# EFFECTS OF CLIMATE CHANGE ON EVAPOTRANSPIRATION FROM PADDY FIELDS IN SOUTHERN TAIWAN

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**Abstract.** The major objective of this study was to investigate the effects of climate change on evapotranspiration from paddy fields. A sensitivity analysis of meteorological variables at the Kao-Hsiung station, one of meteorological stations in southern Taiwan, was carried out using the modified Penman formula. Forty-eight-year records of temperature, relative humidity, sunshine duration, wind speed, and precipitation depth comprised the database. Trend and persistence analyses of the data were performed using the Mann–Kendall test, the Cumulative Deviation test, Linear Regression, and the Autocorrelation Coefficient. The results indicated that only temperature and relative humidity have significant long-term trends and persistence. Two climatic scenarios, viz. (1) linear extrapolation of climatic trends and (2) the predictions of General Circulation Models (GCMs), were assumed to investigate the effects of climate change on evapotranspiration. The study revealed that evapotranspiration from paddy fields increased under both climatic scenarios studied.

## 1. Introduction

A persistent increase in carbon dioxide in the atmosphere, which may be caused by industrialization and deforestation, has been recorded since the 1950s. This increased trend may lead to changes in global and regional climate features, such as average temperature and precipitation. Tickell (1993) predicted that the mean temperature will increase by 1 °C by the year 2050 and by 3 °C by the end of the next century. Tsuang et al. (1998) found that the temperatures of April, June, August, and October show a significantly increasing trend in Taiwan. Moreover, the average temperature will increase by about 0.13 °C per year. These researchers utilized the results predicted by the General Circulation Models (GCMs) of the CCC (Canadian Climate Center), the GFDL (Geophysical Fluids Dynamics Laboratory), and the UKMO (United Kingdom Meteorological Office) to study the effect of carbon dioxide on temperature. They concluded that temperature will increase by about 2 °C to 4 °C when the content of carbon dioxide in atmosphere is doubled.

The effects of hydrological processes and water resources caused by climate change have also received much attention (Gleick, 1986; Burn, 1994). Rao and Al-Wagdany (1995) investigated the effects of changes in precipitation and temperature on runoff by using a water-balance model. Mansell (1997) studied the effects

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of climate change on rainfall trends and flood risk in the western part of Scotland. Herrington (1996) analyzed the impacts of climate change on water demand in England and Wales and concluded that a 1.1 °C rise in temperature would increase water demand for agriculture by 12%. Chang et al. (1992) wrote a detailed review of studies on the effects of climate change on water resources. It is useful to help us understand the effects of climate change on water resources and propose suitable strategies needed to face the impact of climate change.

Recently, considerable works have been devoted to the examination of the potential impact of climate change on the water resource system. These studies revealed that the demand for irrigation water is particularly sensitive to changes in precipitation, temperature, and the concentration of carbon dioxide (Frederick and Major, 1997). The investigation by MaCabe and Wolock (1992), based on an irrigation model, concluded that the increase in mean annual water use is strongly associated with the increase in temperature.

In southern Taiwan, around 76% of the total water resource is used for agriculture, in which paddy fields are one of the major demanders. Changes in climatic regimes may affect agricultural water demands, because evapotranspiration from paddy fields may be affected by changes in meteorological variables (e.g., temperature, solar radiation, wind speed, and relative humidity). Therefore, a sensitivity analysis of these meteorological variables using the Modified Penman formula (Doorenbos and Pruitt, 1984) was first investigated to find which meteorological variables are significantly sensitive to evapotranspiration estimation. The trend and persistence analyses of these sensitive meteorological variables were then studied further to discover whether their trends and persistence exist in the historical time series due to a climate change. Finally, the effects of climate change on evapotranspiration from paddy fields were observed based on a study of the sensitivity and trend analyses.

## 2. Study Area and Data Set

The main production area of rice in Taiwan is found in the southern part of the country. Normally, there are two crop seasons in that area. The first crop season is from January to April and the second from June to September. The first crop season always faces the problem that the irrigation system cannot fully provide the water requirement of the paddy fields, because only 10% of the annual rainfall occurs during the period December to April (that is, the dry period in Southern Taiwan).

The Kao-Hsiung station, a meteorological station in southern Taiwan (shown in Figure 1), has a long period of record-taking (1950 to 1997). The daily meteorological data of this station were used for this study. The data include temperature, relative humidity, sunshine duration, wind speed, and precipitation. The monthly averages of these meteorological variables and the days of no precipitation are displayed in Figure 2. This figure shows that the temporal distribution of precip-

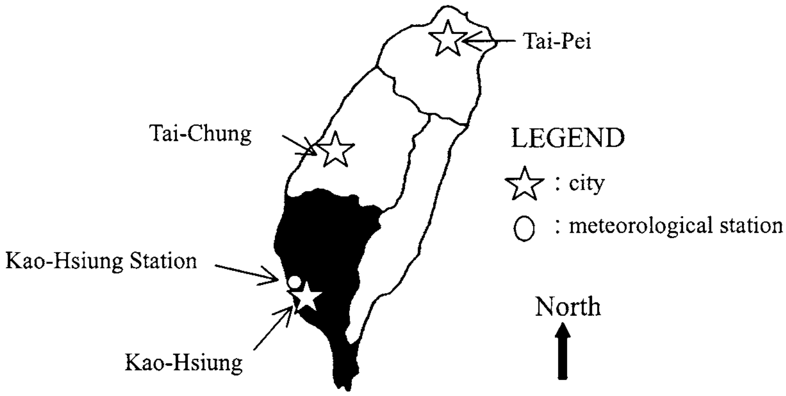


*Figure 1.* The study area and the meteorological station used in this study.

itation and the days of no precipitation are obviously non-uniform, which makes the operation of water supply system for irrigation during the dry period even more difficult.

## 3. Methodology

### 3.1. SENSITIVITY ANALYSIS USING MODIFIED PENMAN FORMULA

The modified Penman formula (shown in Appendix I; Doorenbos and Pruitt, 1984) has been recommended as a suitable tool for estimating the reference evapotranspiration from paddy fields in Taiwan (Zhang, 1995). Therefore, it was chosen in this study to estimate the effect of climate change on evapotranspiration from paddy fields. The actual crop evapotranspiration is normally obtained from the reference evapotranspiration estimated by the modified Penman formula timed by a crop coefficient. Crop coefficients reflect the effects of crop height, crop-soil surface resistance, and the albedo of the crop-soil surface on the actual evapotranspiration. The value of the crop coefficient varies primarily with the crop species and the characteristics of growth. Therefore, the value of the crop coefficient for a specific crop is usually obtained from the literature based on its growth season and planted area. The crop coefficients of the paddy fields in the Kao-Hsiung area (Zhang, 1995) are listed in Table I.

The meteorological variables that are likely to be altered due to climate change (e.g., temperature, relative humidity, solar radiation, and wind speed) are the ones to be tested for their sensitivity in the evapotranspiration estimation using the modified Penman formula. Figures 3 and 4 show the effects of the change rate of input meteorological variables on the estimation of the modified Penman formula for the first and the second crop seasons, respectively. These figures indicate that solar radiation is the most sensitive variable of the modified Penman formula and that

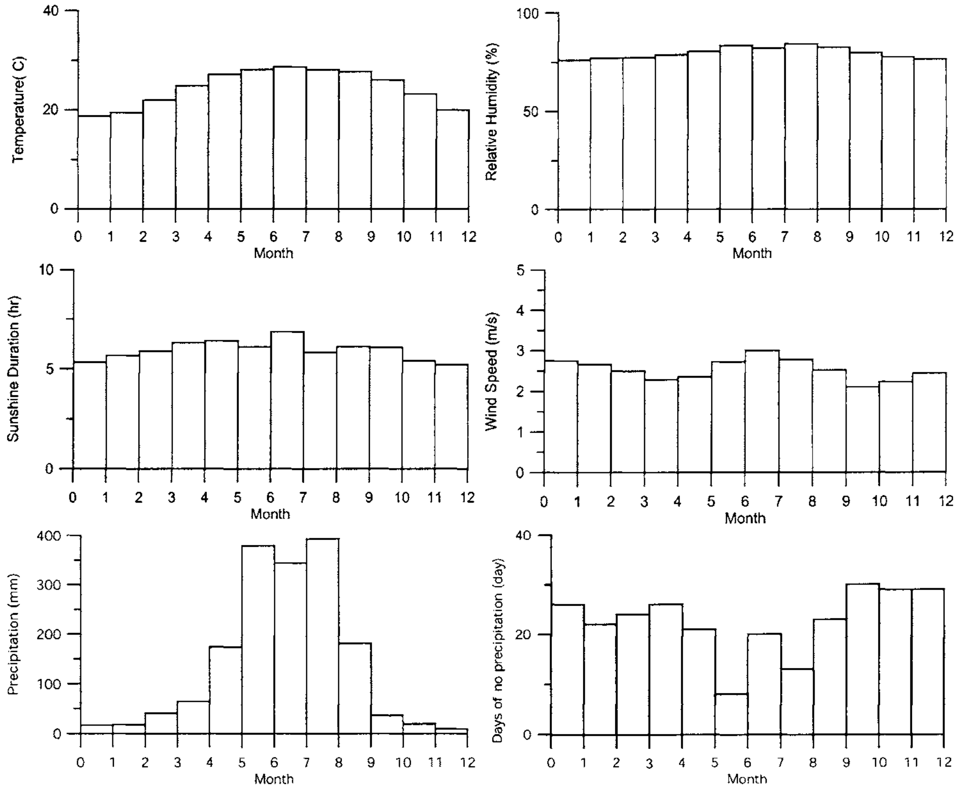


*Figure 2.* Averages of each meteorological variable for every month.

Table I
The values of crop coefficient for the first and the second cropping seasons, respectively

| Days of growth | Stages of growth | Crop coefficient | |
|---|---|---|---|
| | | The first season | The second season |
| 1–30 | Preparing land | – | – |
| 31–45 | Seedlings | 0.5 | 0.9 |
| 46–60 | 1st Tillers | 0.8 | 1.2 |
| 61–75 | 2nd Tillers | 1.2 | 1.5 |
| 76–90 | 1st Blooms | 1.3 | 1.6 |
| 91–105 | 2nd Blooms | 1.3 | 1.5 |
| 106–120 | 1st Maturity | 1.2 | 1.3 |
| 121–135 | 2nd Maturity | 1.1 | 1.1 |
| 136–150 | 3rd Maturity | 0.7 | 0.6 |

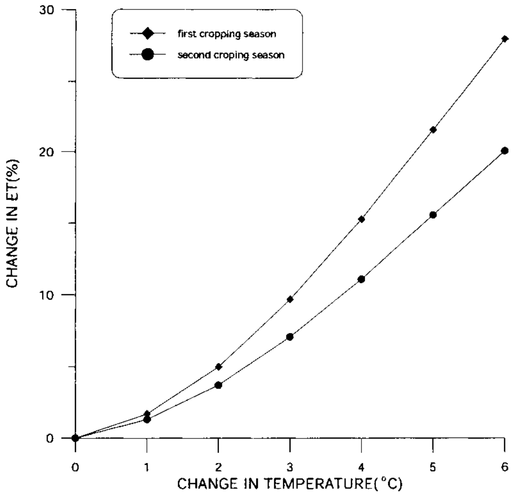


*Figure 3.* The sensitivity of temperature during the first and the second cropping seasons, respectively.

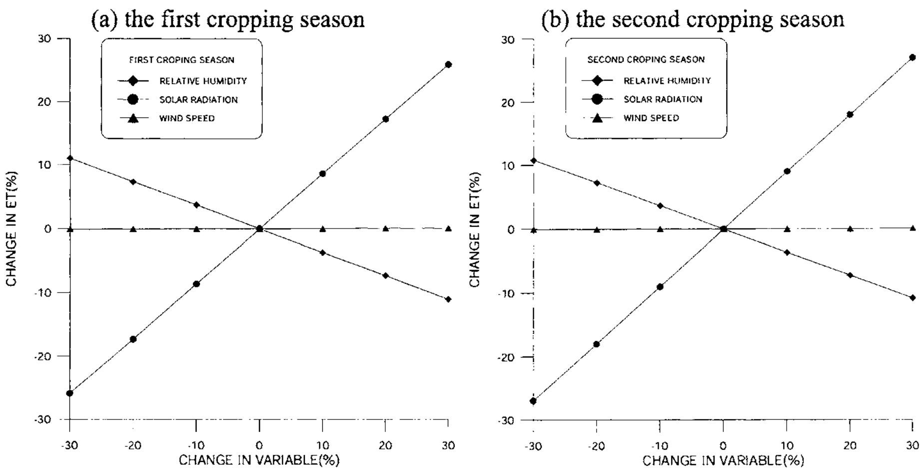


*Figure 4.* The sensitivity of relative humidity, solar radiation, and wind speed during the first and the second cropping seasons, respectively.

wind speed is the least sensitive variable. The relative humidity has the property that increasing its value will decrease the evapotranspiration estimate.

### 3.2. TRENDS AND PERSISTENCE OF METEOROLOGICAL VARIABLES

The trends and persistence in historical meteorological data are helpful in understanding the effect of climate change on evapotranspiration from paddy fields. The trends and persistence of a time series can be tested by different methods. The approaches used in this study are the Mann–Kendall test (Kendall, 1970), the Cumulative Deviation test (Buishand, 1982), regression analysis, and the autocorrelation coefficient, which are shown in Appendix II.

### 3.3. CLIMATE CHANGE SCENARIOS

Usually, scenarios of climate change can be assumed by (1) extrapolating meteorological variables by analyzing the trend of historical data, (2) hypothesizing changing ranges of meteorological variables, and (3) predicting the future meteorological variables using GCMs. To assess the effect of climate change on evapotranspiration from paddy fields, this study used two climatic scenarios based on extrapolating meteorological variables analyzing the trend of historical data (Scenario I) and predicting the future meteorological variables using various GCMs (Scenario II).

## 4. Results

### 4.1. TRENDS AND PERSISTENCE ANALYSIS

The four abovementioned methods (that is, Mann–Kendall test, Cumulative Deviation test, Regression Analysis, and Autocorrelation Coefficient) were utilized to detect trends and persistence of the meteorological variables during the first and second crop season. All but the Regression Analysis method used the records taken during a forty-eight-year period (1950–1997) at the Kao-Hsiung station as their data set. For the Regression Analysis, four different recording lengths (that is, 1950–1997, 1960–1997, 1970–1997, and 1980–1997) were adopted to detect the stability of the trends. If all four recording lengths have significant trends, then the stability of the trend exists in the longest recording length (that is, 1950–1997). Otherwise, the longest recording length has an unstable trend. The detected results are presented in Table II. It reveals that temperature and relative humidity have significant and stable trends and that temperature increases as relative humidity decreases. Sunshine duration was found to have no significant and stable trends, although it did have a significant lag-1 persistence. Rainfall depth was found to have no significant and stable trends and no persistence during either crop season.

### 4.2. EFFECTS OF CLIMATE CHANGE

#### 4.2.1. *Analysis Results of Scenario I*

Based on the former trend detection, temperature and relative humidity were found to have significant trends. The linear regression equations developed using the historical temperature series and the relative humidity series from 1950 to 1997 (as shown in Figure 5) were used to extrapolate the predicted 50-year values for the first and second crop season, separately. The other meteorological variables, such as sunshine duration and wind speed, which had no significant trends in the

Table II

The statistical tests for various meteorological variables during the first and the second cropping seasons

| | Temperature | | Relative humidity | | Sunshine duration | | Wind speed | | Rainfall depth | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd | 1st | 2nd |
| M–K | ↑ | ↑ | ↓ | ↓ | – | – | – | – | – | – |
| C–D | + | + | + | + | + | – | + | + | – | – |
| L–R | s | s | s | s | u | u | u | s | u | u |
| PER | + | + | + | + | + | + | + | + | – | – |

↑: increasing trend; ↓: decreasing trend.
+: significantly homogeneous data; –: not significantly homogeneous data.
s: stable trend for all periods; u: not all periods have trends.
M–K: Mann–Kendall test; C–D: Cumulative Deviations test; L–R: Simple Linear Regression; PER: persistence analysis by autocorrelation coefficient.

Table III

Estimated evapotranspiration for Scenario I

| Cropping seasons | Evapotranspiration (mm) | |
|---|---|---|
| | Mean form 1993–1997 | Estimated value in 50 years |
| 1st | 505 | 530 |
| 2nd | 776 | 800 |

former analysis, will keep their mean values in the future. The calculated results of evapotranspiration for Scenario I are listed in Table III. In this study, the mean values of evapotranspiration from 1993 to 1997 for the first and second crop season, respectively, are assumed to be like the present condition. They reveal that increases in evapotranspiration of around 25 mm and 24 mm may occur in 50 years for the first and second crop season, respectively.

4.2.2. *Analysis Results of Scenario II*

*Scenario II* considers the mean values of evapotranspiration from 1993 to 1997 for the first and second crop seasons, respectively, as the present condition. Increases in temperature predicted by the four GCMs (that is, CCCM, GFDL, GISS, and UK98), with a double content of $CO_2$ in the atmosphere for various months, are shown in Table IV. Since relative humidity and solar radiation have no predicted values in these GCMs in the study area, the present study only considered increases in temperature and used the present values of relative humidity and solar radiation for estimating evapotranspiration in the modified Penman formula. Table IV shows that the increases in evapotranspiration in the various GCMs are similar and that

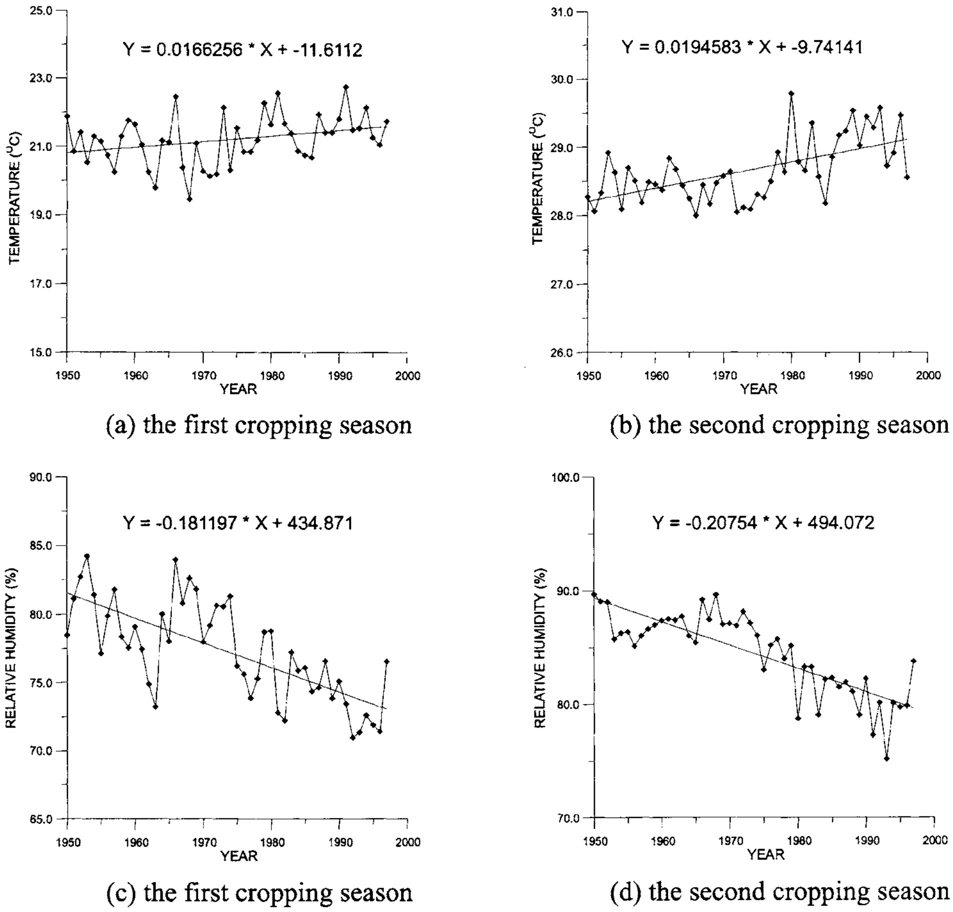


*Figure 5.* The regression analysis of historical temperature and relative humidity during the first and the second cropping seasons, respectively, for extrapolating the values of temperature and relative humidity in 50 years (Scenario I).

evapotranspiration may increase by approx. 28 mm and 25 mm when only considering the increase in temperature for the first and second crop season, respectively. These increases in evapotranspiration appear similar to those of Scenario I, which will be discussed in Section 6.

#### 4.2.3. *Relationship between Evapotranspiration and Changes in Meteorological Variables*

In order to take the relationship between temperature, relative humidity, and solar radiation into account for estimating evapotranspiration in future climatic scenarios, the study further established the relationship charts as shown in Figure 6 for the first and the second crop seasons, respectively. For example, if the temperature increases by 2 °C, the relative humidity decreases by 20%, and the solar radiation

Table IV
Estimated evapotranspiration for Scenario II

| Cropping seasons | | 1993–1997 monthly mean temperature (°C) | CCCM $\Delta T$ (°C) | GFDL $\Delta T$ (°C) | GISS $\Delta T$ (°C) | UK89 $\Delta T$ (°C) |
|---|---|---|---|---|---|---|
| 1st | Jan. | 19.08 | 2.71 | 3.94 | 2.29 | 2.61 |
| | Feb. | 19.84 | 3.66 | 2.82 | 2.43 | 2.85 |
| | Mar. | 22.14 | 4.73 | 4.14 | 2.96 | 2.86 |
| | Apr. | 25.08 | 4.16 | 3.02 | 3.55 | 2.71 |
| | Evapotranspiration (mm) | 505 | 538 | 534 | 529 | 529 |
| 2nd | Jun. | 28.56 | 2.52 | 2.67 | 2.64 | 2.74 |
| | Jul. | 29.20 | 2.09 | 2.20 | 2.28 | 2.75 |
| | Aug. | 28.42 | 1.75 | 2.12 | 3.23 | 2.74 |
| | Sep. | 28.12 | 2.62 | 3.02 | 3.62 | 3.05 |
| | Evapotranspiration (mm) | 776 | 797 | 800 | 803 | 803 |

increases by 30%, the evapotranspiration during the first and second crop season, respectively, is 698 mm and 1071 mm. The increments are 193 mm and 295 mm, respectively, for the first and second crop season.

## 5. Discussion

The increases in evapotranspiration for Scenario I are similar to those for Scenario II in the above analysis. Scenario I extrapolated the temperature and relative humidity over 50 years and found increases of around 1 °C and –10%, respectively. Scenario II only considered increases in temperature for the various GCMs, which are around 2 °C to 3 °C. The estimated values of evapotranspiration for Scenario I and Scenario II, respectively, can be obtained from the right side of Figure 6 and were also found to be similar. If the predicted increases in temperature and relative humidity are around 2 °C and –20%, the increase in evapotranspiration will be nearly twice as large as that when only considering a 2 °C increase in temperature. It can be concluded that just considering a change in temperature will underestimate the amount of evapotranspiration that occurs with climate change. However, since changes in the other meteorological variables, such as relative humidity and sunshine duration, still play important roles in the assessment of evapotranspiration with climate change, the simultaneous consideration of the effects of meteorological variables like temperature, relative humidity, and sunshine duration on the

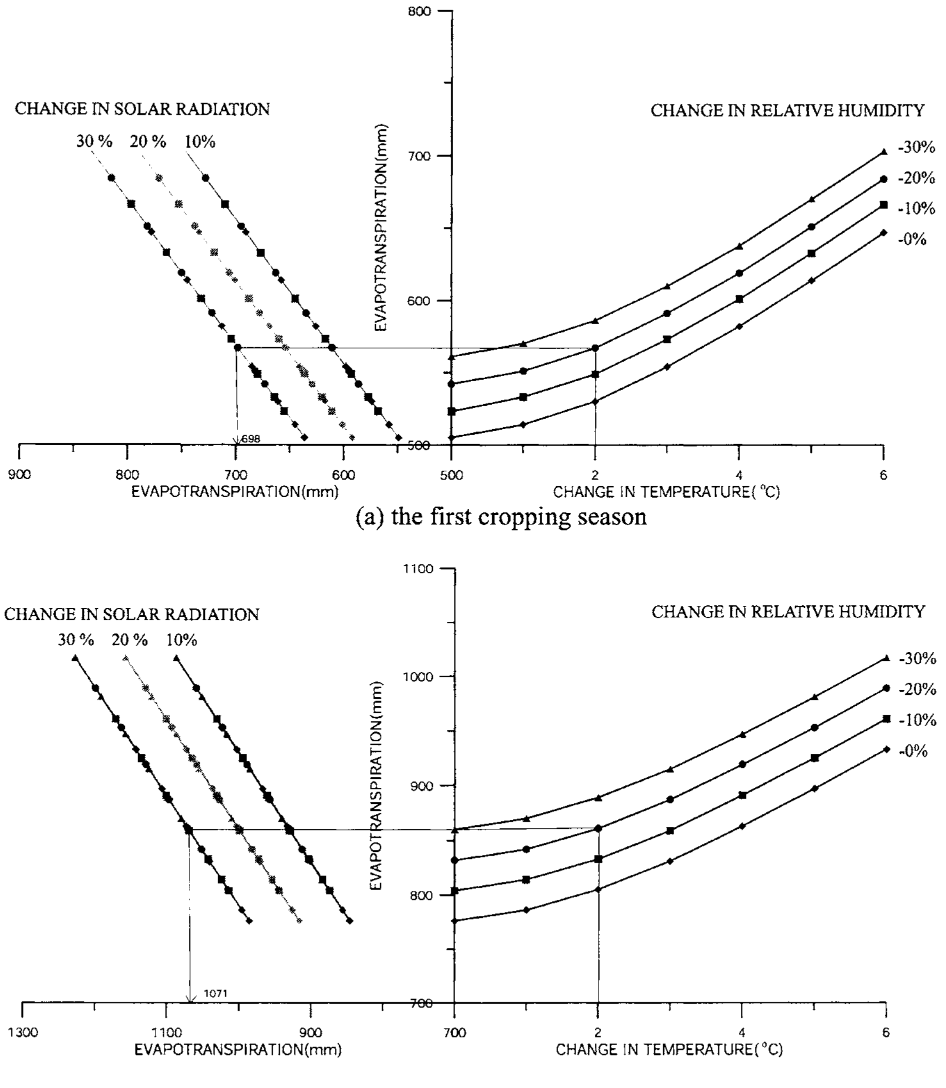


*Figure 6.* The relationship among temperature, relative humidity, solar radiation, and evapotranspiration during (a) the first cropping season and (b) the second cropping season.

evapotranspiration estimation with climate change is necessary. That is why we propose a figure (Figure 6) showing the relationship between temperature, relative humidity, solar radiation, and evapotranspiration to demonstrate this phenomenon.

Changes in some of the physiological characteristics of rice also influence the estimation of evapotranspiration with climate change. They are, therefore, addressed in this section as a caveat, since our work assumes their effects to be minor and thus neglects them.

The phenological stages of the plant might change with climate change. A preliminary study in Taiwan (Lin and Chen, 1988) has found that increased temperature may shorten the early growth duration of rice before the tillers stage. The detailed changes of different growth durations for plants due to climate change are still under exploration in Taiwan. Since these changes could not be found in the literature, they have not been considered in the estimation of evapotranspiration in the present study.

The meteorological variable, ambient temperature, has an effect on the photosynthetic efficiency of plants. Lin and Chen (1988) found that an increased temperature enhances the photosynthetic activity of rice. The stomatal opening of the plants controls transpiration loss, which is influenced by environmental factors such as air temperature, humidity, and concentration of $CO_2$, etc. When the temperature increases, the stomatal opening of the plants should become smaller in order to avoid transpiration and thus conserve water. A higher concentration of $CO_2$ in the air leads to less stomatal opening, thus reducing the transpiration through the stomata. The transpiration of plants, therefore, may change due to a change in climate and $CO_2$ concentration. Although the stomatal opening controls the transpiration of plants, the relationship and interaction between the stomatal opening, the meteorological variables, and the concentration of $CO_2$ are so complicated that detecting the effects of these factors on the transpiration estimation is very difficult. Hence, the effects of these factors were not incorporated in the present study.

## 6. Conclusions

The effect of climate change on water resources is an important aspect of this decade. Since the irrigation water requirement of paddy fields is a primary water demand in Taiwan, the present study investigates the effect of climate change on evapotranspiration from paddy fields and its sensitivity analysis. A sensitivity analysis of each meteorological variable was first carried out using the modified Penman formula. Three meteorological variables, solar radiation, relative humidity, and temperature, were found to influence the evapotranspiration estimation.

Trends and persistence of meteorological variables were further detected using the Mann–Kendall test, the Cumulative Deviation test, Simple Linear Regression, and the Autocorrelation Coefficient. Forty-eight-year records of temperature, relative humidity, sunshine duration, wind speed, and precipitation comprised the database. The results indicated that only temperature and relative humidity show significant long-term trends and persistence in southern Taiwan. As the sunshine duration did not show any statistical trend, the effect of climate change on evapotranspiration will be greatly influenced by temperature and relative humidity.

Based on the linear extrapolation of the trends of the meteorological variables and the predictions of various GCMs separately, two climatic scenarios were used to investigate the effect of climate change on evapotranspiration. In the first scenario, the evapotranspiration from paddy fields for the two crop seasons in the Kao-Hsiung area increased by 4.95% and 3.09%, respectively. In the second scenario, the increased percentages were 5.50% and 3.20%, respectively. These results provide us with a warning for an increase in irrigation water demand in the future. Water supply planning and management should take this phenomenon into account as soon as possible.

In addition to the meteorological variables, the physiological response of the rice plant to the concentration of $CO_2$ plays an important role in the evapotranspiration estimation. However, it was not considered here.

## Appendix I. The Modified Penman Formula

The modified Penman formula is given by the sum of three terms: the short-wave radiation term, the back long-wave radiation term, and the aerodynamic term. The first two terms are measures of radiant energy absorbed by and emanated from a heated body, respectively, whereas the third term is a measure of the effect of the ventilation, turbulence, and dryness of the air above the evaporating surface.

Defining the modified Penman formula gives the following equation:

$$ET_0 = \frac{\Delta}{\gamma + \Delta} \times \frac{R_n}{\ell} + \frac{\gamma}{\gamma + \Delta} \times f(U) \times (e_a - e_d) \,, \tag{A.1}$$

where $ET_o$ is the reference crop evapotranspiration (mm); $\Delta$ is the rate of change of saturated vapor pressure with temperature (hPa × °C$^{-1}$); $\gamma$ is the psychrometric constant (hPa × °C$^{-1}$, $\gamma = 0.66$); $R_n$ is the net radiation (MJ × m$^{-2}$); $\ell$ is the latent heat of vaporization (MJ × m$^{-2}$, $\ell = 2.5 - 0.0024 \times T$); $T$ is the daily mean temperature (°C); $f(U)$ is an empirical wind speed function of the form $f(U) = 0.27(1 + 0.01U)$; $U$ is the wind speed (m/s); $e_a$ is the saturated vapor pressure of mean air temperature (hPa); and $e_d$ is the actual vapor pressure of mean air temperature. A detailed description of each parameter is given by Doorenbos and Pruitt (1984).

## Appendix II. Approaches for Trend and Persistence Analysis

### (1) MANN–KENDALL TEST

The Mann–Kendall Test, suggested by the World Meteorological Organization (1988), is a common method to test the trend of a time series. This method defines the standard normal variate, $T$, as

$$T = \frac{r^*}{\sqrt{\sigma_{r^*}^2}} \tag{A.2}$$

$$r^* = \left[\frac{4p}{n(n-1)}\right] - 1 \tag{A.3}$$

$$\sigma_{r^*}^2 = \frac{2(2n+5)}{[9n(n-1)]}, \tag{A.4}$$

where $p$ is the number of pairs observations $(x_i, x_j, j > i)$ that $x_j > x_i$ was calculated. The time series has a trend at the significant level of 5%, if $|T| > T_{\alpha/2} = 1.96$. A positive value of $T$ indicates an increasing trend in the time series, while a negative value indicates a decreasing trend.

### (2) CUMULATIVE DEVIATION TEST

In order to confirm the presence of trends in meteorological historical records, a test for homogeneity in the data was performed. The test for homogeneity was based on the adjusted partial sums or cumulative deviations from the mean:

$$S_k = \sum_{i=1}^{k}(Y_i - \overline{Y}), \quad k = 1, 2, \ldots, n, \tag{A.5}$$

where $\overline{Y}$ is the mean of $Y_i$ values and $n$ is the number of values. For a homogeneous series of records, the values of $S_k$ fluctuate around zero. The re-scaled adjusted partial sums $S_k^*$ are obtained by dividing the $S_k$ values by the sample standard deviation as follows:

$$S_k^* = S_k / D_Y, \quad k = 1, 2, \ldots, n \tag{A.6}$$

with

$$D_Y^2 = \sum_{i=1}^{n}(Y_i - \overline{Y})^2 / n. \tag{A.7}$$

Based on the $S_k^*$ values a statistic $Q$, which is sensitive to departures from homogeneity, can be defined as:

$$Q = \max_{0 \le k \le n} |S_k^*|. \tag{A.8}$$

High values of $Q$ indicate a change in mean. Critical values for $Q/\sqrt{n}$ for the 95% confidence interval were found to be equal to 1.27.

### (3) REGRESSION ANALYSIS

The meteorological variables in the regression analysis were first smoothed by using the moving average method. Five years of moving average was adopted in this analysis.

A simple linear regression equation was then selected to detect the long-term trends of the meteorological variables.

$$Y = \hat{a} + \hat{b}X\,, \tag{A.9}$$

where $Y$ is the meteorological variable, $X$ is the time, and $\hat{a}$ and $\hat{b}$ are the regression coefficients calculated by the least square method.

Determining the $T$ value distributed with $n - 2$ degrees of freedom by the following equations tests the significance of the regression slope

$$T = \frac{\hat{b}}{\sqrt{MSE/S_{xx}}}\,, \tag{A.10}$$

where $MSE$ is the mean square error and $S_{xx}$ is:

$$S_{xx} = \sum_{i=1}^{n}(X_i - \overline{X})^2\,. \tag{A.11}$$

If $|T| > t_{\alpha/2,n-2}$ , the null hypothesis ($H_0$: slope $\hat{b}$ is not significantly different from zero) is rejected and slope $\hat{b}$ is significantly different from zero to show that a trend exists.

(4) AUTOCORRELATION COEFFICIENT

Persistence analysis is used to detect the relationship of variables between two continuous time steps in a series. This study uses the autocorrelation coefficients of meteorological variables to test their persistence in time. The autocorrelation coefficient with a lag time of k is defined as follows:

$$r_k = \frac{\sum_{t=1}^{N-k}(X_t - \overline{X})(X_{t+1} - \overline{X})}{\sum_{t=1}^{N}(X_t - \overline{X})^2}\,, \tag{A.12}$$

where $X_t$ is the meteorological variable at time $t$, $N$ is the number of samples, $k$ is the time lag, and $\overline{X}$ is the mean of $X_t$. The significance of $r_1$ is tested by determining the $(r_1)_t$ value with the following equation:

$$(r_1)_t = \frac{-1 \pm t_g\sqrt{N-2}}{N-1}\,, \tag{A.13}$$

where $t_g$ is the standard normal variate of a Gaussian distribution.

In Equation (A.13), if $r_1$ is negative, the series has a significant oscillation with a high frequency and its period is short. In contrast, if $r_1$ is positive, the series has a Markov linear type persistence.

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