



# **Irrigation efficiency under Northwester storm conditions**

**Summer Scholarship Report**

*WCFM Report 2012-002*

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TITLE: **Irrigation efficiency under Northwester storm conditions**

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## Executive Summary

This project aimed to identify and model the effects of Northwesterly storms on irrigation uniformity and efficiency. In doing this, climate conditions associated with Northwesterly storms were also investigated.

Historical climate data from one representative site on the Canterbury Plains was used to establish a definition for a Northwesterly storm event. This was a maximum daily temperature greater than 25°C, wind gusts higher than 40 km/h and relative humidities less than 30%. Northwesterly storms generally occur in summer months.

ASCE standardised reference evapotranspiration was calculated for six sites on the Canterbury Plains for 2010. The results show an obvious seasonal variation; summer months have higher evapotranspiration values due to increased solar radiation. Location was also found to be important; evapotranspiration values increase from south to north and west to east. The highest daily evapotranspiration values occurred at Waipara station, which is located the farthest north of the six sites and is in a sheltered valley.

To determine the impact of key meteorological variables (relative humidity, air temperature and wind speed) on reference evapotranspiration, a sensitivity analysis was performed for each of the six sites. Evapotranspiration was relatively insensitive to air temperature in winter, and achieved a maximum in summer. Sensitivity coefficients associated with air temperature varied spatially, with evapotranspiration further north being more responsive to changes in temperature. However, changes in relative humidity were found to have the greatest impact on evapotranspiration, and no relationship was observed with wind speed coefficients.

Two statistically derived equations (Yazar's & Bavi's models) were used to calculate the evaporative losses throughout 2010 at the Winchmore EWS site. The results from Yazar's model showed generally lower losses than Bavi's model. However Yazar's model was more impacted by the Northwesterly storm events showing evaporative losses of up to 9% during 2010. Their models did not take account of wind effects, which would further increase this loss. If Yazar's model is correct, alternative irrigation schedules would be useful during Northwesterly storm events.

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## **Section 1 Introduction**

### **1.1 Background**

#### **1.1.1. Northwest winds**

A foehn wind describes a warm, dry wind which descends the lee slopes of a mountain range. On the Canterbury Plains of New Zealand, the local foehn is referred to as the northwester (NW), in reference to the usual direction of this wind. The wind is caused by the orographic effect which occurs as air travels over the Southern Alps from the west. This wind is typically associated with warm ambient air temperatures, low humidities and gusty winds (McGowan & Sturman, 1994). These three factors are key driving factors behind evapotranspiration (ET), one of the essential processes of crop growth. High wind speeds associated with the NW also affect irrigation uniformity. Sprinkler systems, such as centre pivots, are common on the Canterbury Plains. The airborne water particles exiting these systems are extremely vulnerable to the strong winds associated with the NW and as a result the pattern of application will be distorted by wind, affecting the application uniformity (Edling, 1985). The warm and dry NW wind will also cause direct evaporation of water particles during their flight path from the nozzle to the ground, which can result in complete evaporation of the smallest particles (Molle et al., 2011). Consequently, the NW wind negatively impacts on irrigation efficiency.

Generally, water is lost during storage, conveyance and field application. In sprinkler irrigation systems, the loss that occurs in the field is the largest of the three. Minimising the loss of water from irrigation systems is important for achieving water and energy conservation. (McLean et al., 2000). Taking measures to improve water conservation in irrigation processes is of particular importance in the Canterbury Plains, as the area of irrigated land has doubled every decade over the last 50 years. As a result of this stress falling groundwater levels and low flows in spring fed streams are evident (Mabin et al., 2006).

#### **1.1.2 Evapotranspiration Effects**

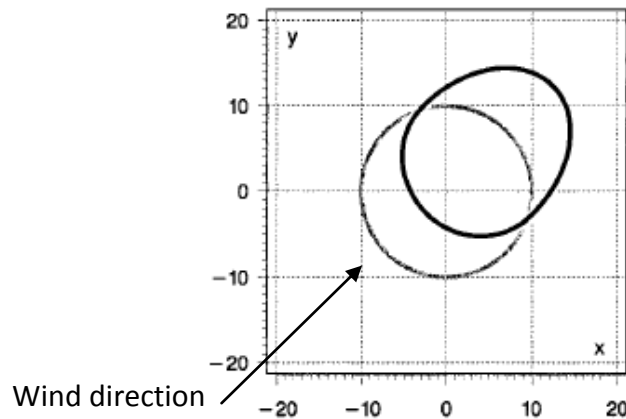
Accurate estimations of crop water requirements are necessary to ensure efficient use of water resources (Estévez et al., 2009). One way of measuring this is by the crop reference evapotranspiration ( $ET_o$ ).  $ET_o$  is an important variable in the agrohydrological systems, which depends only on climatic parameters and provides the ET of an ideal and well-water grass surface. A number of equations are available for estimating  $ET_o$  (e.g. Blaney and Criddle, 1950; Hargreaves and Samani, 1985; FAO-56 Penman-Monteith, 1998; ASCE-EWRI, 2005). Among these equations, the ASCE Standardised Reference Evapotranspiration Equation (ASCE-EWRI, 2005) that incorporates both energy balance and aerodynamic theory, is considered to be the most appropriate model to predict  $ET_o$  (Zhang et al., 2010).

To understand the relative importance of climatic variables in the ASCE model, a sensitivity analysis is required. Several papers have previously carried out a sensitivity analysis of the ASCE model to climate variables (Estévez et al., 2009; Beven, 1979). Gong et al. (2006), Zhang et al. (2010) and Liqiao et al. (2008) completed similar investigations with data from a number of locations, to assess spatial variation of calculated sensitivity coefficients, made clear by these reports. Little research has been undertaken, however, regarding the sensitivity of crop evapotranspiration to climate factors on the Canterbury Plains. Due to the dependence on location of sensitivity coefficients, numerical conclusions made in previous investigations elsewhere cannot be simply applied to Canterbury.

Methods are available for modelling and measuring the water losses that occur to the atmosphere, as by evaporation, while water is travelling from the sprinkler nozzle to the crop canopy. Kincaid and Longley (1989) found that many investigators have combined losses due to evaporation and spray drift together, into 'Spray losses', largely due to the difficulties encountered with the measurement techniques necessary to separate the two. They therefore developed a model for predicting evaporation and temperature changes in water droplets travelling through air and evaluated this with laboratory data. McLean et al. (2000) used an electrical conductivity (EC) method to determine the above canopy spray evaporation loss (ACSEL) from different types of sprinkler irrigation systems, calculated at increasing distances from the sprinkler nozzles. Again using the EC method, Hermsmeir (1973) reported that evaporation from sprinklers could range from 0 to 50% over short periods. Hermsmeir also found that the air temperature and the rate of application were better factors for estimating sprinkler evaporation, than wind speed or relative humidity. Till (1957) used similar methods and measured the spray evaporation losses using the change in concentration of chloride ions in irrigation water travelling from the sprinkler nozzle to the ground. Similarly, Yazar (1983) used the electrical conductivity method to develop equations that could determine evaporative losses in various climate conditions.

### **1.1.3 Wind Effects**

Le Gat and Molle (2000) developed a model describing the application pattern produced by a single sprinkler. Data measured in the field were then used to assess the wind effect on the shift of the centre of gravity of the irrigated area. The main practical interest of their model lay in the fact that once the parameters have been estimated, and provided the wind speed and direction are known, the depth of water falling on any sufficiently small surface element can be computed using a single equation. It can thus be easily implemented in a larger module to simulate the water application under centre pivots and moving laterals. Figure 1 shows a visual representation of the expected water distribution under a centre-pivot irrigator, given a moderate wind.



**Figure 1** Effect of wind, in the direction shown, on centre pivot irrigation distribution (Le Gat & Molle, 2000)

Edling (1985) modelled evaporation and drift losses from low pressure spray nozzles using the model of Williamson and Threadgill (1974). A simulation model was developed to estimate kinetic energy, evaporation and wind drift of droplets from low pressure irrigation sprinklers. A number of parameters, including droplet size, air temperature and wind direction and velocity were changed to determine the influence on evaporation and travel of the droplet. It was found that evaporation increases rapidly when droplet diameter is increased, and that the influence of air temperature and wind drift is more evident for smaller droplet sizes. These findings were confirmed by Molle et al. (2011), who showed that droplets less than 1mm in diameter displayed the highest losses.

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## 1.2 Aim

Although research has been conducted into the impacts of various weather conditions on application uniformity and efficiency, none has been found that assesses the combined effect of the specific meteorological factors associated with a NW storm, namely high temperatures, high wind speeds and low relative humidities. In addition, no investigations specific to the Canterbury Plains have been conducted.

The aim of this project is to identify and model the effects of NW storms on evapotranspiration processes, as well as an irrigation uniformity and efficiency. In doing so, the climate conditions associated with NW storms on the Canterbury Plains will also be defined. The results of the project will be used to decide whether or not the impact of the NW wind is significant enough for alternative irrigation schedules to be considered for these times.



## **Section 2 Methodology**

This investigation comprises of three main components: establishing and analysing the climate characteristics associated with a NW storm, investigating the effect of the NW storm on crop evapotranspiration and modelling irrigation efficiency and uniformity under NW storm conditions.

### **2.1 Northwesterly Climate Characteristics**

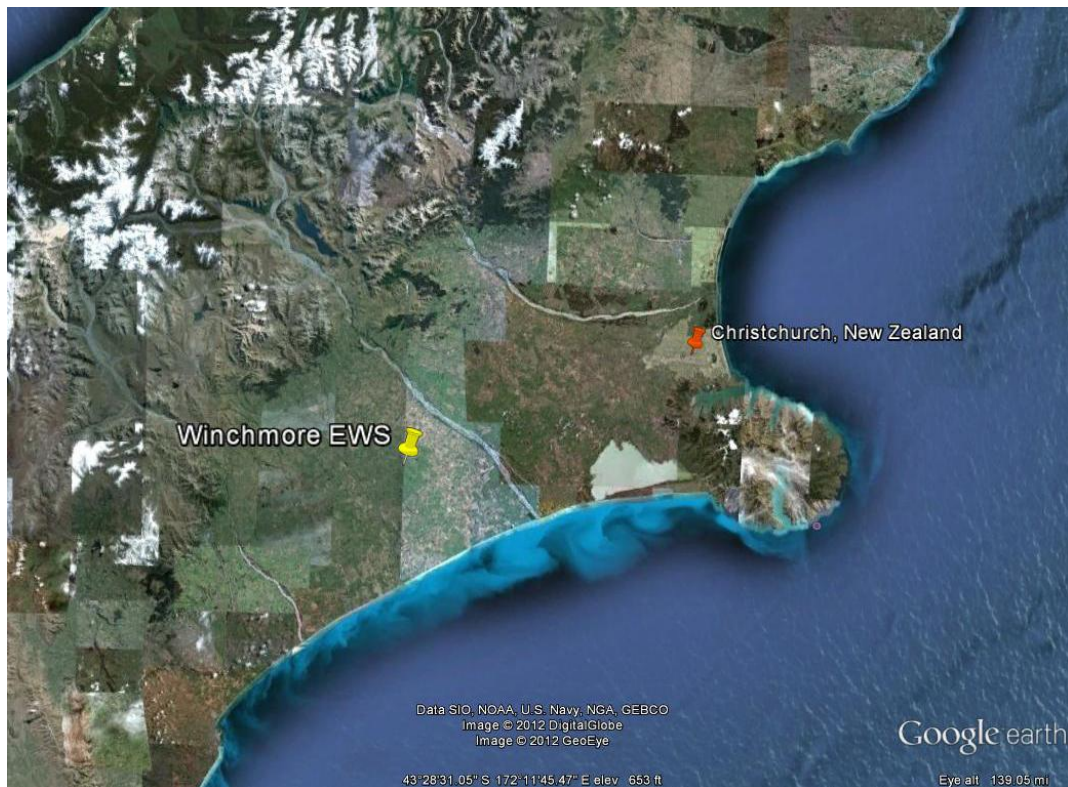
It has previously been established that NW storms are typically associated with warm ambient air temperatures, low humidities and gusty winds (McGowan & Sturman 1994). However, no previous research has numerically defined the climatic conditions of the NW storm. This component of the project involves using climate data from the Canterbury Plains to establish numerical values that define a NW storm.

#### **2.1.1 Site Selection**

The National Institute of Water and Atmospheric Research of New Zealand (NIWA) has online a database (Cliflo) of climate data, from a large number of weather stations in New Zealand. The data has been recorded over a number of years. There are approximately 70 separate weather stations spread across the Canterbury area.

For the purpose of defining a NW storm event, the Winchmore EWS station was selected for analysis. This particular site is located in the mid-Canterbury Plains and was therefore thought to be representative of the entire region.

Figure 2 shows the location of Winchmore EWS on the Canterbury Plains.



**Figure 2** Winchmore EWS location

### 2.1.2 Data Analysis

Hourly climate data for Winchmore EWS from 1996 to 2011 was obtained from the NIWA Cliflo database. MetService New Zealand (2011) has previously defined ‘very low humidity’ on the Canterbury Plains as bring relative humidities below 30%. Therefore, using conditional formatting in Microsoft Excel, all hours with relative humidities at 30% or lower were highlighted. The corresponding hourly maximum temperature and hourly maximum wind speeds and direction were then analysed, to allow a NW ‘definition’ to be established.

## 2.2 Effect of Northwesterly on Crop Evapotranspiration

The high temperatures, low relative humidities and high wind speeds associated with NW storm that frequently occur throughout the Canterbury Plains, impact on the crop water requirements. The reason for this is that a change in these factors alters the value for  $ET_o$ . Investigating the sensitivity of the  $ET_o$  equation to climatic factors will allow a more in depth understanding of the specific impacts of NW storms on irrigation water requirements to be gained.

### 2.2.1. Site Selection

Daily meteorological data from six of the NIWA stations were collected from the Cliflo database for the period 1 January 2010 – 31 December 2010. The six stations used are shown in Figure 3: Waipara West EWS, Darfield EWS, Methven CWS, Winchmore EWS, Orari

Estate EWS and Ashburton Aero Aws. These particular stations were selected as the literature review completed previously suggested that  $ET_o$  will vary with location. Stations located at a range of locations throughout the Canterbury Plains, varying both Northeast to Southwest and Northwest to Southeast, were therefore selected as can be seen in Figure 3.



**Figure 3** Location of weather stations used in evapotranspiration calculations

As well as spatial variability being a factor in selecting the weather stations for this investigation, it was also important that the stations selected recorded the data required for calculation of reference evapotranspiration: daily minimum and maximum temperatures, daily minimum and maximum relative humidities, mean daily wind speed and daily solar radiation. The measured daily data was converted to standard input parameters for the  $ET_o$  model (see the following section).

### 2.2.2 ASCE Standardised Reference Evapotranspiration

The P-M method for estimating daily reference evapotranspiration (Allen et al., 1998) is:

$$ET_o = \frac{0.408 \Delta (R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 u_2)}$$

Where  $ET_o$  is reference evapotranspiration ( $\text{mm day}^{-1}$ ),  $\Delta$  the slope of the saturation vapour pressure curve ( $\text{kPa}^\circ\text{C}^{-1}$ ),  $R_n$  the net radiation at the surface ( $\text{MJm}^{-2}\text{day}^{-1}$ ),  $G$  the soil heat flux ( $\text{MJm}^{-2}\text{day}^{-1}$ ),  $R_n - G$  the available energy ( $\text{MJm}^{-2}\text{day}^{-1}$ ),  $\gamma$  the psychrometric constant ( $\text{kPa}^\circ\text{C}^{-1}$ ),  $T_{mean}$  the mean temperature at 2m height ( $^\circ\text{C}$ ),  $u_2$  the mean daily wind speed at 2m height ( $\text{ms}^{-1}$ ),  $e_s$  the saturation vapour pressure ( $\text{kPa}$ ),  $e_a$  the actual vapour pressure ( $\text{kPa}$ ) and  $e_s - e_a$  is a vapour pressure deficit ( $\text{kPa}$ ). The computation of all data required for calculating daily reference evapotranspiration followed the procedures in ASCE-EWRI (2005). These components, as well as the  $ET_o$  were calculated in a Microsoft Excel spreadsheet. The accuracy of the spreadsheet was checked by inputting values given in ASCE-EWRI (2005), for which the corresponding resultant  $ET_o$  values were also provided.

### 2.2.3 Crop Evapotranspiration Sensitivity Analysis

To determine the impact of the change of key meteorological factors on  $ET_o$ , in particular those associated with NW storms, a sensitivity analysis needs to be undertaken. In evaporation (Gong et al., 2006), as well as other hydrological (Anderton et al., 2002) and ecological (Beres and Hawkins, 2001) applications, a number of sensitivity coefficients have been defined depending on the purposes of the analyses. A simple but practical way of completing a sensitivity analysis is to plot relative changes of a dependent variable against relative changes of an independent variable as a curve (Hupet and Vanclooster, 2001). More often however, a mathematically defined sensitivity coefficient is used in sensitivity analysis. For multi-variable models, such as the P-M model, different variables have different dimensions and different ranges of values, which makes it difficult to compare the sensitivities simply by partial derivatives. Consequently, the partial derivative is transformed into a non-dimensional form (Beven, 1979; Gong et al., 2006; Liqiao et al., 2008):

$$S_{V_i} = \lim_{\Delta V_i \rightarrow 0} \left( \frac{\Delta ET_o / ET_o}{\Delta V_i / V_i} \right) = \frac{\partial ET_o}{\partial V_i} \cdot \frac{V_i}{ET_o}$$

Where  $S_{V_i}$  is the sensitivity coefficient for the  $i$ th variable and  $V_i$  is the  $i$ th variable. The non-dimensional relative sensitivity coefficient is now widely used in evapotranspiration studies. A positive/negative sensitivity coefficient indicates that  $ET_o$  will increase/decrease with the increase of a climatic variable. The larger the absolute sensitivity coefficient, the larger the effect of a given variable on  $ET_o$ . A sensitivity coefficient of 0.5 for a variable would mean that a 10% increase in that variable may increase  $ET_o$  by 5%, while all other variables are held constant.

Sensitivity coefficients will be calculated for mean air temperature, wind speed and relative humidity across the Canterbury Plains. The partial derivatives needed for the determination of the sensitivity coefficients, have been calculated analytically using Mathematica software (attached as Appendix 1). These will then be compared for the different variables and locations, to see the different impacts changing these factors has on  $ET_o$ .

## 2.3 Irrigation Efficiency and Uniformity in Northwesterly Storm Conditions

Airborne water particles exiting centre pivot and other sprinkler systems are extremely vulnerable to the wind, which will cause them to drift away from their intended application location. In addition, the particles are susceptible to evaporation, particularly under warm, dry conditions. The high speed, dry winds, as well as the high temperatures, associated with the NW storm events that occur on the Canterbury Plains therefore impact on the irrigation uniformity and efficiency.

Presently, although it is known that the NW winds impact upon irrigation uniformity and efficiency on the Canterbury Plains (Chapman, 2011), the exact effects are unknown. Using models and equations already established in literature reviewed, it is proposed that a series of models will be created which will enable this to be done. Inputs will include, but not be limited to, air temperature, wind speed and direction relative to centre pivot direction and relative humidity.

Due to time constraints, only models that calculated evaporation losses were investigated and evaluated. It is hoped that future research in this area will be carried out that will obtain and/or create models for wind drift losses.

### 2.3.1 Yazar's Model

Yazar (1984) quantitatively determined evaporation losses under various operating conditions. These losses were determined by an electrical conductivity method. It was found that wind velocity and vapour pressure deficit were the most significant factors affecting the evaporation losses. An exponential relationship between the evaporation losses and both wind velocity and vapour pressure deficit were determined. This is shown below:

$$E = 0.389 \exp (0.18u) (e_s - e_o)^{0.7}$$

Where E is the percentage of discharged flow lost to evaporation; W is the wind speed at 2m (m/s) and  $(e_s - e_o)$  is the vapour pressure deficit (kPa).

This model was used to calculate and predict the evaporative losses that would occur at Winchmore EWS daily in 2010. The data obtained from Cliflo for this site was used again, with the variables converted in standard input parameters for Yazar's equation.

### 2.3.2 Bavi's Model

Bavi et. al (2009) used the catch can method to measure evaporation losses from a sprinkler irrigation system under various climate conditions. Like in Yazar's research, it was also found that wind velocity vapour pressure deficit were the most significant factors affecting the evaporation losses. In this paper, the following statistical equation was established, expressing evaporation losses as a function of wind speed and vapour pressure deficit:

$$E = 4.337 \exp (0.077u) (e_s - e_o)^{-0.098}$$

Where  $E$  is the evaporation losses expressed as the percentage of the total volume discharged by the sprinklers;  $u$  is the wind velocity at 2m (mil/h) and  $(e_s - e_a)$  is the vapour pressure deficit (mbar).

As with Yazar's model, the model created by Bavi et. al was used to predict the daily evaporative losses for Winchmore in 2010.

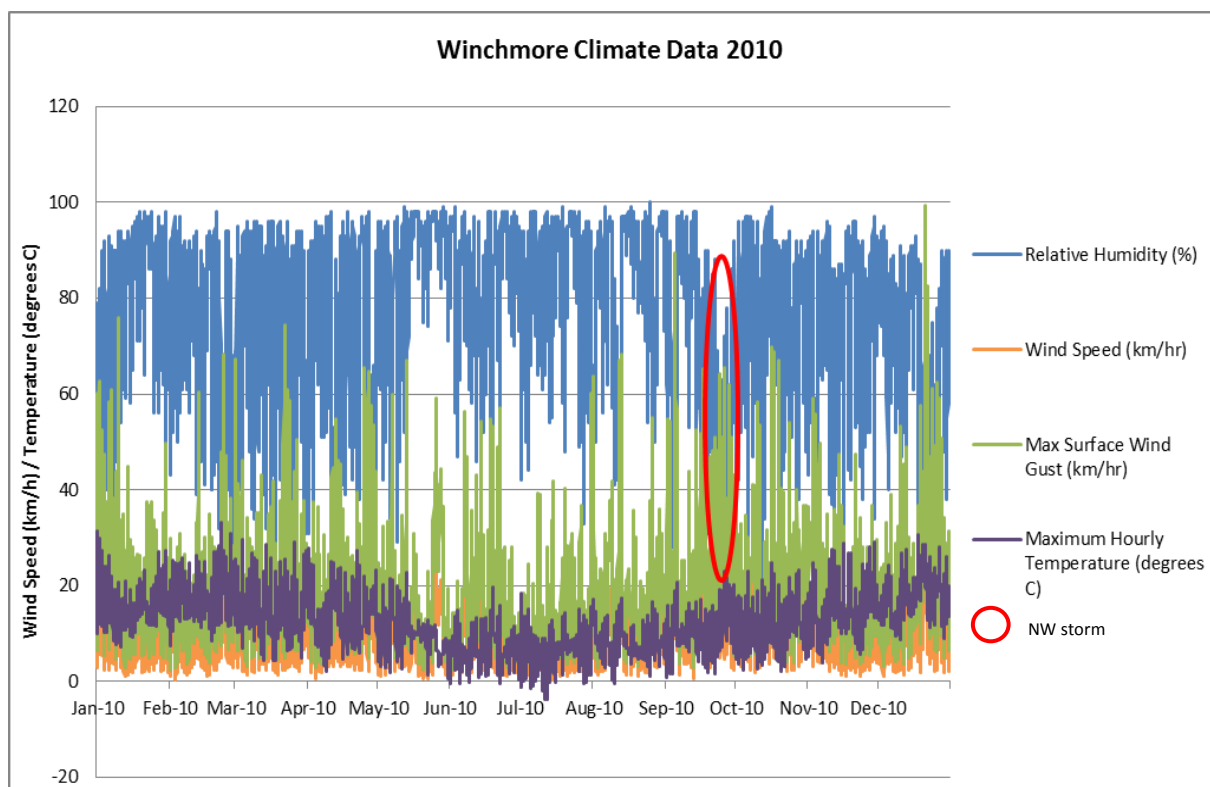


## Section 3 Results

### 3.1 Northwesterly Climate Characteristics

#### 3.1.1 Winchmore Climate

Figure 4 shows a plot of the hourly data for the period 1/01/2010 to 31/12/2010, for the Winchmore weather station. From this graph, NW storms can be seen, where both the hourly maximum temperature and maximum surface gust speed are high, and the relative humidity is low. One extreme example of this is circled in red, however many more can also be seen throughout 2010.



**Figure 4** Winchmore Climate Data 2010 (red highlighting one case of a NW storm)

### 3.1.2 Northwesterly Storm Definition

From the Winchmore data set, it was established that NW storms would be generally defined as a maximum temperature of 25°C or higher, wind gusts higher than 40km/h and relative humidities lower than 30%. The most important of these three components is the relative humidity, as this is the key characteristic of a NW storm.

The number of days with NW storm conditions for each month in 2010 were then quantified loosely using this definition. In addition, the hourly climate data was also graphed. Figure 5 shows the number of days per month, in 2010, that the Winchmore weather station experienced the NW storm conditions previously defined. As would be expected, these storms can be seen to occur in summer months, when air temperatures are higher due to increased solar radiation.

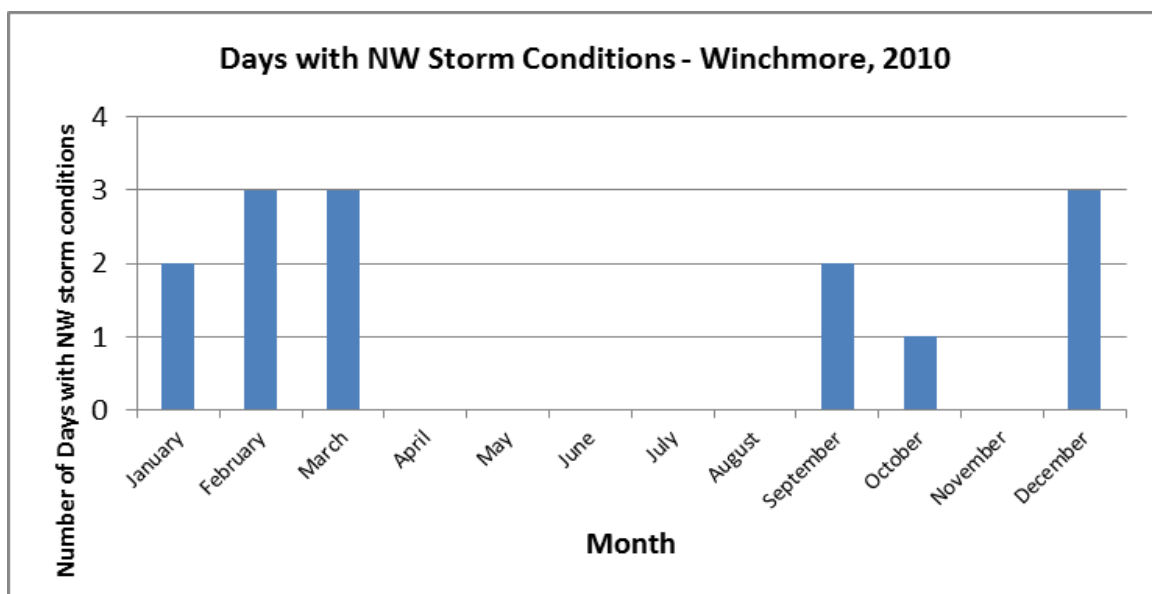


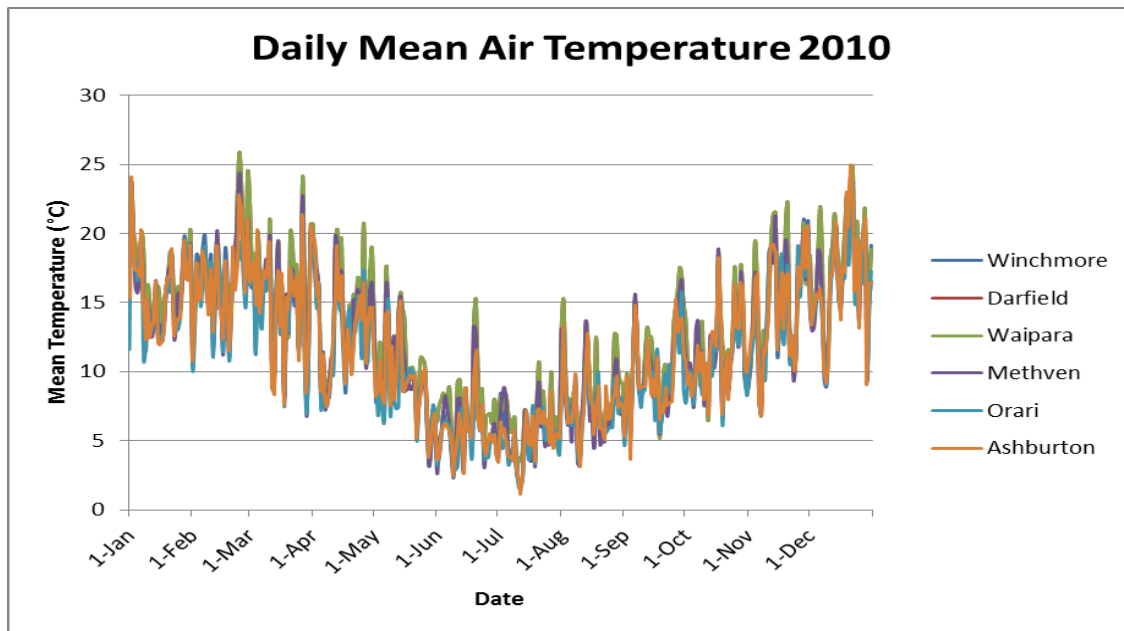
Figure 5 NW Storm Frequency, Winchmore, 2010

## 3.2 Effect of Northwesterly on Crop Evapotranspiration

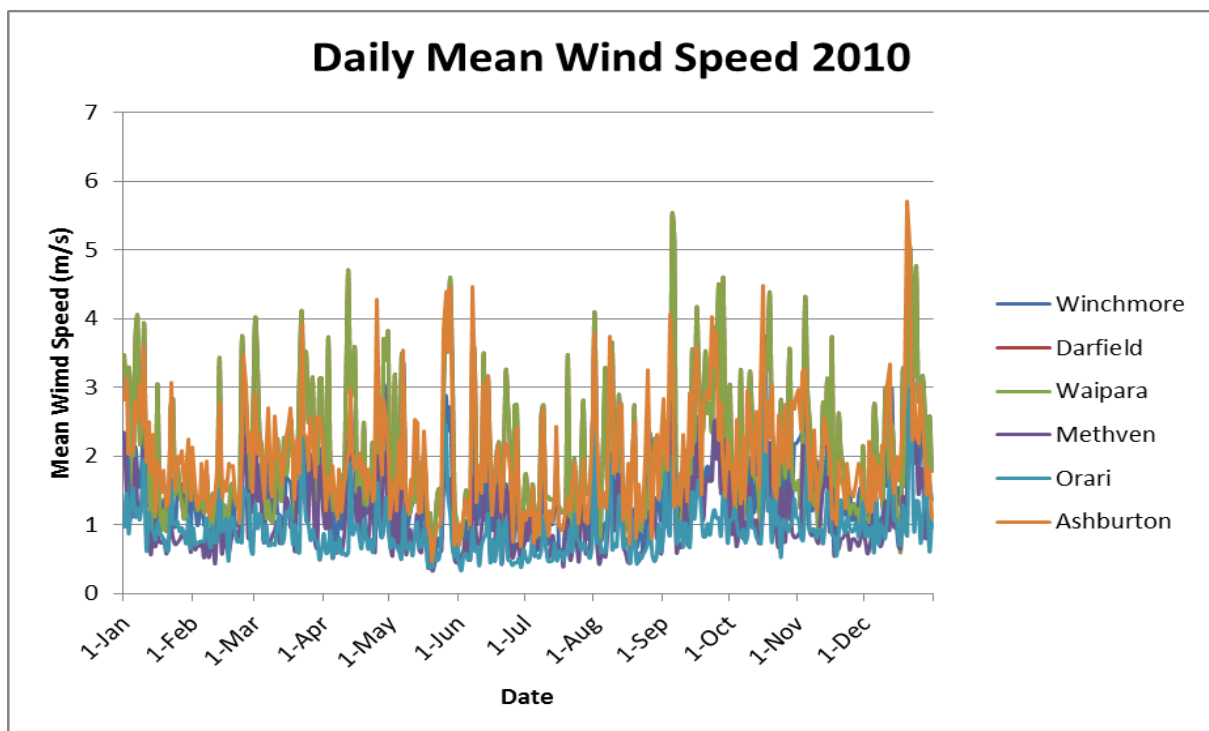
### 3.2.1 Raw Climate Data

Figures 6, 7 and 8 show the raw climate data for the six selected sites in 2010. There is an obvious trend in Figure 6, of higher temperatures in summer months (December through February) compared with winter months. This is to be expected, as during this time solar radiation is higher. The other two graphs show no real seasonal trend. However, in Figure 8, several dips in the average daily relative humidity can be seen. These correspond with NW storm days previously identified.

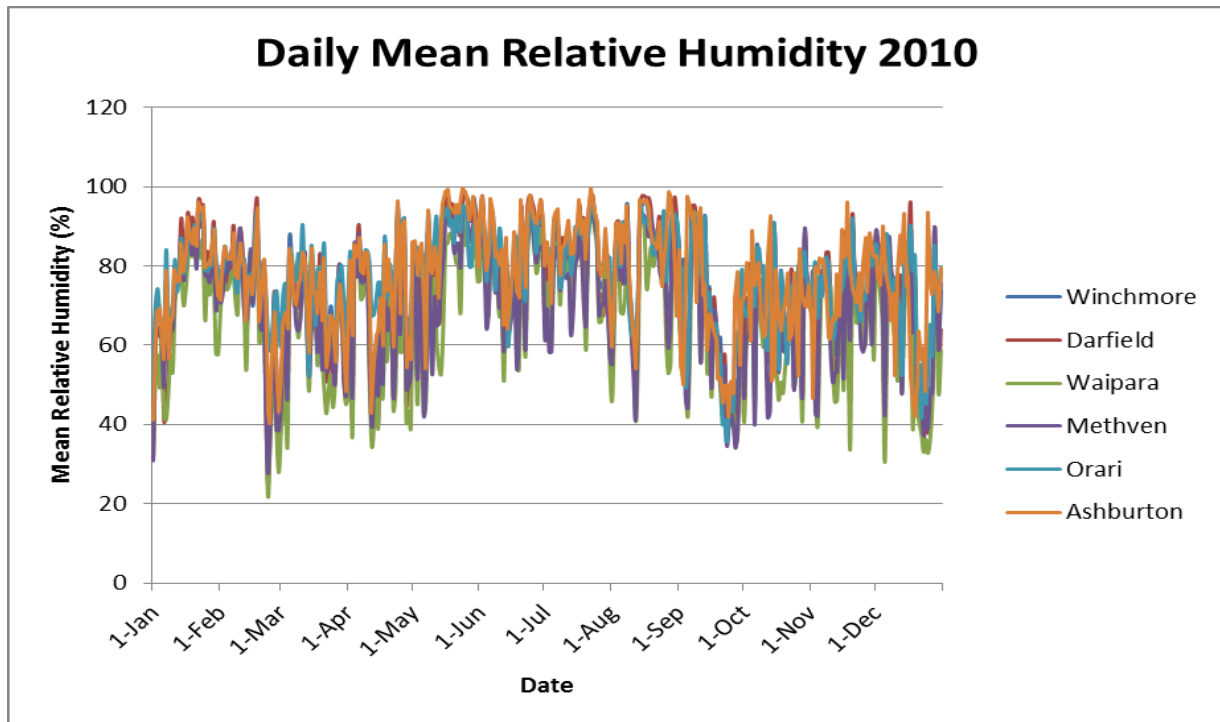




**Figure 6** Daily average temperature data for 2010



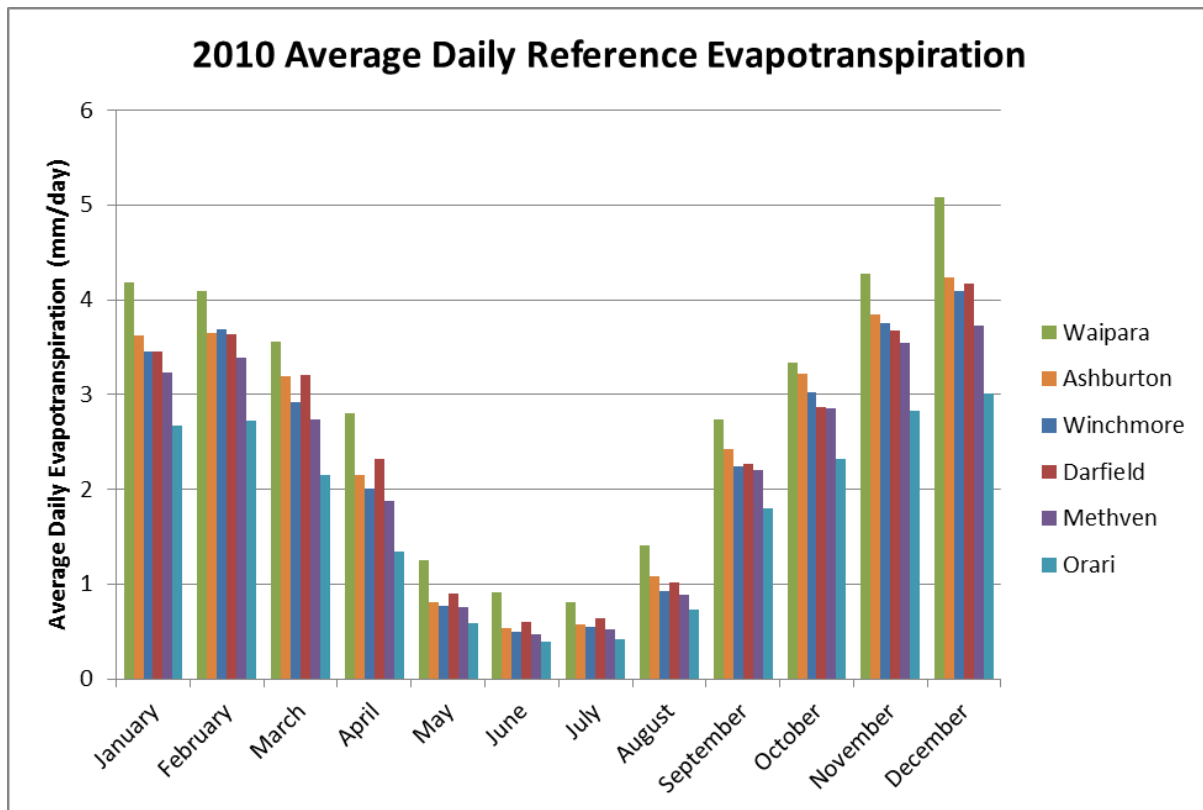
**Figure 7** Daily average wind Speed data for 2010



**Figure 8** Daily average relative humidity data for 2010

### 3.2.2 ASCE Standardised Reference Evapotranspiration

Figure 9 shows the calculated evapotranspiration values for the year 2010 for the six selected weather stations. An obvious seasonal variation can be seen, as would be expected – summer months have higher  $ET_0$  values due to increased air temperatures, a direct effect of higher solar radiation values. Location can also be seen to be important, both north to south and east to west. The highest daily evapotranspiration values occur at the Waipara station, which is also the most north and is near to the coast. Ashburton has generally the next highest evapotranspiration values. This station is located midway between the furthest north and south weather stations, however is near to the coast on the east. In addition, this site is located in a very sheltered valley, therefore temperatures will frequently reach very high temperatures. The remainder of the values generally follow the trend that the further north and to the coast (east) they are located, the higher the average daily evapotranspiration values.

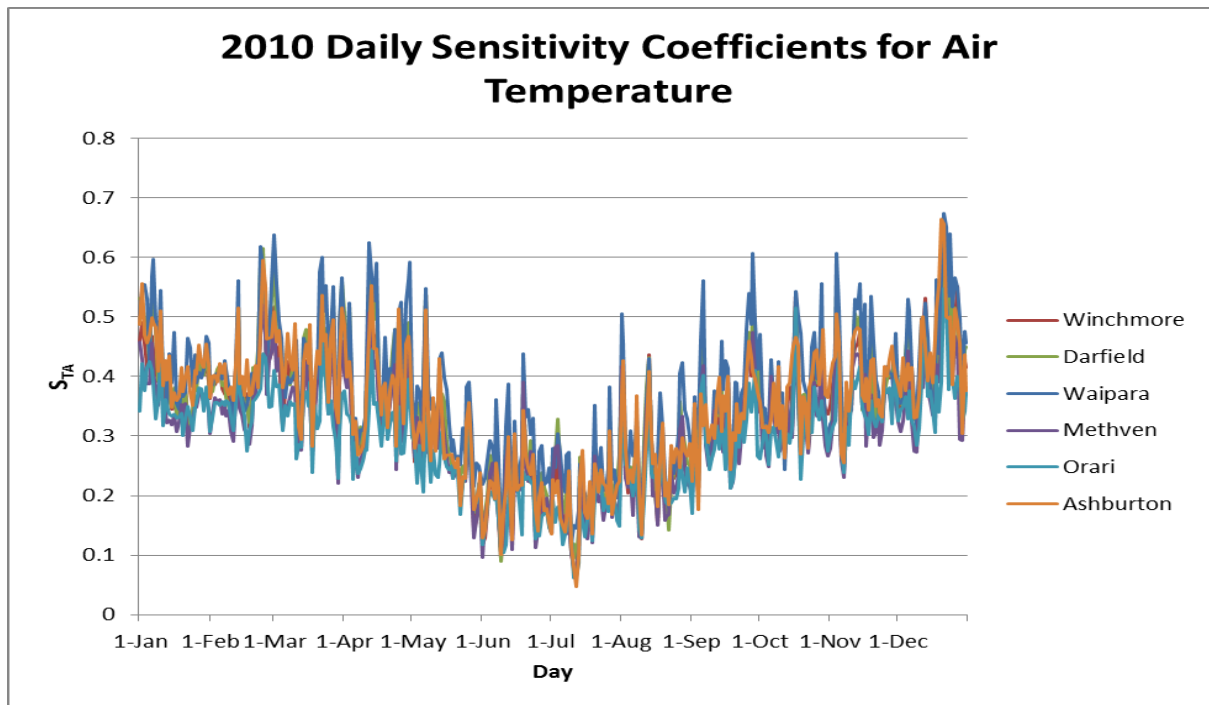


**Figure 9** Average Daily  $ET_0$  for 2010

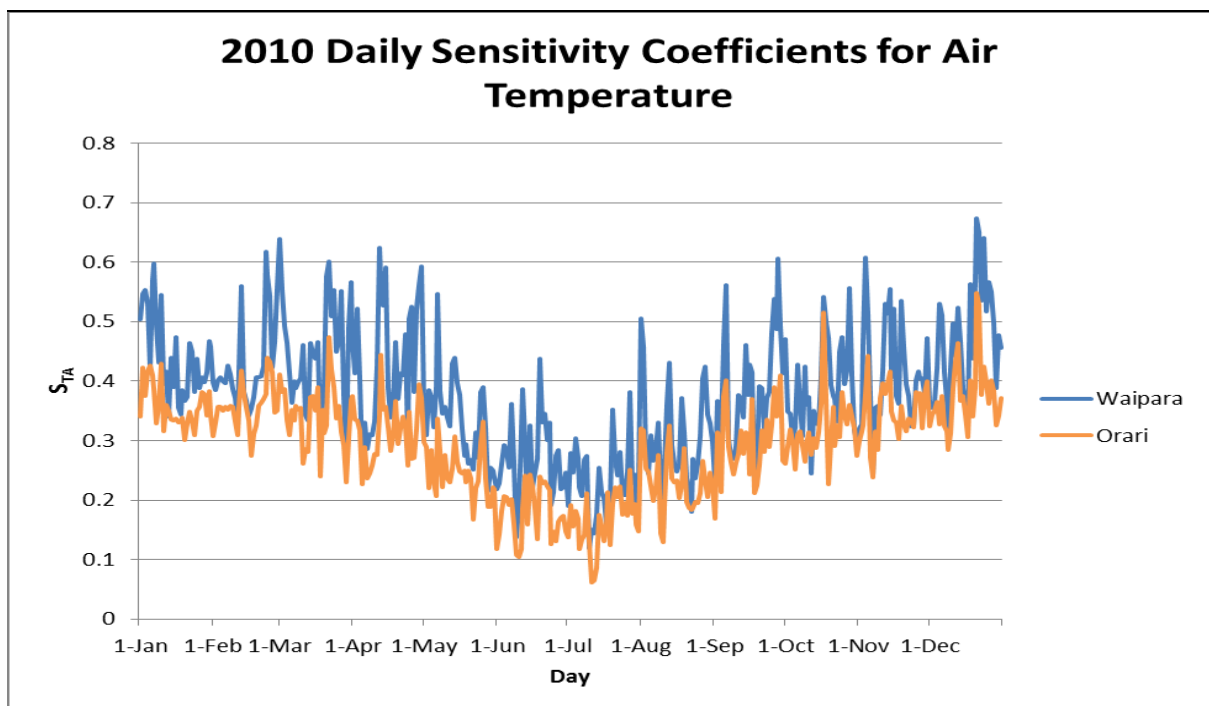
### 3.2.3 Sensitivity Analysis

The calculated daily sensitivity coefficients show large fluctuations throughout the 2010 year in all cases (Figures 10, 11, 12 and 13). Similar features have also been reported by Hupet and Vanclooster (2001) and Gong et. al (2006).

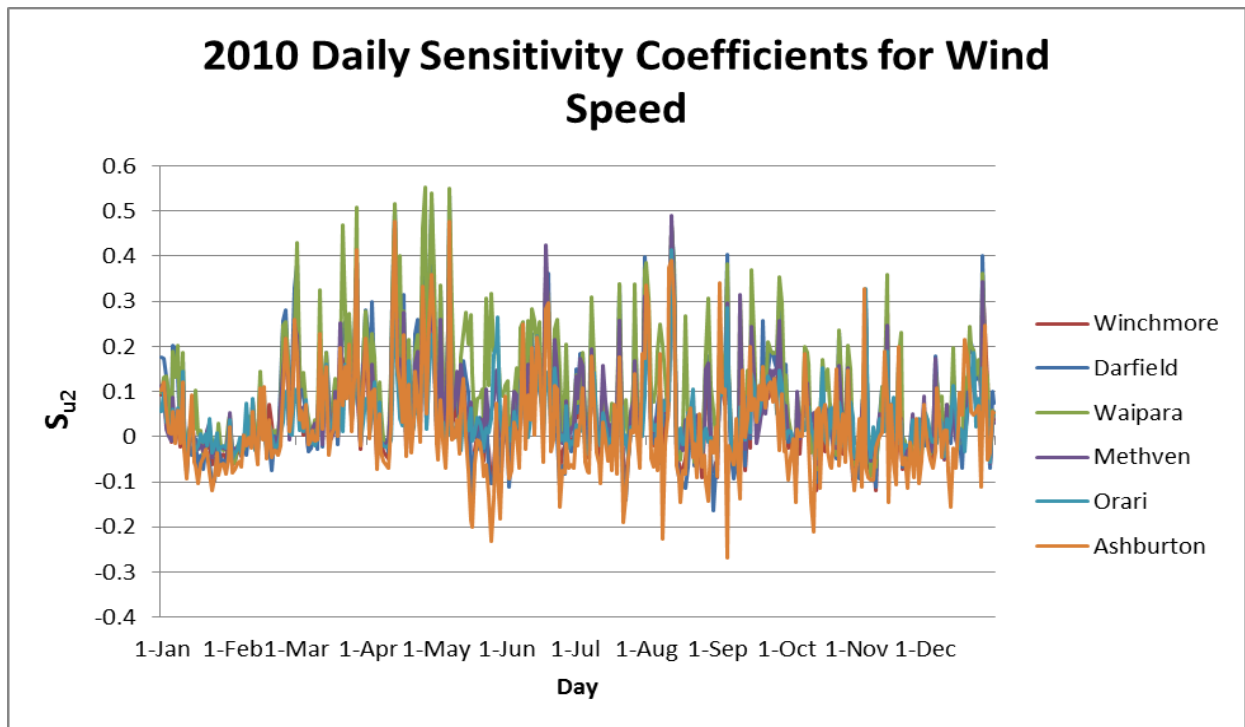
The 2010 daily variation patterns of  $S_{TA}$  (Figure 10) agree generally with those of air temperature shown in Figure 6.  $ET_0$  is relatively insensitive to air temperature in winter, and achieves its maximum value in summer of in most cases equal to or greater than 0.6 (Figure 10). With regards to spatial variation in sensitivity of  $ET_0$  to changes in air temperature, it is difficult to observe this in Figure 10. However when the two extremes of air temperature are graphed alone (Figure 11), it can be seen that  $ET_0$  at the location with the generally highest air temperature (Waipara) is more sensitive to changes in air temperature than the location with the lowest air temperature (Orari). These results can be generalised to say that the higher the average air temperature of a location, the more sensitive  $ET_0$  is to changes in air temperature. In terms of the NW storm, it can be said that the associated warmer temperatures will have more of an impact on locations with already higher temperatures.



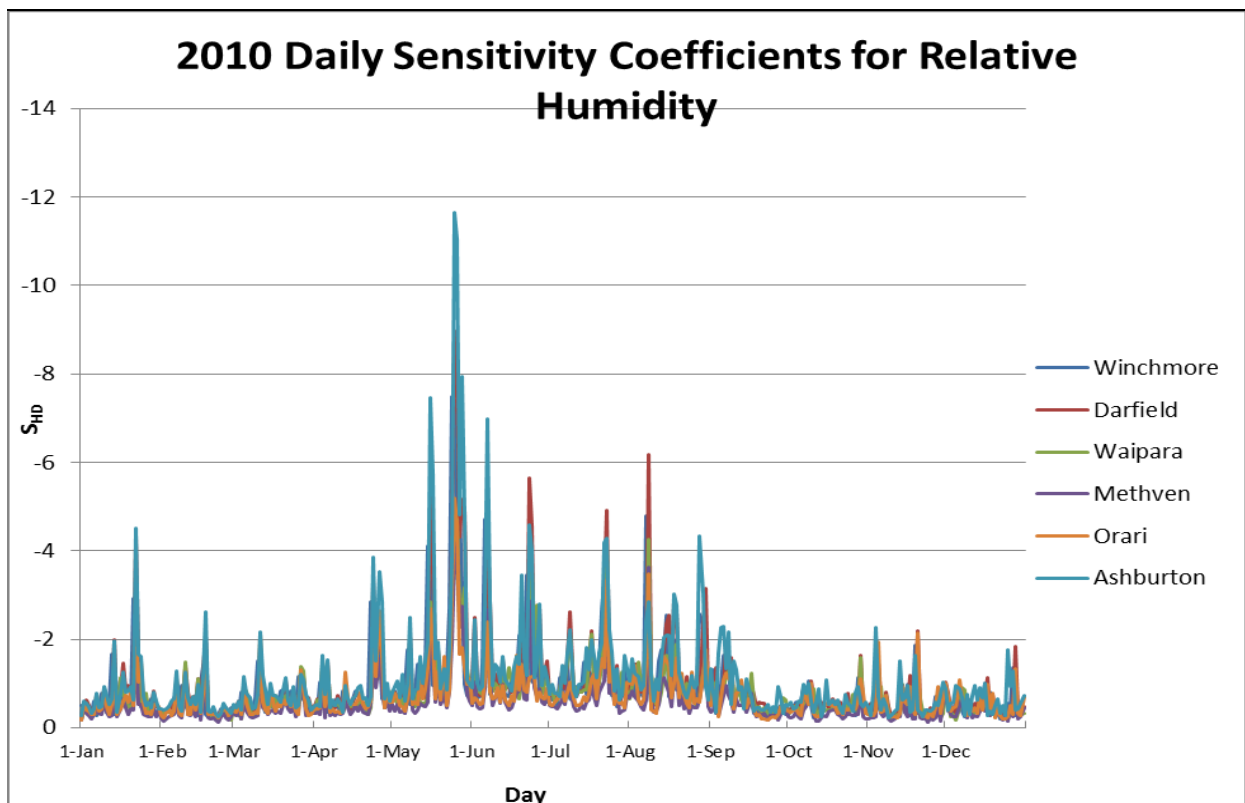
**Figure 10** 2010 Daily Sensitivity Coefficients for Air Temperature



**Figure 11** 2010 Daily Sensitivity Coefficients for Air Temperature (Waipara and Orari)



**Figure 12** 2010 Daily Sensitivity Coefficients for Wind Speed



**Figure 13** 2010 Daily Sensitivity Coefficients for Relative Humidity

With the data set used in this investigation, there is no clear pattern evident in the 2010 daily variation patterns of both  $S_{u2}$  and  $S_{HD}$  (Figures 12 and 13). In particular, the wind speed sensitivity coefficient can be seen to fluctuate from positive to negative, showing its extremely variable effect on evapotranspiration. Relative humidity is more consistent - in all cases an increase in relative humidity causes a decrease in evapotranspiration, as would be expected. This is important in terms of the NW storm as it means that under the associated dry conditions, ET would increase therefore crop water requirement would increase and irrigation demand would rise.

From the analysis completed using only data from one year (2010), it appears that the spatial variation of the wind speed and relative humidity coefficients is insignificant.

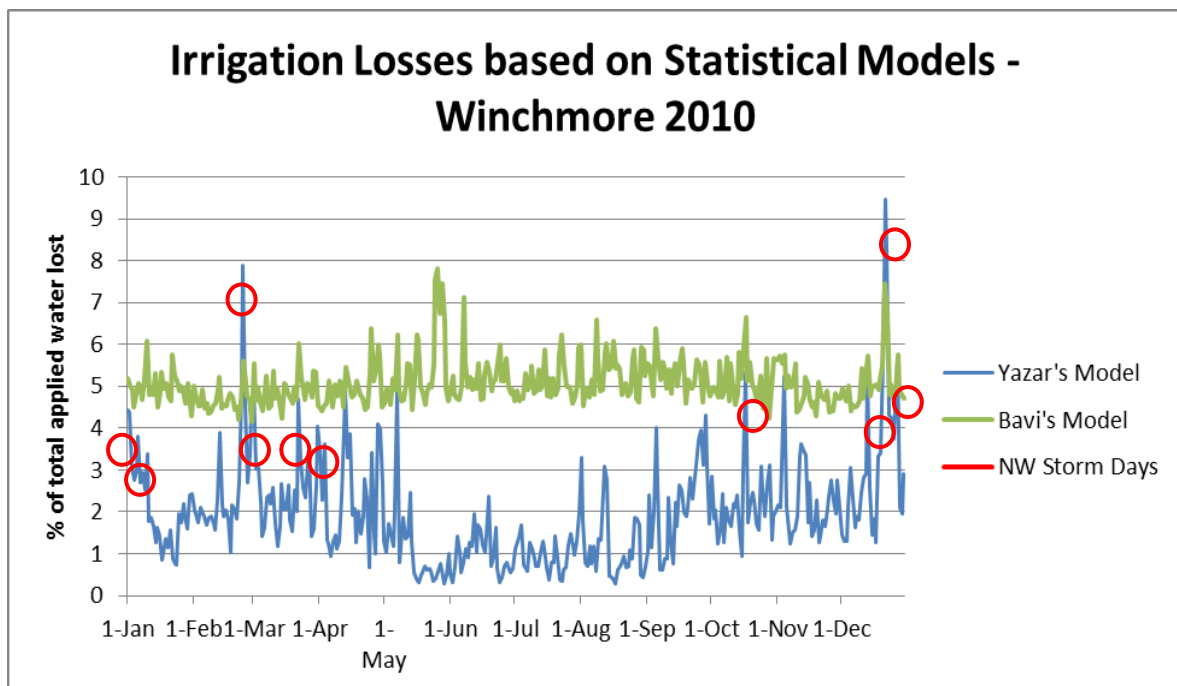
Overall, in general it can be seen that  $ET_0$  is most sensitive to changes in relative humidity at the daily scale. Variations in windspeed and air temperature were less influential, with variations in windspeed causing the least variation in  $ET_0$ .

### **3.3 Irrigation Efficiency and Uniformity in Northwesterly Storm Conditions**

#### **3.3.1 Yazar's Model & Bavi's Model**

The calculated daily evaporation losses for Winchmore in 2010 using each of the models are shown in Figure 14. From this graph it can be seen that for the majority of the year, the model created by Bavi et. al gives higher values for the percentage of water lost due to evaporation. Exceptions to this are seen in two instances, in late February and late December, where the model produced by Yazar results in a higher percentage of water lost due to evaporation.

Circled in red on Figure 14 are the days with NW storm conditions present, identified using the definition established earlier in this project. The line corresponding to Yazar's model has been circled as, from the graph, it can be seen that the effects of the NW storm are more significant using this model. Days where NW storm conditions are present cause significant peaks in the evaporation losses under Yazar's model. Bavi's model, on the other hand, only appears to be affected by the NW storm conditions to a very small degree. Also, the highest evaporation losses under Bavi's model are observed in the winter months. This may suggest that the evaporation losses under this model are more dependent on wind speed and relative humidity than air temperature, as these factors are only affected minimally by solar radiation so can still be at their extremes during winter (unlike air temperature).



**Figure 14** Irrigation losses based on Yazar's and Bavi's statistical models – Winchmore 2010

## **Section 4 Discussion**

### **4.1 NW Storm Definition**

The definition of a NW storm for this study was based on the climate data from one site alone, Winchmore EWS. This site is located in the mid-Canterbury Plains and therefore should be a good representation of the climate of the region as a whole. A more accurate definition could be established if climate data from a large number of sites, for example the six chosen later on in the project, were analysed instead. It may be possible that the climate variation across the Canterbury Plains is enough that several definitions need to be established, depending on a particular sites location. In addition, the NW storm frequency analysis should also be performed, using this new definition, across more than just one year of data.

### **4.2 Evapotranspiration**

The calculation of ASCE standardised reference crop evapotranspiration for six different sites was performed for the year of 2010. The evapotranspiration values were higher in summer, due to increased solar radiation during this season. As with the NW definition, more accurate and representative results could be obtained if the ASCE evapotranspiration calculations were performed for a larger range of data, (e.g. over a period of thirty years). However, seasonal and spatial patterns in evapotranspiration observed from 2010 data alone were as expected.

$ET_0$  was more sensitive to changes in air temperature in the summer season. This is interesting as summer is the time when the NW storm frequency is highest. As the NW storms characteristically bring high temperatures, they will therefore have an increased effect on the crop water requirement and therefore irrigation demand. In addition to this, the sensitivity analysis showed that a decrease in relative humidity causes an increase in  $ET_0$ . Again, one of the key conditions associated with a NW storm is a low humidity. Therefore, a higher crop water requirement will exist under NW storm conditions, again increasing irrigation demand. In this investigation, no relationship was found between the wind speed and relative humidity conditions.

### **4.3 Evaporation Modelling**

The statistical models of Yazar (1984) and Bavi et. al (2009) were used to calculate the possible losses of applied irrigation water due to evaporation, at Winchmore EWS in 2010. Evaporation rates of up to 8-9% are predicted during NW storms, with a mean rate of 1-5%. The calculated losses varied between models; Yazar's model showing more susceptibility to changing climate conditions, such as those that would be present under a NW storm. One reason for the variation could be the conditions for which each model was derived. Table 1



shows the temperature, wind speed and vapour pressure deficit ranges for the Winchmore 2010 data used, as well as for the climate conditions under which the two statistical models were determined.

**Table 1** Temperature, windspeed and vapour pressure deficit ranges

Location	Temperature Range	Wind Speed Range	Vapor Pressure deficit
<b>Winchmore</b>	1.75°C - 24.7°C	0.353m/s – 4.715m/s	0.218mbar - 19.0mbar
<b>Mead, NE (Yazar)</b>	18.9°C – 36.7°C	0.91m/s – 6.71m/s	4.16mbar – 33.14mbar
<b>SE Khuzestan Province, Iran (Bavi)</b>	19.8°C – 45.4°C	3.00m/s – 9.50m/s	0.70mbar – 8.90mbar

From Table 1, it can be seen that in both cases calculating the evaporation losses for Winchmore would often require extrapolation rather than interpolation. This is not recommended in statistical analysis, as predicting outside the range for which the model was established may cause errors. Because of this, accurate results would only be able to be found statistically from a model that was created using experimental data from the Canterbury Plains.

If Yazar’s model is correct however, it would suggest that under NW storm conditions, the losses due to evaporation alone would be significant enough (up to 10%) for alternative irrigation schedules to be considered. The actual losses under NW storm conditions would be even higher than this as the strong wind gusts also associated with a NW storm would cause additional losses and these are not accounted for in our models.

## **Section 5 Conclusions and Recommendations**

### **5.1 Conclusions**

Completing this investigation showed that the Northwesterly storm does increase the irrigation demand. It does this in two ways. Firstly, the extreme climate conditions associated with the storms, namely high air temperatures, strong winds and low relative humidities, cause increases in daily evapotranspiration values. This means an increase in crop water requirement and therefore an increased irrigation demand. Secondly, the extreme climate conditions also cause an increase in the amount of water lost due to evaporation, which occurs in the time water is travelling from the sprinkler to the canopy.

### **5.2 Recommendations**

The results obtained and conclusions made in this project will be useful in the field of irrigation engineering. However due to time constraints, many aspects of this research could not be investigated.

As a result, it is hoped that this research can be continued in this field, using the following recommendations.

#### **5.2.1 Sensitivity Coefficients**

The sensitivity coefficients method is potentially extremely useful in the field of irrigation engineering. However due to time constraints, only one year of data has been analysed using these methods so far. Performing the same calculations for the same six (or more) sites over a longer time frame, such as 30 or 40 years, and averaging the results would be a more meaningful. Obtaining average values for the sensitivity coefficients would cause random peaks and troughs to be eliminated. This is particularly the case with the wind speed and relative humidity coefficients, however it would be useful to analyse the air temperature coefficients in this way also.

It is also recommended that the results already obtained, or the results for a longer period of time, be interpreted further. Although the North to South variation has been analysed, it would be interesting to see if there is a northwest to southeast, or northeast to southwest variation in the sensitivity coefficients. The sites selected would enable this to be done, due to their location relative to each other.

### **5.2.2 Northwesterly Storm Index**

The results from the sensitivity analysis are useful for irrigation engineers, however for the general public, they mean very little as are difficult to understand. One way that would make the results from this analysis easier to comprehend would be to use them to establish a simple method to determine what would be called a 'Northwesterly Storm Index'. Using inputs of air temperature, relative humidity and wind speed, the index would give an indication of how 'bad' a NW storm actually is. As the sensitivity analysis has shown, the amount by which the  $ET_0$  changes with changes in the three factors varies depending on the climate variable of interest. Therefore, the results from the sensitivity analysis will be largely used in the creation of the NW Storm Index.

### **5.2.3 Wind Drift Losses Model**

Like has been done with the evaporative losses, it would be useful to find a statistical model that calculates the amount of water lost due to wind drift under various climatic conditions. Several pieces of literature have been found that do this, however combining them together or determining which one is the more relevant would take some time. It is recommended that this is done in the future and the results of this analysis be combined with the evaporative losses model to establish a model for the total losses.

### **5.2.4 Theoretical Loss Models**

Literature has been found that theoretically models irrigation losses due to evaporation under wind drift. In the future, these models could be combined and applied to the NW storms on the Canterbury Plains. The results could then be compared to the losses calculated statistically and any differences explained.

### **5.2.5 Creation of Canterbury Plains Statistical Loss Model**

As has been seen in this project, it is difficult to apply statistical models to a particular location, when they have been derived from conditions at another site completely. To solve this problem, it is recommended that a statistical model be established for the Canterbury Plains under NW storm conditions. This could be done by using the electrical conductivity method referred to previously, to measure the actual amounts of water lost due to wind drift and evaporation. This would largely eliminate the problem of extrapolation that exists with the two models used.

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## Notation

$ET_o$	= reference evapotranspiration ( mmday <sup>-1</sup> )
$R_n$	= net radiation at the surface (MJm <sup>-2</sup> day <sup>-1</sup> )
$G$	= soil heat flux (MJm <sup>-2</sup> day <sup>-1</sup> )
$\gamma$	= psychrometric constant (kPa°C <sup>-1</sup> )
$\Delta$	= slope of saturation vapour pressure curve (kPa°C <sup>-1</sup> )
$T_{mean}$	= mean temperature at 2m height (°C)
$u_2$	= mean daily wind speed at 2m height (ms <sup>-1</sup> )
$e_s$	= saturation vapour pressure (kPa)
$e_a$	= actual vapour pressure (kPa)
$S_{vi}$	= sensitivity coefficient for the <i>ith</i> variable
$V_i$	= <i>ith</i> variable
$E$	= % of discharged flow lost to evaporation
$W$	= wind speed at 2m (m/s)
$(e_s - e_a)$	= vapour pressure deficit (kPa) or (mbar)
$u$	= wind velocity at 2m (mil/h)

## Appendix 1: Mathematica Script for Sensitivity Coefficient Calculation

```

"Process to calculate evapotranspiration"
P=101.3*((293-0.0065*H)/293)^5.26;
γ=0.000665*P;
Δ=2503*Exp[(17.27*TA/(TA+237.3))]/(TA+237.3)^2;
es=0.6108*Exp[17.27*TA/(TA+237.3)];
ea=HD/100*es;
φ=π/180*LAT;
δ=0.409*Sin[2*π*DAY/365-1.39];
Ws=ArcCos[-Tan[φ]*Tan[δ]];
dr=1+0.033*Cos[2*π*DAY/365];
Ra=24/π*4.92*dr*(Ws*Sin[φ]*Sin[δ]+Cos[φ]*Cos[δ]*Sin[Ws]);
Rso=(0.75+(2*10^(-5))*H)*Ra;
Rsso=Min[RS/Rso,1];
fcd=1.35*Rsso-0.35;
Rnl=(4.901*10^(-9))*fcd*(0.34-0.14*Sqrt[ea])*(TA+273)^4;
Rns=(1-0.23)*RS;
Rn=Rns-Rnl;
et=(0.408*Δ*Rn+γ*(900/(TA+273))*u2*(es-ea))/(Δ+γ*(1+0.34*u2));

"Analytical determination of sensitivity coefficients"
a=TA/et;
b=u2/et;
c=HD/et;
a1=D[et,{TA,1}]*a;
a2=D[et,{u2,1}]*b;
a3=D[et,{HD,1}]*c;

"Importing specific climate variable data to calculate numerical
sensitivity coefficients and ET values"
TA=Import["L:\\Summer Projects\\Northwester Irrigation Efficiency\\Climate
Study\\Mathematica\\Variables\\TA.csv"];
HD=Import["L:\\Summer Projects\\Northwester Irrigation Efficiency\\Climate
Study\\Mathematica\\Variables\\HD.csv"];
H=Import["L:\\Summer Projects\\Northwester Irrigation Efficiency\\Climate
Study\\Mathematica\\Variables\\H.csv"];
LAT=Import["L:\\Summer Projects\\Northwester Irrigation Efficiency\\Climate
Study\\Mathematica\\Variables\\LAT.csv"];

```

```
RS=Import["L:\\Summer Projects\\Northwester Irrigation Efficiency\\Climate  
Study\\Mathematica\\Variables\\RS.csv"];  
DAY=Import["L:\\Summer Projects\\Northwester Irrigation Efficiency\\Climate  
Study\\Mathematica\\Variables\\DAY.csv"];  
u2=Import["L:\\Summer Projects\\Northwester Irrigation Efficiency\\Climate  
Study\\Mathematica\\Variables\\u2.csv"];
```



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