.05**	**0.35**
37	**0.58**	0.14	-0.02	-0.32	0.02	0.07	-0.03	-0.13	0.08	**0.30**	0.55	**1.04**	**0.19**
39	**0.69**	0.37	0.23	0.02	0.23	**0.33**	**0.24**	**0.22**	**0.26**	**0.34**	**0.56**	**1.13**	**0.39**
41	0.35	-0.02	-0.05	**-0.36**	-0.16	-0.05	-0.05	-0.08	0.05	0.23	0.50	**0.97**	0.11
43	0.25	0.17	0.12	0.02	0.08	0.11	0.14	**0.19**	**0.24**	**0.29**	0.46	**0.93**	**0.25**
44	0.35	0.17	0.14	-0.09	0.04	0.13	0.16	**0.12**	**0.18**	0.16	0.28	**0.76**	**0.20**
45	0.53	0.36	0.09	0.00	0.16	**0.19**	**0.21**	**0.15**	0.14	0.22	**0.36**	**0.90**	**0.28**
46	0.40	0.18	**0.27**	0.03	0.15	**0.22**	0.11	**0.09**	**0.22**	**0.31**	0.34	**0.86**	**0.27**
48	0.30	-0.02	-0.11	-0.27	0.02	0.19	0.06	**0.10**	**0.17**	0.22	0.38	**0.81**	0.15
49	0.36	0.01	-0.07	-0.36	0.01	0.15	0.09	0.06	0.06	0.15	0.37	**0.71**	0.13
50	0.50	0.28	-0.04	-0.43	-0.13	0.24	0.15	0.19	0.18	0.17	0.49	**0.90**	0.21
51	0.40	0.10	0.01	-0.17	**0.22**	**0.45**	**0.42**	**0.18**	**0.20**	**0.30**	0.44	**0.90**	**0.29**
56	0.41	**0.49**	**0.36**	0.09	0.05	0.08	0.05	-0.04	0.02	0.06	0.26	**0.76**	**0.22**
57	0.17	0.41	**0.49**	0.08	-0.10	-0.20	-0.20	-0.25	-0.10	-0.10	-0.01	0.54	0.06
58	0.44	0.35	**0.20**	-0.02	0.05	0.18	**0.25**	**0.28**	**0.28**	**0.39**	**0.49**	**0.85**	**0.31**

APPENDIX C: Monthly rate of change with daily minimum temperatures during 1983-2012. Bold values indicate the rates of change that are statistically significant at $p<0.05$ by Kendall'tau non-parametric test. (con't)

ID	Rate of change with daily minimum temperature (°C/decade)												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
59	0.46	0.32	0.25	-0.14	0.02	0.06	0.16	0.13	0.13	0.20	0.35	**0.99**	**0.24**
62	**0.45**	0.37	0.27	-0.02	0.13	0.07	0.04	0.06	0.05	0.22	**0.45**	**0.90**	**0.25**
63	**0.51**	0.33	0.15	-0.16	0.04	0.14	0.16	0.22	0.23	**0.34**	0.39	**0.72**	**0.26**
64	**0.62**	0.39	**0.50**	0.15	**0.27**	**0.27**	**0.34**	**0.32**	**0.31**	**0.50**	**0.55**	**1.08**	**0.44**
65	**1.42**	**1.10**	**0.93**	**0.38**	**0.41**	**0.34**	**0.37**	**0.35**	**0.24**	**0.49**	**0.91**	**1.83**	**0.73**
66	0.58	0.37	**0.42**	0.09	0.18	**0.17**	**0.22**	**0.20**	**0.26**	**0.27**	0.39	**0.95**	**0.34**
68	0.57	0.45	**0.32**	0.11	**0.28**	**0.33**	**0.38**	**0.29**	**0.27**	0.27	0.44	**0.88**	**0.38**
69	0.30	0.07	-0.02	-0.14	0.18	**0.29**	0.17	0.17	0.14	0.29	0.37	**0.71**	0.21
71	0.43	0.18	**0.33**	0.07	0.12	0.18	**0.22**	**0.22**	**0.27**	**0.24**	0.27	**0.77**	**0.28**
72	**0.51**	0.20	**0.22**	-0.04	**0.22**	**0.24**	**0.24**	**0.25**	**0.26**	**0.41**	**0.42**	**0.85**	**0.31**
74	0.41	0.34	0.05	-0.39	-0.28	-0.16	-0.15	-0.14	-0.05	0.01	0.08	0.64	0.03
75	0.64	**0.80**	**0.66**	0.10	0.02	0.11	0.26	0.28	0.32	0.25	0.37	**1.19**	0.42
76	**0.86**	**0.72**	**0.47**	0.10	0.03	0.20	**0.29**	0.13	**0.22**	**0.30**	**0.45**	**1.14**	**0.41**
79	0.35	0.33	**0.29**	0.10	0.11	0.20	**0.31**	**0.27**	**0.32**	**0.31**	**0.50**	**0.85**	**0.33**
81	**0.59**	**0.59**	**0.61**	**0.38**	0.33	0.36	**0.53**	**0.47**	**0.44**	**0.49**	**0.58**	**1.03**	**0.53**
82	**0.87**	**0.69**	**0.39**	0.25	**0.38**	**0.40**	**0.52**	**0.50**	**0.55**	**0.64**	**0.81**	**1.22**	**0.60**
84	**0.34**	0.10	-0.08	-0.23	-0.14	-0.20	0.06	0.02	**0.20**	**0.38**	**0.69**	**0.80**	**0.16**
85	0.27	0.04	-0.19	-0.33	-0.03	0.05	0.18	0.14	**0.25**	**0.29**	**0.39**	**0.50**	0.13
87	**0.58**	**0.54**	**0.34**	0.13	0.14	0.15	0.18	0.07	**0.16**	**0.22**	0.29	**0.73**	**0.29**
88	**0.73**	0.31	-0.02	-0.13	0.14	0.16	**0.30**	0.20	**0.30**	**0.31**	**0.49**	**0.87**	**0.31**
89	**0.67**	**0.47**	0.37	0.07	0.16	0.07	0.17	0.07	**0.25**	**0.26**	**0.40**	**0.66**	**0.30**
90	**0.47**	**0.39**	**0.27**	0.04	0.12	0.15	0.14	0.12	**0.12**	**0.25**	0.26	**0.58**	**0.24**
91	**0.60**	**0.39**	**0.31**	0.11	0.18	**0.28**	**0.25**	**0.25**	**0.31**	**0.37**	**0.46**	**0.87**	**0.37**
92	**0.72**	**0.62**	**0.36**	0.13	0.22	**0.26**	0.13	0.12	**0.34**	**0.36**	**0.38**	**0.71**	**0.36**
93	**0.54**	**0.41**	**0.26**	0.05	0.00	0.09	0.19	0.06	**0.20**	**0.29**	**0.47**	**0.68**	**0.27**
95	**0.35**	0.07	-0.06	-0.16	-0.10	0.11	0.02	0.01	0.05	**0.16**	**0.32**	**0.38**	**0.10**
97	**0.31**	**0.37**	**0.35**	0.11	0.04	0.01	**0.15**	0.05	**0.14**	**0.12**	**0.23**	**0.47**	**0.20**
98	**0.40**	0.39	**0.31**	0.03	0.02	0.06	0.05	0.15	**0.14**	0.00	0.05	**0.24**	**0.15**
101	0.00	0.05	-0.24	-0.15	-0.08	-0.01	0.12	0.06	**0.16**	**0.17**	0.06	0.12	0.02
104	-0.03	-0.04	0.00	-0.12	-0.06	-0.14	0.08	-0.02	0.14	-0.06	-0.13	-0.09	-0.04
106	0.38	**0.45**	**0.57**	**0.39**	**0.32**	**0.21**	**0.42**	**0.30**	**0.36**	**0.31**	**0.22**	**0.38**	**0.36**
108	-0.02	0.20	0.10	0.11	0.05	-0.04	0.07	0.00	0.11	0.02	0.15	0.13	0.07
109	**0.65**	**0.66**	**0.48**	**0.50**	**0.43**	0.22	**0.48**	**0.34**	**0.38**	**0.38**	**0.43**	**0.68**	**0.47**
111	**0.60**	**0.50**	**0.33**	0.15	-0.05	-0.26	-0.01	-0.27	-0.07	0.08	**0.21**	**0.42**	0.14
112	0.23	0.23	0.04	0.06	0.19	-0.03	0.13	0.06	**0.20**	**0.23**	**0.24**	**0.33**	**0.16**
114	**0.42**	0.47	**0.47**	**0.35**	0.23	0.25	0.29	0.16	0.24	0.13	0.24	**0.31**	**0.30**
118	**0.36**	0.25	**0.30**	**0.28**	0.17	0.18	**0.28**	**0.20**	**0.26**	**0.16**	**0.28**	**0.36**	**0.26**
119	0.14	0.35	0.21	0.27	0.10	0.10	0.16	0.10	0.18	0.19	0.25	0.28	**0.20**
120	**0.32**	**0.42**	**0.44**	**0.44**	**0.32**	**0.28**	**0.40**	**0.26**	**0.34**	**0.26**	**0.27**	**0.29**	**0.34**
121	**0.62**	**0.71**	**0.68**	**0.56**	**0.64**	**0.67**	**0.82**	**0.68**	**0.66**	**0.45**	**0.50**	**0.52**	**0.63**
122	0.03	0.14	0.06	0.12	0.03	0.08	0.14	0.08	0.06	0.03	**0.09**	0.05	0.07

APPENDIX D: Monthly rate of change with mean daily temperatures during 1983-2012. Bold values indicate the rates of change that are statistically significant at p<0.05 by Kendall'tau non-parametric test.

ID	Rate of change with mean daily temperature (ºC/decade)												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
1	**0.56**	-0.03	-0.15	-0.13	-0.30	0.10	0.02	0.04	0.02	0.09	0.15	**0.56**	0.08
2	**0.39**	0.14	-0.02	-0.15	**-0.29**	0.07	0.06	0.01	0.04	**0.13**	0.06	**0.51**	0.08
4	**0.45**	**-0.63**	-0.24	-0.34	-0.13	0.07	0.08	0.04	**0.13**	**0.29**	0.22	**0.84**	0.07
5	0.31	0.13	-0.27	-0.39	-0.08	0.19	**0.16**	0.09	**0.17**	0.13	0.05	**0.74**	0.10
7	**0.43**	0.12	-0.15	-0.13	-0.30	0.06	-0.03	-0.07	0.02	0.16	0.27	**0.74**	0.09
8	0.29	0.24	-0.09	-0.11	-0.20	0.16	0.09	0.06	**0.14**	**0.19**	0.12	**0.65**	0.13
10	**0.29**	0.09	-0.24	-0.33	-0.41	0.08	0.00	0.02	0.06	**0.18**	0.07	**0.55**	0.03
11	0.39	0.00	-0.27	-0.38	-0.37	-0.01	-0.12	**-0.14**	-0.03	0.09	0.28	**0.77**	0.02
12	0.17	0.23	-0.11	-0.27	-0.09	0.17	0.10	0.02	0.04	**0.19**	0.09	**0.58**	0.09
14	**0.44**	0.08	-0.16	**-0.28**	-0.05	0.20	0.17	0.06	0.02	**0.16**	0.20	**0.89**	0.15
16	**0.44**	-0.04	-0.31	-0.39	-0.20	0.20	0.05	0.02	0.07	**0.27**	**0.48**	**0.89**	0.13
17	0.17	0.12	-0.19	-0.31	0.02	0.19	0.12	0.05	0.08	**0.39**	0.34	**0.77**	0.15
18	0.31	-0.01	-0.19	-0.25	-0.09	0.07	-0.01	-0.05	-0.06	**0.15**	0.33	**0.93**	0.10
20	-0.08	**0.23**	0.00	-0.11	0.11	0.20	0.11	0.11	0.10	**0.35**	**0.58**	0.38	**0.16**
22	0.33	0.18	-0.12	-0.27	0.15	**0.33**	**0.17**	**0.12**	0.11	**0.36**	**0.47**	**0.61**	**0.20**
23	0.17	0.27	0.01	-0.28	0.01	0.16	0.01	-0.03	-0.01	**0.23**	**0.63**	**0.52**	**0.14**
27	**0.53**	0.10	-0.22	-0.33	-0.45	0.16	-0.06	0.02	0.04	**0.18**	**0.49**	**1.01**	0.12
28	**0.42**	**0.31**	0.04	-0.05	-0.19	0.18	0.08	0.09	0.06	**0.21**	0.25	**0.83**	**0.18**
29	0.07	0.09	-0.26	-0.37	-0.38	0.16	-0.06	-0.03	-0.02	0.14	0.08	0.42	-0.01
31	0.26	0.04	-0.15	-0.18	-0.13	0.16	0.03	0.06	0.00	0.06	0.28	**0.70**	0.09
32	0.05	-0.02	0.02	0.10	0.00	-0.02	-0.01	-0.01	-0.01	0.02	0.04	0.00	0.01
33	0.31	-0.02	-0.10	-0.17	-0.15	0.19	0.01	0.03	0.01	**0.25**	0.32	**0.85**	0.13
34	0.18	0.13	0.04	0.00	-0.01	0.28	0.04	0.05	0.05	**0.22**	0.15	**0.67**	**0.15**
35	0.30	0.13	0.02	-0.06	0.10	**0.30**	**0.14**	**0.17**	**0.14**	**0.32**	**0.38**	**0.88**	**0.24**
36	**0.39**	**-0.25**	-0.32	-0.42	-0.36	0.00	-0.13	-0.04	0.00	**0.16**	**0.46**	**0.77**	0.02
37	0.01	-0.13	-0.33	-0.42	-0.08	0.18	0.02	0.00	-0.01	**0.22**	0.34	0.32	0.01
39	0.47	**0.51**	0.24	-0.03	0.18	**0.44**	**0.21**	**0.15**	**0.17**	**0.42**	**0.85**	**0.86**	**0.37**
41	0.21	0.09	-0.13	-0.25	0.10	**0.33**	**0.20**	**0.12**	**0.17**	**0.42**	-2.40	**0.71**	-0.03
43	0.14	-0.20	-0.33	-0.36	-0.23	-0.12	**-0.14**	0.01	0.01	**0.24**	0.33	**0.68**	0.01
44	0.18	0.02	-0.17	-0.21	-0.16	0.01	-0.05	0.04	0.06	**0.22**	0.18	0.39	0.04
45	0.00	**-0.41**	**-0.54**	**-0.35**	-0.28	-0.04	-0.10	-0.03	0.05	**0.19**	0.29	0.38	-0.07
46	0.18	0.12	-0.20	-0.26	-0.10	0.14	-0.01	-0.04	-0.07	**0.22**	0.49	0.49	0.08
48	0.01	-0.05	-0.15	-0.31	-0.07	**0.22**	0.03	0.02	-0.01	**0.22**	0.29	0.40	0.05
49	0.14	0.16	-0.03	0.00	0.08	**0.33**	**0.16**	**0.15**	0.03	**0.24**	**0.56**	**0.55**	**0.20**
50	0.30	0.18	-0.09	-0.12	0.01	**0.30**	0.13	0.12	0.09	**0.37**	**0.81**	**0.77**	**0.24**
51	0.26	0.05	-0.12	-0.09	-0.07	0.23	0.09	0.07	-0.01	**0.21**	**0.46**	0.40	0.12
56	0.26	0.09	-0.02	0.05	-0.08	0.08	-0.01	0.05	0.13	**0.29**	**0.53**	**0.57**	**0.16**
57	-0.52	0.20	0.18	0.26	**0.41**	**0.21**	0.09	0.15	0.12	0.16	0.15	0.01	0.12
58	**0.60**	**-0.56**	**-0.94**	**-0.92**	**-0.57**	-0.01	**-0.18**	-0.10	-0.15	**0.19**	**0.56**	**0.87**	-0.10

APPENDIX D: Monthly rate of change with mean daily temperatures during 1983-2012. Bold values indicate the rates of change that are statistically significant at p<0.05 by Kendall'tau non-parametric test. (con't)

ID	Rate of change with mean daily temperature (°C/decade)												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
59	0.13	0.03	-0.27	-0.33	-0.16	0.06	-0.05	-0.03	0.01	**0.28**	**0.64**	0.29	0.05
64	0.05	-0.05	-0.26	-0.31	-0.08	0.18	0.02	0.07	0.01	**0.23**	**0.55**	0.50	0.08
65	-0.25	**-0.31**	**-0.57**	**-0.56**	-0.38	-0.09	**-0.18**	-0.13	**-0.22**	0.00	0.15	0.11	**-0.20**
66	**0.38**	0.12	-0.14	-0.14	0.05	**0.22**	0.06	0.12	**0.10**	**0.35**	**0.69**	**0.77**	**0.22**
68	0.38	0.04	-0.22	-0.24	-0.06	0.17	0.04	0.06	0.02	**0.27**	0.31	0.47	0.11
69	0.20	-0.09	-0.35	-0.39	-0.10	0.23	0.10	0.12	0.09	**0.31**	0.30	0.55	0.08
71	0.28	0.05	-0.16	-0.18	-0.07	0.10	0.04	**0.08**	0.03	**0.22**	0.20	**0.60**	0.10
74	**0.66**	-0.37	**-0.66**	**-0.61**	**-0.39**	0.06	-0.08	-0.01	-0.06	-0.01	0.27	**0.75**	-0.03
75	**-0.79**	**0.88**	**0.59**	**0.41**	-0.07	-0.16	-0.24	-0.23	-0.02	**0.22**	-0.54	-0.59	-0.05
76	-0.67	**-0.59**	**-0.57**	-0.33	-0.17	-0.01	-0.08	0.12	0.09	0.17	0.17	**1.08**	-0.06
79	**0.72**	**-0.50**	**-0.62**	**-0.65**	**-0.46**	**-0.22**	**-0.30**	-0.09	0.10	**0.36**	**0.55**	**1.21**	0.01
81	**0.65**	**0.68**	0.52	**0.55**	0.30	**0.24**	0.10	0.08	0.12	**0.32**	**0.58**	**0.93**	**0.42**
87	0.24	**0.69**	0.53	**0.64**	**0.37**	**0.33**	**0.27**	**0.29**	**0.30**	**0.24**	**0.53**	0.38	**0.40**
92	**0.35**	**0.69**	**0.56**	**0.55**	**0.31**	**0.33**	0.03	0.14	**0.26**	**0.27**	**0.33**	**0.39**	**0.35**
94	**0.41**	0.16	-0.09	-0.06	-0.02	**0.25**	0.10	0.13	0.09	**0.14**	**0.38**	**0.57**	**0.17**
97	**0.11**	0.08	-0.04	-0.08	0.04	0.18	0.05	**0.18**	**0.15**	**0.08**	0.17	**0.20**	**0.09**
98	-0.13	-0.13	-0.30	-0.15	-0.09	0.10	-0.01	**0.16**	0.10	0.03	0.03	-0.03	-0.03
101	0.00	0.03	-0.08	-0.14	0.02	0.06	-0.01	0.12	0.07	0.02	0.02	0.07	0.02
104	-0.01	0.09	-0.08	-0.16	0.12	0.09	0.04	0.08	0.04	-0.02	0.05	0.13	0.03
106	0.08	0.12	0.00	-0.01	0.15	**0.16**	0.09	**0.21**	**0.14**	0.08	0.14	**0.17**	**0.11**
108	0.02	0.10	-0.01	-0.08	0.13	0.09	0.04	0.11	0.07	0.07	0.10	0.12	0.06
110	0.03	0.10	-0.06	-0.10	0.16	0.11	0.07	**0.19**	**0.22**	0.14	0.15	0.06	**0.09**
111	0.01	0.04	-0.16	-0.05	0.04	0.04	0.02	0.11	0.12	0.05	0.13	0.07	0.03
112	-0.10	-0.07	-0.32	0.04	-0.05	-0.01	0.07	0.04	**0.09**	**0.13**	0.08	0.00	-0.01
114	-0.05	-0.04	-0.16	-0.11	0.17	**0.19**	**0.18**	**0.28**	**0.28**	**0.15**	0.08	0.03	0.09
118	0.07	0.11	-0.01	-0.07	0.14	0.09	0.05	**0.13**	**0.12**	**0.10**	**0.14**	0.16	0.09
119	0.02	0.07	-0.09	-0.06	0.15	0.10	**0.10**	**0.16**	**0.18**	**0.16**	0.15	0.12	**0.09**
120	**0.13**	**0.29**	0.07	0.02	0.17	0.20	**0.20**	**0.23**	**0.21**	**0.20**	**0.27**	**0.24**	**0.19**
121	0.04	0.13	-0.08	-0.10	0.07	0.11	**0.09**	**0.14**	**0.09**	0.05	0.13	0.13	0.07
122	**-0.39**	**-0.34**	0.02	**-0.35**	**-0.13**	**-0.11**	**-0.14**	-0.07	-0.04	**-0.14**	-0.13	-0.10	**-0.16**

APPENDIX E: The monthly cumulated number of days with maximum temperatures ≥35°C (days/30 years).

	Cumulative number of days with daily maximum temperature ≥ 35ºC(days)												
ID	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
1	2	186	787	837	609	175	70	46	51	42	3	1	2,809
2	11	293	781	818	476	60	21	11	29	63	19	6	2,588
4	0	17	334	519	214	47	19	2	1	0	0	0	1,153
5	0	77	546	634	304	91	39	14	1	3	0	0	1,709
7	1	104	563	686	395	120	55	23	16	4	0	0	1,967
8	40	419	778	802	569	275	212	128	74	53	50	9	3,409
10	5	286	756	771	494	174	110	51	16	7	9	0	2,679
11	11	264	716	778	490	201	117	54	17	5	14	0	2,667
13	3	130	576	621	309	74	38	13	1	4	4	0	1,773
14	0	122	601	654	342	97	49	14	1	2	0	0	1,882
16	61	393	753	807	594	312	241	142	138	144	95	23	3,703
17	20	176	482	621	373	170	99	40	20	11	23	3	2,038
18	32	261	541	583	308	139	85	41	14	9	23	1	2,037
20	26	232	531	632	407	183	129	42	21	20	36	5	2,264
22	34	173	446	534	268	99	53	15	6	5	29	11	1,673
23	16	126	384	501	296	84	46	23	7	8	12	1	1,504
27	155	527	788	793	472	159	97	97	79	21	54	17	3,259
28	9	295	732	789	338	40	6	4	5	13	25	2	2,258
29	79	484	772	782	530	236	214	185	162	44	42	5	3,535
31	0	89	439	459	107	2	0	0	0	0	1	0	1,097
32	4	268	685	783	525	259	137	54	14	9	23	1	2,762
33	116	453	718	760	441	201	105	43	20	28	61	30	2,976
34	85	348	659	718	464	209	116	54	28	36	80	27	2,824
35	114	447	743	767	516	329	195	87	33	36	64	34	3,365
36	69	391	700	742	471	184	139	89	43	23	36	8	2,895
37	53	277	544	632	363	222	142	57	14	7	36	8	2,355
39	65	239	557	638	417	170	89	38	33	33	56	17	2,352
41	95	333	611	706	519	349	285	147	50	50	81	36	3,262
43	153	532	782	808	591	417	300	184	57	24	73	30	3,951
44	70	400	743	757	464	237	156	70	8	2	31	16	2,954
45	36	270	642	749	515	315	233	137	34	23	49	18	3,021
46	66	337	626	675	398	197	131	58	17	6	40	12	2,563
48	33	218	516	588	309	100	46	5	3	0	24	3	1,845
49	79	321	625	677	347	108	35	10	8	5	48	24	2,287
50	75	348	646	678	412	174	64	22	16	9	55	22	2,521
51	43	292	596	672	399	144	42	6	2	1	22	3	2,222
56	29	259	680	794	622	436	341	293	144	28	49	6	3,681
57	28	347	676	764	550	368	296	212	107	10	12	3	3,373
58	91	393	728	756	522	290	199	122	28	18	43	36	3,226

APPENDIX E: The monthly cumulated number of days with maximum temperatures ≥35°C (days/30 years). (con't)

ID	Cumulative number of days with daily maximum temperature ≥ 35ºC(days)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
59	182	516	743	786	534	355	282	151	35	35	79	55	3,753
62	156	471	757	775	526	277	151	89	44	59	109	89	3,503
63	258	546	764	765	478	194	83	33	32	45	98	83	3,379
64	43	333	604	676	480	342	265	141	23	3	26	5	2,941
65	8	109	373	378	140	25	14	0	0	0	4	0	1,051
66	50	284	571	639	391	264	175	89	10	4	22	12	2,511
68	51	339	647	691	497	289	165	56	21	9	38	7	2,810
69	45	300	611	682	453	225	97	38	9	1	32	5	2,498
71	80	351	621	670	433	292	203	86	18	3	27	15	2,799
72	131	466	719	750	484	259	115	56	32	12	48	30	3,102
74	234	571	775	792	595	422	324	257	195	32	57	56	4,310
75	191	539	800	792	373	89	31	15	31	57	87	72	3,077
76	17	241	611	730	501	294	226	158	66	5	17	2	2,868
79	8	37	246	575	363	154	108	53	39	9	21	4	1,617
81	43	193	493	648	426	228	171	114	84	65	61	34	2,560
82	114	100	309	559	318	156	85	36	13	57	111	96	1,954
84	6	13	14	25	24	5	0	0	0	0	3	2	92
85	18	14	49	159	186	91	67	47	22	20	61	47	781
87	1	3	19	93	128	78	66	61	38	6	4	2	499
88	48	74	200	267	224	132	106	77	67	86	83	79	1,443
89	14	12	68	231	127	45	13	15	3	1	17	15	561
90	31	30	54	156	78	2	3	2	4	11	42	20	433
91	31	17	26	48	24	1	0	0	0	2	17	28	194
92	6	31	121	314	254	144	114	80	69	21	20	7	1,181
94	29	291	623	687	390	205	160	123	59	4	9	2	2,582
97	0	14	99	331	168	45	23	8	4	1	0	0	693
98	21	229	447	397	98	5	0	0	0	3	2	1	1,203
101	0	0	3	28	48	28	25	14	3	0	0	0	149
104	0	5	58	234	276	247	201	215	82	2	1	0	1,321
108	0	0	27	155	121	119	87	122	39	8	0	0	678
110	19	77	189	199	52	13	2	10	2	1	0	0	564
111	3	48	184	130	35	0	0	0	0	0	1	0	401
112	10	110	254	240	65	3	1	0	0	0	0	1	684
114	28	302	552	521	189	57	22	20	8	8	6	0	1,713
115	0	13	88	282	219	151	133	143	46	8	0	0	1,083
119	12	252	371	268	66	6	1	1	0	1	2	1	981
120	0	14	86	236	151	67	47	28	8	1	0	0	638
121	6	122	431	517	326	172	113	122	39	14	0	1	1,863
122	0	0	7	81	94	81	51	69	23	11	2	0	419

APPENDIX F: Monthly rate of change for numbers of days with daily maximum temperatures ≥35ºC during 1983-2012. Bold values indicate the rates of change that are statistically significant (* p<0.10, ** p<0.05 and *** p<0.01) by Kendall'tau non-parametric test.

ID	Number of days with daily maximum temperature ≥ 35ºC (days)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	-0.1	-0.6	-3.6	-1.4	**-6.2***	2.8	-0.5	-1.3	0.0	0.7	0.0	0.0
2	0.2	6.4	1.4	-2.5	**-7.5***	0.5	0.9	0.0	**1.4***	**3.2****	**1.1***	0.0
4	0.0	1.0	**-7.9***	**-8.4***	-2.8	-0.5	-0.9	0.1	0.1	0.0	0.0	0.0
5	0.0	3.4	-5.4	-4.6	0.5	0.3	-0.1	-0.3	0.1	0.0	0.0	0.0
7	0.0	2.1	-3.0	-2.8	**-9.1***	1.5	-0.3	-0.1	0.9	0.3	0.0	0.0
8	0.7	**9.1****	-0.3	-1.5	-3.3	4.6	3.2	1.7	**4.8****	**3.9*****	**4.2****	0.4
10	0.1	3.8	-3.6	-3.4	**-7.5***	0.3	-0.1	-1.1	**1.6*****	0.6	1.1	0.0
11	-0.4	2.6	-2.7	-3.4	**-8.6***	-0.5	-2.8	**-2.9****	-0.3	0.1	**1.5***	0.0
13	0.1	5.2	-4.9	-5.5	-3.1	3.2	0.5	-1.0	0.2	**0.4***	**0.5****	0.0
14	0.0	2.5	-2.9	-3.5	-0.6	4.2	1.9	-0.1	**0.2***	0.0	0.0	0.0
16	1.0	1.7	-4.1	-1.0	-2.5	6.5	1.1	1.3	**4.6****	**10.3*****	**9.1*****	0.9
17	0.3	4.8	-3.4	-4.0	-2.0	2.2	-12.6	0.3	**2.1**	0.4	**3.1****	0.2
18	0.9	3.5	-3.3	-6.1	-0.6	1.6	-0.7	-0.8	-0.4	0.4	**2.0****	0.0
20	1.1	**7.7****	-0.4	-2.9	2.2	2.4	2.5	0.2	**1.6****	0.7	**4.0*****	0.3
22	0.9	4.5	-3.4	-1.3	1.9	3.3	2.0	-0.3	0.6	0.5	**3.3*****	**1.4***
23	0.9	**4.9***	-0.3	-4.3	0.4	0.2	-0.6	0.3	0.4	0.4	**1.7****	0.0
27	**4.4***	1.6	-2.4	-4.3	-7.5	4.0	-2.3	2.3	1.6	**1.1***	**4.4****	0.5
28	0.3	**10.9****	2.2	-3.2	-6.8	1.8	0.2	0.2	**0.4***	1.1	**2.0****	0.1
29	2.1	1.9	-3.3	-4.9	-7.0	2.6	-2.9	1.7	1.4	1.0	**3.4****	0.2
31	0.0	3.0	-3.9	-7.5	-2.4	**0.3***	0.0	0.0	0.0	0.0	0.1	0.0
32	-0.2	-6.3	-4.9	-3.3	-8.3	-0.5	-3.5	-1.5	0.0	0.5	**2.3****	0.0
33	1.1	0.6	-1.8	-3.7	-7.2	2.4	-0.3	0.7	0.7	2.1	**5.0****	2.7
34	2.0	**9.4*****	1.8	-2.3	0.4	5.0	1.0	0.6	**1.6****	**3.1***	**6.9*****	2.3
35	2.1	2.4	1.3	-0.6	3.8	**11.1****	**4.3***	**3.8****	**2.3****	**2.3***	**5.3*****	**3.1****
36	0.3	-3.9	**-5.8***	-3.9	-7.2	-1.7	-5.4	-1.5	0.9	**1.0***	**3.2****	0.0
37	0.8	-1.7	-3.5	-4.2	-1.2	3.3	-0.1	-0.5	0.8	0.4	**3.3****	0.0
39	3.1	**11.0*****	2.6	0.5	4.5	**8.2****	**5.5****	**2.8*****	**2.4*****	**1.9****	**5.2*****	1.4
41	3.0	1.9	-0.8	-4.1	3.7	**8.8****	**9.2**	**4.4****	**3.3****	**3.0****	**7.0*****	**2.9*****
43	-0.7	-4.6	-3.2	-2.4	-5.3	**-6.5***	**-7.7****	-0.4	0.6	**1.7***	**5.3**	1.3
44	1.5	2.1	-1.4	-1.7	-3.0	-1.7	-4.3	-1.1	0.3	**0.3***	**2.6**	**1.1***
45	-2.4	**-14.8*****	**-9.4****	-3.8	-6.5	**-8.1***	**-8.4****	-0.6	**3.0***	2.0	**6.4*****	**2.4****
46	**2.0***	2.9	-3.4	-4.2	-4.5	2.1	-0.8	-0.9	-0.5	0.4	**3.6****	0.2
48	0.5	2.6	-3.0	-5.6	-1.5	3.7	**1.1***	-0.2	0.1	0.0	**2.5****	0.4
49	2.2	4.2	1.4	0.6	2.4	2.7	**2.6***	0.5	0.1	0.5	**4.7*****	**2.9*****
50	1.2	5.1	0.6	-1.4	1.8	4.8	1.9	**1.1****	0.1	**0.8***	**5.1*****	**2.3****

APPENDIX F: Monthly rate of change for numbers of days with daily maximum temperatures ≥35ºC during 1983-2012. Bold values indicate the rates of change that are statistically significant (* p<0.10, ** p<0.05 and *** p<0.01) by Kendall'tau non-parametric test. (con't)

ID	Number of days with daily maximum temperature ≥ 35ºC (days)											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
51	-0.5	5.5	-2.6	-0.9	-0.4	2.6	1.5	0.3	-0.3	**0.2***	**2.3****	**0.5****
56	-0.3	**6.9****	4.1	-1.5	-0.7	2.2	0.1	3.3	**5.0****	1.5	**3.5*****	0.1
57	-0.4	-3.0	-6.1	-3.3	-3.8	-2.7	**-5.7***	-1.5	1.8	0.4	**1.3***	0.1
58	-1.0	**-7.5***	**-7.0***	**-7.3****	-7.5	-4.8	**-6.7****	1.5	-0.3	0.5	2.9	1.6
59	0.4	-2.0	-3.5	-1.1	-1.9	2.3	-1.8	**5.6****	**1.8***	1.1	**6.4****	**4.1****
62	3.2	**10.4*****	2.6	1.5	**9.6****	**13.7*****	**6.5*****	**7.4*****	**4.5*****	**5.3*****	**10.5*****	**6.6*****
63	-2.7	-2.3	-3.1	-3.6	0.2	**10.1*****	**5.3*****	**1.3****	2.3	**0.8***	**5.6****	2.1
64	1.3	-0.1	-5.1	-4.8	-2.9	3.4	0.5	3.1	-0.2	0.3	**2.4****	0.0
65	-0.5	**-3.7***	**-15.2*****	**-14.2*****	-4.7	0.4	-0.5	0.0	0.0	0.0	0.3	0.0
66	1.6	4.6	-3.0	-2.3	2.5	**6.2***	0.6	**4.4*****	0.2	0.6	**2.2****	**1.0****
68	0.5	2.5	-4.3	-3.5	-1.5	3.7	-0.6	0.2	**0.8****	**0.9***	**3.8*****	**0.9****
69	0.2	-0.1	-4.9	**-5.1***	-2.2	2.4	0.4	**0.1***	0.1	**0.2***	**3.0*****	0.6
71	2.5	0.7	-3.8	-2.8	1.2	1.0	-1.1	1.7	0.0	0.2	**2.4****	0.8
72	2.8	0.5	-0.6	-1.8	3.9	**7.4***	**3.4***	**2.8****	**2.1****	0.8	**4.0*****	**2.0****
74	-1.5	-5.1	**-6.3***	**-4.8****	-6.1	0.5	-4.4	-0.1	-0.6	0.4	**3.7****	0.0
75	**12.8*****	**13.9*****	3.3	-0.9	-3.1	3.8	**2.9****	0.9	**3.0*****	**5.1*****	**8.9*****	**5.8****
76	0.5	3.5	-4.1	-3.9	-4.9	0.8	-4.3	1.0	0.7	0.3	**2.1**	0.2
79	0.5	0.4	**5.6***	-1.3	-1.5	0.7	-2.0	**2.8****	0.8	**1.2*****	**2.3****	**0.5***
81	-1.3	2.0	3.4	-1.0	-3.2	2.6	-1.2	1.2	0.9	1.9	1.8	1.9
82	-2.3	0.2	**-5.9****	**-8.1***	-2.5	1.9	-0.7	**1.5****	0.8	**4.1*****	**4.5****	1.6
84	-0.3	-0.3	-0.2	0.4	0.1	0.0	0.0	0.0	0.0	0.0	0.2	0.0
85	**1.4****	1.1	**4.0****	**11.8*****	4.3	3.0	0.5	**2.1***	0.4	**1.7*****	**5.1*****	**4.0*****
87	0.0	-0.2	-1.3	5.0	3.9	1.4	0.7	-0.5	**1.6****	-0.2	**0.5***	0.2
88	1.4	2.1	5.9	3.3	-0.1	1.7	2.3	1.2	1.5	2.4	1.5	2.3
89	0.9	0.9	**5.4*****	**15.7*****	**3.8***	**3.9***	0.7	**1.5****	-0.2	0.1	0.8	1.6
90	0.0	0.9	1.2	**6.2****	**3.7***	0.0	0.3	-0.1	**0.4***	**0.9***	**2.9****	**2.3*****
91	0.2	0.0	-0.9	**-2.5***	0.7	0.0	0.0	0.0	0.0	0.1	**1.3****	**1.8***
92	0.4	**2.2****	**9.9*****	**16.7*****	**9.9****	**6.3****	-0.6	2.0	**5.1*****	1.5	**2.4*****	0.6
94	**1.6****	6.7	-3.3	-4.4	-3.4	**6.7****	1.5	**4.8****	1.8	0.2	0.4	0.2
97	0.0	0.1	-1.2	-3.5	1.7	0.8	0.5	0.2	**0.6***	0.1	0.0	0.0
98	**-0.8***	**-5.8***	**-8.9***	-5.8	0.4	-0.4	0.0	0.0	0.0	0.0	0.0	-0.1
101	0.0	0.0	**-0.4****	-0.4	-0.9	1.0	-1.4	**2.0****	-0.1	0.0	0.0	0.0
104	0.0	0.0	-1.9	-6.3	4.0	6.3	2.0	1.9	-0.7	0.2	-0.1	0.0
108	0.0	0.0	-1.7	-0.8	6.5	**6.8***	1.0	**6.1***	1.3	**1.1****	0.0	0.0
110	0.2	3.3	3.9	-4.6	3.1	**1.7****	-0.3	**1.9****	**0.3****	0.0	0.0	0.0

APPENDIX F: Monthly rate of change for numbers of days with daily maximum temperatures ≥35ºC during 1983-2012. Bold values indicate the rates of change that are statistically significant (* $p<0.10$, ** $p<0.05$ and *** $p<0.01$) by Kendall'tau non-parametric test. (con't)

ID	Number of days with daily maximum temperature ≥ 35ºC (days)											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
111	-0.1	0.9	-3.4	-2.0	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
112	0.1	-2.0	**-10.3****	**-7.6***	-0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0
114	0.0	-2.4	-6.8	-7.8	3.6	**3.0****	**1.3****	**2.5*****	**0.8***	0.2	**1.0***	0.0
115	0.0	0.7	0.8	3.4	**7.6***	**4.9***	**5.5****	**9.5*****	**2.5****	**0.6****	0.0	0.0
119	0.8	0.7	-1.6	-4.5	2.3	0.2	0.0	-0.1	0.0	**0.2***	0.1	-0.2
120	0.0	**1.8****	0.9	-1.2	4.3	**4.8***	**1.5****	**2.9*****	0.2	0.1	0.0	0.0
121	0.3	3.5	-4.7	-6.6	3.5	**8.9*****	**2.6*****	**6.8*****	0.6	0.9	0.0	-0.2
122	0.0	0.0	-0.7	**-7.8*****	**-4.4****	**-3.3***	**-3.0***	-3.1	**-1.8****	-0.6	-0.3	0.0

APPENDIX G: Monthly numbers of ≥ 3 consecutive days with daily maximum temperatures ≥35°C during 1983-2012.

	Numbers of ≥ 3 consecutive days with daily maximum temperature ≥35° C											
ID	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	0	1	4	2	0	0	0	0	0	1	0	0
2	0	2	6	1	1	0	0	0	0	0	0	0
4	0	0	2	2	1	0	0	0	0	0	0	0
5	0	0	5	1	1	1	0	0	0	0	0	0
7	0	0	0	0	0	0	0	1	0	0	0	0
8	0	0	2	2	0	0	1	0	0	0	3	0
10	0	0	2	1	1	1	0	0	0	0	0	0
11	0	1	1	4	1	0	0	0	0	0	0	0
13	0	0	1	2	1	0	0	0	0	0	0	0
14	0	0	3	0	0	0	0	0	0	0	0	0
16	0	1	0	0	1	2	0	0	0	1	2	0
17	0	0	1	2	1	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	1	1	0	0	0	0	0
22	1	0	0	1	0	0	1	0	0	0	0	0
23	0	0	0	1	2	0	0	0	0	0	0	0
27	0	1	3	0	1	1	0	1	0	0	0	0
28	0	4	0	3	0	0	0	0	0	0	0	0
29	0	3	2	3	0	0	0	0	0	0	0	0
31	0	0	2	1	1	0	0	0	0	0	0	0
32	0	1	2	3	1	0	0	0	0	0	0	0
33	0	0	4	2	2	1	0	0	0	0	0	0
34	0	0	0	3	2	0	0	0	0	0	0	0
35	1	0	2	2	0	0	1	0	0	0	0	0
36	0	1	0	0	0	0	1	0	0	0	0	0
37	0	1	1	1	0	0	0	0	0	0	0	0
39	0	0	0	1	1	0	0	0	0	0	0	0
41	0	0	4	1	2	4	1	0	0	1	0	0
43	1	1	0	0	1	0	1	0	0	0	0	0
44	0	1	3	1	2	1	1	0	0	0	0	0
45	0	1	3	3	0	1	1	0	0	1	0	0
46	0	1	0	0	0	1	1	0	0	0	0	0
48	0	0	2	2	1	0	0	0	0	0	0	0
49	0	0	0	0	1	0	0	0	0	0	0	0
50	0	0	2	2	0	0	0	0	0	0	0	0
51	0	0	3	2	0	1	0	0	0	0	0	0
56	0	2	6	2	2	0	3	0	0	0	0	0
57	0	0	1	1	1	2	1	0	0	0	0	0
58	1	1	2	4	3	1	0	1	0	0	0	0

APPENDIX G: Monthly numbers of ≥ 3 consecutive days with daily maximum temperatures ≥35°C during 1983-2012. (con't)

	Numbers of ≥ 3 consecutive days with daily maximum temperature ≥35° C											
ID	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
59	1	0	1	0	1	0	0	0	0	0	1	0
62	0	1	1	2	2	2	0	1	0	1	0	0
63	1	1	0	1	2	0	0	0	0	0	0	0
64	0	0	0	1	1	1	0	0	0	0	0	0
65	0	1	2	2	0	1	0	0	0	0	0	0
66	0	1	2	0	1	3	1	0	0	0	0	0
68	0	2	2	0	1	0	0	0	0	0	0	0
69	0	0	0	3	1	0	0	0	0	0	0	0
71	0	0	0	0	1	0	0	1	0	0	0	0
72	0	1	1	1	2	0	0	0	0	0	0	0
74	0	0	2	1	2	1	0	0	1	0	0	1
75	1	5	3	2	4	1	1	0	0	0	0	1
76	0	0	2	1	1	0	2	1	0	0	0	0
79	0	0	1	0	1	1	1	0	0	0	0	0
81	0	2	4	1	1	0	0	0	0	0	0	0
82	0	0	0	3	0	0	0	0	0	0	0	0
84	0	0	0	0	0	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0	0	0	0	0	0
87	0	0	0	0	0	0	1	0	0	0	0	0
88	0	3	0	0	1	1	0	0	0	0	1	0
89	0	0	0	5	0	0	0	0	0	0	0	1
90	0	0	0	0	0	0	0	0	0	0	0	0
91	0	0	0	0	0	0	0	0	0	0	0	0
92	0	0	0	0	0	0	0	0	0	0	0	0
94	0	1	2	0	0	1	0	0	0	0	0	0
97	0	0	0	4	1	0	0	0	0	0	0	0
98	0	0	0	0	0	0	0	0	0	0	0	0
101	0	0	0	0	0	0	0	1	0	0	0	0
104	0	0	0	0	0	0	1	0	1	0	0	0
108	0	0	0	1	0	0	0	1	0	0	0	0
110	0	1	0	0	2	0	0	0	0	0	0	0
111	0	0	0	1	0	0	0	0	0	0	0	0
112	0	1	2	1	1	0	0	0	0	0	0	0
114	0	1	4	3	1	0	0	0	0	0	0	0
115	0	0	0	0	2	0	1	1	1	0	0	0
119	0	1	2	1	0	0	0	0	0	0	0	0
120	0	0	0	0	0	0	0	0	0	0	0	0
121	0	0	2	3	1	1	0	0	0	0	0	0
122	0	0	0	0	0	0	0	0	0	0	0	0

APPENDIX H: The monthly cumulated number of days with mean temperatures ≤22°C (days/30 years).

	Cumulative number of days with mean daily temperature ≤22ºC(days)												
ID	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
1	820	184	13	1	0	0	0	0	0	0	122	702	1,842
2	776	212	12	0	0	0	0	0	0	0	91	618	1,709
4	896	235	77	9	7	0	0	0	1	14	390	801	2,430
5	750	188	41	8	9	0	0	0	0	20	271	733	2,020
7	553	47	19	1	5	0	0	0	0	3	91	510	1,229
8	371	26	19	2	4	0	0	0	0	3	80	485	990
10	566	36	16	2	4	0	0	0	0	3	120	543	1,290
11	401	28	18	1	3	0	0	0	0	0	83	466	1,000
12	495	63	22	3	3	0	0	0	0	4	87	508	1,185
14	770	131	33	0	3	0	0	0	0	5	196	662	1,800
16	95	14	14	1	1	0	0	0	0	0	25	179	329
17	349	97	48	2	1	0	0	0	0	2	109	417	1,025
18	525	86	43	1	0	0	0	0	0	2	169	566	1,392
20	294	85	48	2	1	0	0	0	0	3	94	337	864
21	497	158	75	6	1	0	0	0	0	5	117	801	1,660
23	382	142	64	3	0	0	0	0	0	2	102	350	1,045
27	123	13	15	0	0	0	0	0	0	3	44	318	516
28	297	20	8	0	0	0	0	0	0	0	45	393	763
29	163	22	16	1	0	0	0	0	0	2	42	304	550
31	731	193	23	0	0	0	0	0	0	5	366	728	2,046
32	18	5	6	0	0	0	0	0	0	0	3	18	50
33	100	14	15	0	0	0	0	0	0	0	34	204	367
34	83	17	18	1	0	0	0	0	0	0	35	170	324
35	63	4	6	0	0	0	0	0	0	0	19	122	214
36	78	10	12	0	0	0	0	0	0	1	21	140	262
37	175	54	39	2	1	0	0	0	0	4	39	217	531
39	357	140	65	8	0	0	0	0	0	6	112	360	1,048
41	232	51	39	0	0	0	0	0	0	0	11	244	577
43	56	7	8	0	0	0	0	0	0	0	17	103	191
44	16	3	8	0	0	0	0	0	0	0	4	53	84
45	31	5	8	0	0	0	0	0	0	0	16	55	115
46	89	25	22	0	0	0	0	0	0	0	34	140	310
48	261	78	42	0	0	0	0	0	0	3	96	294	774
49	186	65	22	1	0	0	0	0	0	2	68	238	582
50	168	60	24	1	0	0	0	0	0	6	86	227	572
51	242	60	17	1	0	0	0	0	0	0	44	206	570
56	40	3	8	0	0	0	0	0	0	0	3	44	98
57	20	6	7	0	0	0	0	0	0	0	14	60	107
58	23	0	9	0	0	0	0	0	0	1	10	34	77

APPENDIX H: The monthly cumulated number of days with mean temperatures ≤22°C (days/30 years). (con't)

ID	Cumulative number of days with mean daily temperature ≤22ºC(days)												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
59	59	7	9	1	0	0	0	0	0	0	28	114	218
64	117	25	20	0	0	0	0	0	0	1	30	178	371
65	150	28	23	1	0	0	0	0	0	7	76	275	560
66	180	23	20	0	0	0	0	0	0	2	50	256	531
68	261	44	21	0	0	0	0	0	0	4	55	274	659
69	218	50	24	0	0	0	0	0	0	2	50	198	542
71	208	36	16	0	0	0	0	0	0	4	50	271	585
74	47	4	10	0	0	0	0	0	0	1	15	64	141
75	21	13	3	0	0	0	0	0	0	0	6	43	86
76	32	6	6	0	0	0	0	0	0	0	15	243	302
79	24	1	4	0	0	0	0	0	0	0	0	57	86
81	27	0	5	0	0	0	0	0	0	0	5	34	71
87	18	1	6	0	0	0	0	0	0	0	7	17	49
92	2	0	4	0	0	0	0	0	0	0	1	0	7
94	65	6	8	0	0	0	0	0	0	0	12	139	230
97	6	0	2	0	0	0	0	0	0	0	0	1	9
98	0	0	1	0	0	0	0	0	0	0	0	0	1
101	0	0	0	0	0	0	0	0	0	0	0	0	0
104	0	0	0	0	0	0	0	0	0	0	0	0	0
106	0	0	0	0	0	0	0	0	0	0	0	0	0
108	0	0	0	0	0	0	0	0	0	0	0	0	0
110	0	0	0	0	0	0	0	0	0	0	0	0	0
111	0	0	0	0	0	0	0	0	0	0	0	0	0
112	0	0	0	0	0	0	0	0	0	0	0	0	0
114	0	0	0	0	0	0	0	0	0	0	0	0	0
118	0	0	0	0	0	0	0	0	0	0	0	0	0
119	0	0	0	0	0	0	0	0	0	0	0	0	0
120	0	0	0	0	0	0	0	0	0	0	0	0	0
121	0	0	0	0	0	0	0	0	0	0	0	0	0
122	1	0	0	0	0	0	0	0	0	0	0	0	1

APPENDIX I: Monthly rate of change for numbers of days with mean daily temperatures ≤22ºC during 1983-2012. Bold values indicate the rates of change that are statistically significant (* p<0.10, ** p<0.05 and *** p<0.01) by Kendall'tau non-parametric test.

ID	Number of days with mean daily temperature ≤ 22ºC (days)											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	**-8.6*** **	3.4	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1	**-7.2***
2	**-9.3*****	0.3	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6	**-8.9****
4	**-3.8****	**13.8*****	**4.9*****	-0.3	0.4	0.0	0.0	0.0	0.0	0.3	-1.7	**-8.4*****
5	**-6.4****	2.9	1.9	0.1	0.6	0.0	0.0	0.0	0.0	-0.6	0.7	**-9.3****
7	-7.1	0.2	0.7	0.1	0.3	0.0	0.0	0.0	0.0	-0.2	-0.4	**-14.5*****
8	-5.4	0.8	0.8	0.2	0.3	0.0	0.0	0.0	0.0	-0.2	0.2	**-11.3****
10	-5.2	0.7	0.8	0.1	0.3	0.0	0.0	0.0	0.0	-0.2	0.4	**-10.5****
11	-6.9	1.6	0.8	0.1	0.3	0.0	0.0	0.0	0.0	0.0	-0.8	**-13.5*****
12	-2.5	0.5	0.8	0.2	0.3	0.0	0.0	0.0	0.0	0.1	0.5	**-10.6****
14	**-8.6****	2.4	1.7	0.0	0.3	0.0	0.0	0.0	0.0	0.1	-1.0	**-12.1*****
16	**-4.1***	0.7	0.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0	-1.7	**-8.8*****
17	-0.8	2.7	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.1	-1.8	**-8.7***
18	**-7.0****	2.5	0.7	0.1	0.0	0.0	0.0	0.0	0.0	0.3	-3.5	**-14.6*****
20	2.9	2.4	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.4	-1.5	-2.8
21	-4.0	0.3	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0	-2.9	-6.0
23	-0.1	1.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.3	**-3.9****	-5.6
27	**-5.3***	0.5	1.1	0.0	0.0	0.0	0.0	0.0	0.0	-0.2	-2.0	**-13.8****
28	**-7.2****	0.9	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.2	**-14.4*****
29	0.6	0.6	1.0	0.1	0.0	0.0	0.0	0.0	0.0	-0.1	0.4	-4.2
31	-4.2	3.6	**2.0***	0.0	0.0	0.0	0.0	0.0	0.0	0.3	-5.6	**-10.6****
32	**2.7*****	0.6	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.4***	**2.5*****
33	-3.3	1.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.3	**-7.6****
34	-1.3	1.2	0.6	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.2	-4.4
35	-1.7	0.3	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.8	**-6.6****
36	-2.8	0.7	1.1	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.6	**-6.3****
37	2.2	2.5	1.0	0.1	0.0	0.0	0.0	0.0	0.0	0.3	0.4	-2.1
39	-6.0	**-1.3****	-0.8	0.1	0.0	0.0	0.0	0.0	0.0	0.5	**-6.2***	**-9.9****
41	-3.4	2.4	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**1.5****	**-8.2****
43	-1.0	0.6	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.8	**-4.2***
44	1.0	0.2	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	-0.1
45	0.6	0.6	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.6	-2.1
46	-0.2	0.9	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.8	-4.4
48	3.2	2.5	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	-0.7	-3.6
49	1.1	2.5	0.9	-0.2	0.0	0.0	0.0	0.0	0.0	0.3	-0.8	-4.9
50	-1.9	1.4	0.2	-0.2	0.0	0.0	0.0	0.0	0.0	0.0	**-3.7****	**-7.7****

APPENDIX I: Monthly rate of change for numbers of days with mean daily temperatures ≤22ºC during 1983-2012. Bold values indicate the rates of change that are statistically significant (* p<0.10, ** p<0.05 and *** p<0.01) by Kendall'tau non-parametric test. (con't)

ID	Number of days with mean daily temperature ≤ 22ºC (days)											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
51	-2.3	2.0	0.6	-0.2	0.0	0.0	0.0	0.0	0.0	0.0	-0.6	-2.7
56	-0.9	0.2	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**-0.5***	-1.1
57	**3.0*****	0.6	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.3	0.6
58	-0.9	0.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.6	**-3.1****
59	1.2	**0.8***	1.1	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	-0.3	0.2
64	0.3	0.8	0.6	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	0.0	-3.7
65	3.2	1.4	1.4	0.1	0.0	0.0	0.0	0.0	0.0	0.1	-0.1	-1.5
66	-2.9	0.6	0.5	0.0	0.0	0.0	0.0	0.0	0.0	**-0.3***	-1.5	**-9.3****
68	-5.3	1.8	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.1	-0.6	-3.2
69	-1.5	2.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	-4.8
71	-1.7	0.8	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.7	**-6.9***
74	-2.1	0.5	1.3	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.2	**-4.4***
75	**2.8***	0.7	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.8***	**4.3****
76	**1.0****	0.7	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	**-11.4*****
79	-1.0	0.1	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**-3.8****
81	**-1.1***	0.0	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	**-2.2****
87	**-0.7****	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	-0.3
92	0.3	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
94	-1.5	0.7	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	-3.4
97	0.9	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
98	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
101	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
104	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
106	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
108	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
110	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
111	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
112	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
114	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
118	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
119	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
120	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
121	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
122	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

APPENDIX J: Monthly numbers of ≥ 3 consecutive days with mean daily temperatures ≤22°C during 1983-2012.

	Numbers of ≥ 3 consecutive days with mean daily temperature ≤22°C											
ID	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	0	0	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0	0	0	2
4	1	1	0	0	0	0	0	0	0	0	0	1
5	4	0	0	0	0	0	0	0	0	0	0	1
7	0	0	0	0	0	0	0	0	0	0	0	1
8	1	0	0	0	0	0	0	0	0	0	0	1
10	1	0	0	0	0	0	0	0	0	0	0	0
11	1	0	0	0	0	0	0	0	0	0	0	2
12	2	0	0	0	0	0	0	0	0	0	0	2
14	1	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	1
17	0	0	0	0	0	0	0	0	0	0	0	2
18	0	0	0	0	0	0	0	0	0	0	0	0
20	1	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	1
27	0	0	0	0	0	0	0	0	0	0	0	1
28	1	0	0	0	0	0	0	0	0	0	0	1
29	0	0	0	0	0	0	0	0	0	0	0	0
31	2	1	0	0	0	0	0	0	0	0	1	1
32	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0
34	0	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	0
37	0	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	0	0	0	0	0	0	0	0	1
44	0	0	0	0	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	0	0	0
48	1	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0	0	0	0	0
51	0	0	0	0	0	0	0	0	0	0	0	0
56	0	0	0	0	0	0	0	0	0	0	0	0
57	0	0	0	0	0	0	0	0	0	0	0	0
58	0	0	0	0	0	0	0	0	0	0	0	0

APPENDIX J: Monthly numbers of ≥ 3 consecutive days with mean daily temperatures ≤22°C during 1983-2012. (con't)

	Numbers of ≥ 3 consecutive days with mean daily temperature ≤22°C											
ID	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
59	0	0	0	0	0	0	0	0	0	0	0	0
64	0	0	0	0	0	0	0	0	0	0	0	2
65	0	0	0	0	0	0	0	0	0	0	0	0
66	0	0	0	0	0	0	0	0	0	0	0	0
68	0	0	0	0	0	0	0	0	0	0	0	1
69	0	0	0	0	0	0	0	0	0	0	0	0
71	0	0	0	0	0	0	0	0	0	0	0	0
74	0	0	0	0	0	0	0	0	0	0	0	0
75	0	0	0	0	0	0	0	0	0	0	0	1
76	0	0	0	0	0	0	0	0	0	0	0	0
79	0	0	0	0	0	0	0	0	0	0	0	0
81	0	0	0	0	0	0	0	0	0	0	0	0
87	0	0	0	0	0	0	0	0	0	0	0	0
92	0	0	0	0	0	0	0	0	0	0	0	0
94	0	0	0	0	0	0	0	0	0	0	0	0
97	0	0	0	0	0	0	0	0	0	0	0	0
98	0	0	0	0	0	0	0	0	0	0	0	0
101	0	0	0	0	0	0	0	0	0	0	0	0
104	0	0	0	0	0	0	0	0	0	0	0	0
106	0	0	0	0	0	0	0	0	0	0	0	0
108	0	0	0	0	0	0	0	0	0	0	0	0
110	0	0	0	0	0	0	0	0	0	0	0	0
111	0	0	0	0	0	0	0	0	0	0	0	0
112	0	0	0	0	0	0	0	0	0	0	0	0
114	0	0	0	0	0	0	0	0	0	0	0	0
118	0	0	0	0	0	0	0	0	0	0	0	0
119	0	0	0	0	0	0	0	0	0	0	0	0
120	0	0	0	0	0	0	0	0	0	0	0	0
121	0	0	0	0	0	0	0	0	0	0	0	0
122	0	0	0	0	0	0	0	0	0	0	0	0