

Technical Memorandum #7:

**Investigation of the
Relationship between
Cloud Cover and
Temperature in the
Puget Sound Region and
its Implication on
Climate change**

Prepared for:

**Climate Change Technical
Committee**



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The report benefited from the committee members, including:

| Member | Affiliation |
|--|---|
| Jane Lamensdorf-Bucher | King County Department of Natural Resources and Parks – Committee Chair |
| James Battin | NOAA |
| Geoff Clayton | Woodinville Water District Commissioner, Position 4 |
| Holly Coccoli | Muckleshoot Tribe |
| Jefferson Davis | City of Kent |
| Paul Fleming | Seattle Public Utilities |
| Paul Hickey | Tacoma Water |
| Joan Kersnar | Seattle Public Utilities |
| Erin Leonhart | City of Kirkland |
| Maher Maher | Steward and Associates |
| Bruce Meaker | Snohomish PUD |
| Jim Miller | City of Everett |
| Phil Mote | University of Washington, Speaker |
| Steve Nelson | RH2 Engineering |
| Kelly Peterson | City of Kent |
| Jim Simmonds | King County Department of Natural Resources and Parks |
| Amy Snover | University of Washington, Principal, Climate Impacts Group |
| Chris Thorn | City of Auburn |
| Kurt Unger | Washington State Department of Ecology |
| Seshu Vaddey | US Army Corps of Engineers |
| Lara Whitely Binder | University of Washington, Climate Impacts Group |
| Facilitator and Technical Support Staff | |
| Tamie Kellogg | Committee Facilitator – Kellogg Consulting |
| Richard Palmer | Technical Lead, University of Washington, Principal Climate Impacts Group |
| Eset Alemu | Technical Support Staff, University of Washington |
| Donee Alexander | Technical Support Staff, University of Washington |
| Ben Enfield | Technical Support Staff, University of Washington |
| Kathleen King | Technical Support Staff, University of Washington |
| Courtney O'Neill | Technical Support Staff, University of Washington |
| Austin Polebitski | Technical Support Staff, University of Washington |
| Lee Traynham | Technical Support Staff, University of Washington |
| Matthew Wiley | Technical Support Staff, University of Washington |

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Technical Memorandum #7: Investigation of the Relationship Between Cloud Cover and Temperature in the Puget Sound Region and Its Implication on Climate Change

Introduction

This research investigates the relationship between cloud cover and temperature and its implication on climate in the Puget Sound region, specifically the area in and around King County, Pierce County and Snohomish County. The research uses statistical analysis to identify factors influencing the change in distribution of cloud cover. It also identifies highly correlated surrogates of climatic variables to identify the change in cloud cover. The study investigates only the spring and summer seasons. These seasons are chosen as they are the periods during which the region's water demands are the largest. The research question that motivates this research is "Will future increases in temperature result in increasing cloudiness in the Puget Sound." The research also tests hypotheses pertaining to the regional relationships between cloud cover and temperature variables.

The premise for the study of relationship between temperature and cloudiness is that cloudiness in Western Washington is driven by climatic factors in Central Washington. It is common local knowledge in the Northwest that the two sides of the Cascades experience different temperatures. While the Western coast of Washington is smothered with fog and low clouds, inland areas east of the Cascades are usually sunny. It is common for Western Washington to begin the day under clouds or fog which burn away by mid- to late-morning. It has been suggested that cloudiness in Western Washington is highly influenced by pressure gradient movements and climatic variations that occur east of the Cascades.

Studies indicate that regional-scale processes that affect cloudiness, especially along the coast, can not be effectively captured by global models (Zhang, 2004). A combination of observational and modeling studies is required to better understand the relationship between climate and cloudiness in the Puget Sound region (Salathe et al., 2007). The potential impacts of climate change on cloud cover in the Puget Sound region has been shown in Chapter 10 of the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (found at <http://ipcc-wg1.ucar.edu/wg1/wg1-report.html>). A multi-model ensemble shows projections of decreases in cloud cover at much of the low and middle latitudes (Figure 1) as well as a projection of increase of cloud cover off of California coast. Rather than relying on forecasts of clouds cover from models, this report focuses on historical data in the Puget Sound and in Central Washington.

Data Sources

The data used in this research includes cloud cover observations that estimate the percentage of the sky covered with clouds at approximately hourly intervals (recorded from 15 to 24 times a day). These observations record cloudiness on a scale from 0 (clear skies) to 10 (100% cloud cover). These records do not explicitly measure fog or ground level clouds. Three sites with long records of cloud cover have measurements starting as early as 1948 and extending to 1996. The system was automated in 1996, changing cloud cover measurement and protocol. The new system uses a

ceilometer that derives cloudiness at or below 12,000 feet, while past measurements reported higher clouds. The difference in units between the two types of recording methods currently prevents integrating the two data sets. Technical difficulties exist in converting the sky cover codes into equivalent units for comparison to those taken using the previous scale (0 to 10). Table 1 lists the stations that served as sources of hourly cloud cover and temperature. The data set used was purchased from EarthInfo and made available by King County for this research.

Other temperature data used are obtained from the Cooperative Stations network, a system operated by the National Climatic Data Center (NCDC) (Table 2). These stations are distributed throughout the US, with data available online via the NCDC website. These data are used to obtain daily maximum and minimum temperature for stations in counties lying to the east of King, Pierce, and Snohomish counties, which are referred to as the “Central Washington Stations” as well as two counties to the South and one in the Northwest part of the state (Figure 2). Meteorological stations in Chelan, Kittitas, Yakima and Klickitat counties are used to create the an average Central Washington temperature index, while stations in Lewis, Thurston and Clallam are used along with stations in King, Snohomish and Pierce counties as Western Washington temperature indices. The data have been thoroughly reviewed for consistency.

Evaluation of Data

Statistical Methods

The hourly cloud cover and temperature measurements were converted to daily values by taking the arithmetic average of hourly values. Daily maximum and minimum temperature recordings were extracted from hourly measurements obtained from the NCDC database. The time series representing the diurnal temperature variations were then constructed as the difference between the daily maximum and minimum temperatures. A time series of daily cloud cover, diurnal temperature variation and daily maximum temperature measurements were constructed. The longest complete historical time series is 48 years in length (at the Sea-Tac meteorological station) while the other records are very near the same length, (47 and 46 years for Olympia and Stampede Pass).

A relationship between cloud cover in the region and average diurnal temperature variation and maximum temperature during spring and summer months was sought. Three locations (Sea-Tac, Olympia, and Stampede Pass) were used to construct daily average cloud cover, daily average diurnal temperature and daily average maximum temperature standard normals for the April 1 through August 31 time period. These data were transformed into standard normal variables by subtracting the seasonal mean of each station observation and dividing it by the seasonal standard deviation. The seasonal mean refers to the mean of the daily average temperatures between the months of April and August.

Relationship between cloudiness and diurnal temperature ranges

The first relationship explored is between cloudiness and the diurnal temperature range. Figure 3 presents the results of a linear regression of the standardized cloud cover values and standardized average diurnal temperature variation. The regression indicates a very high coefficient of determination (R^2) for all three of the stations. The slopes of the three regression lines are almost identical; indicating that the relative impact of cloud cover on diurnal temperature range on each of

the three stations is similar. In addition, the variability of the data is greatest when cloud cover is above normal and temperatures are below normal, and the variability of the data is least when cloud cover is below normal and temperatures are above normal.

Relationship between cloudiness and maximum temperature

Next, the relationship between cloudiness and maximum temperature is explored. The same technique is used in converting maximum temperatures to normal variables as in the previous analysis. Figure 4 illustrates the significant correlation between cloud cover and maximum daily temperature when the temperature is above average. When temperature is below average, the correlation between the two variables is not as significant.

For further exploration, the maximum temperature variables for Sea-Tac station are segregated into monthly categories (Figure 5). The figure indicates a more discernable relationship between cloud cover and maximum temperatures for the months of June, July, and August, than seen in the months of April and May. From these figures, it is clear that there is a significant correlation between maximum temperature and cloud cover in the warmest months. Increased cloud cover is known to reduce the region's maximum temperature and the range of temperatures that are experienced.

Comparative analysis of Western and Central WA temperature variables

Next, the relationship between temperature in Western Washington and Central Washington is explored. The seasonally normalized, diurnal temperature variations come from three stations (Sea-Tac, Everett, and Landsburg) in the counties under study, two additional stations to the west, (Olympia and Centralia) and one station on the Western coast of the state (Forks). The average Central Washington temperature was obtained by averaging temperature variables of several stations in Central Washington, located in counties of Chelan, Kittitas, Klickitat and Yakima Counties. The daily maximum temperature and the diurnal temperature variation for these stations were averaged to acquire the average Central Washington maximum temperature and diurnal temperature variation.

To ensure the accuracy of these values, an extensive data consistency evaluation was conducted to ensure completeness (no gaps in time) of the time series from 1948 to 1996. This resulted in the elimination of 25 out of 40 stations in the four counties, thus leaving fifteen stations upon which to base the analysis. The criteria that were used for evaluating the stations in Central Washington were: observations starting by or before 1948, continued observations through 1996, and continual observations with less than a one year gap in the dataset.

In regressing seasonally normalized maximum temperatures of six Western Washington stations against average Central Washington maximum temperature standards (Figure 6), a high coefficient of determination was found (higher than 0.95 for all six Western stations). The linear correlation had little scatter until reaching one standard deviation on both axes. This occurrence of greater spread of the above average Western Washington temperatures can be attributed to the higher temperature peak in Central Washington. Although there is a strong relationship between standardized temperature between Western Washington and Central Washington, it can be seen from the graph that the two parts of the state do not warm to the same extent.

For further analysis, the maximum temperature of Western Washington was plotted against the average Central Washington temperatures for 48 years of data for the months of July and August (Figure 7). The cluster of points above 35°C on the Central Washington axis for both the months of July and August show that Central Washington warms by at least 5°C more during these summer months for the historical time series. Between the clusters of points it can be seen that Western Washington reaches an upper limit for warming that is exceeded by Central Washington warming.

The average diurnal temperature ranges at the representative stations in Western Washington show good correlation to average Central Washington diurnal temperature ranges with the lowest coefficient of determination 0.54 (Figure 8). This regression exhibits a higher y intercept as well as a cluster of points relating the highest Western Washington seasonal standards and associated Central Washington highs. Plotting the monthly progression of diurnal temperature ranges of all Western stations and the average Central Washington diurnal temperature range shows the increased fluctuation of Western Washington stations when compared to Eastern Washington averages. This might be attributed to the higher influence of coastal weather variability in addition to cloudiness.

The Inland Heating Effect Hypothesis

Based on the relationship between cloudiness and temperature variations at a station and the relationship between average Central Washington maximum temperatures and Western Washington cloudiness, a hypothesis is formulated that reflects on the relationship between cloudiness in Western Washington stations and its Central Washington neighboring counties. The hypothesis suggests that inland heating of Central Washington draws colder air to the Puget Sound. This hypothesis addresses one of the research questions that theorizes that the Seattle area might become more cloudy (and thus cooler) as Eastern Washington warms in the future. This premise was tested by regressing the regional temperature variables and cloud cover against the average Central Washington diurnal temperature variations and maximum temperature. The hypothesis would be supported by past data if there was a relationship between increasing Central Washington temperatures and increasing cloudiness in Western Washington.

The regional average temperature values were averaged at a daily time-step for the 48 years and were seasonally normalized for the summer months of June 1 through August 31 with the same statistical techniques used on the previous investigations. The months of June through August were chosen so as to represent the high pressure months in which a distinct cloud cover and temperature relationship exists, which is seen on Figure 9. A linear regression was created relating the average Central Washington standardized maximum temperatures and cloud cover standardized variables from Western Washington (Figure 9). The regression exhibits an inverse linear relationship between the two variables associated with a very high coefficient of determination (R^2) for all three Western Washington stations. The nearly identical slopes of the regression line indicate that the state of temperature in Central Washington has a similar effect on the cloudiness in the region. This relationship does not prove the hypothesis that there is a pull of cold marine air as a result of inland heating but incidentally is not enough to disprove the premise either.

An alternate explanation for the relationship is the commutative relationship between Western Washington cloud cover, Western Washington maximum temperatures and average Central Washington maximum temperatures. Since there is a high correlation between cloud cover and Western Washington maximum temperature and Western Washington maximum temperature and average Central Washington temperature, the high correlation evident between Western Washington cloud cover and average Central Washington (Figure 9) could be a result of the regional temperature consistency.

The Air-Conditioning Effect Hypothesis

A second major hypothesis devised for relating the overall progression of cloudiness in the spring and summer to the progression of temperature changes in the same time period was to test for the existence of an “air conditioning” effect. It investigates the climate-induced changes in cloud cover on a regional scale. The term “air-conditioning” refers to the “pull” of colder and denser air from the Western coast of the state into the Puget Sound area in response to the warming of Central Washington. This phenomenon can be explained by the Cascade Mountains blocking off the cool ocean air, causing hot air to rise to the east of it, which in turn creates a kind of vacuum that draws marine air bearing low clouds. If this is indeed a common phenomenon, it would be exhibited by consecutive hot days in Central Washington followed by increased cloudiness in Western Washington.

This hypothesis calculates the cross covariance coefficient for the number of lags (measured in days) between cloudiness at a station in Western Washington and average maximum temperature of Central Washington. This allows evaluation of the degree to which consecutive days of high temperature and cloudy days are delayed. This was calculated by plotting the cross covariance relationship between the daily measurements of maximum temperature in Central Washington and cloud cover observations in Western Washington. The cloud cover observations used are from the Sea-Tac weather station, which is one of the region’s most reliable stations. This hypothesis would be supported by a cross covariance relationship plot that exhibits a high negative peak at present day (point 0) with an increasing signal toward positive correlation and peaks within 5 or more days.

While the cloud cover time series is taken solely from Sea-Tac, the maximum temperature time series used in the analysis is the average of Central Washington maximum temperatures. This was used to provide the appropriate regional scale. The variables to be analyzed are daily measurements of cloud cover and maximum temperature of two months taken from the warmest years chosen from a historical time series of 48 years. The warmest months were chosen based on the condition that it showed a maximum temperature greater than 24° C for more than 20 days in a month, for the months of July-August. These years were chosen so as to be able to clearly observe a distinct air conditioning effect taking place. An investigation of the average Central Washington maximum temperatures identified 11 years of such conditions for the months of July and August.

The time series composed of the warmest July-August months in all the historical data series were analyzed for cross-covariance and the associated lag. The cross covariance between the time series of maximum temperature and cloudiness were used to find the lag time, shown by the distance from point 0 on the plot. A significance level was assigned to extract the statistically significant covariance relationship, which is indicated by the dotted, blue lines in the covariance plots.

No consistent pattern in the covariance relationship between cloud cover and average Central Washington maximum temperature was detected (Figure 10). The highest covariance relationship is seen at present day followed by a decay towards a positive covariance which would indicate an occurrence of both warm and cloudy days. The year 1972, found on the first column and second row in Figure 10, provides an example of what the air conditioning effects cross covariance plot would look like. It embodies a distinct decay towards positive correlation, which is needed to prove the hypothesis, but is not replicated by the other 10 hot years. The covariance plots at the other stations are rarely positively correlated, which can be attributed to the high degree of inverse correlation between maximum temperature and cloudiness at that station. From these cross covariance relationships it is difficult to ascertain if high temperature is the driving force behind cloudiness in Western Washington.

Conclusions

There is strong statistical evidence that diurnal temperature range is highly correlated (inversely) to cloudiness. This relationship is most apparent in high diurnal temperature ranges being associated with less cloudiness and low temperature ranges associating with more cloudiness. This inverse relationship also extends to the relationship between cloud cover and maximum temperatures. It is important to note that the above correlations show climatic relationship but not cause-effect relationship between cloudiness and temperature.

The “air conditioning” phenomenon, which is an increase in cloudiness in the Puget Sound and cooler temperatures due to a warming in Central Washington, was not demonstrated in this research. This hypothesis has failed to explain the relationship between inter-regional climatic trends of cloudiness and high temperatures. This can be attributed to the greater role other climatic variables, such as pressure variations and storm fronts that influence cloud movements inland. One of the initial questions of the study addressing the relationship between increasing cloudiness and increasing inland temperatures has not been adequately answered. Results of the hypothesis suggest that there are larger climatic factors that draw clouds inland. The global models attempt to simulate changes in cloudiness, but there is considerable disagreement among the various models on the changes in the Puget Sound (Zhu et al., 2007).

The current approach to model a change in the diurnal cycle, used by the Climate Impacts Group, precludes interpolation of future cloudiness from the above stated relationships. The maximum and minimum temperatures can be archived from many of the global models, as well as from the regional model simulations, and used to construct the diurnal temperature range. The resulting dataset could be used to extrapolate future states of cloudiness.

Future changes in climate are projected to bring about a decrease in the diurnal temperature range in the Northern Hemisphere (Karl et al., 1993). The Fourth Assessment Report of the Intergovernmental Panel on Climate Change has also projected a faster increase in daily minimum temperatures as compared to daily maximum temperatures. This is associated with a decrease in the diurnal temperature range in the middle and high latitude (Figure 11).

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Tables and Figures

Table 1: Locations and Sources of hourly cloud cover and temperature observations

| <i>Station name</i> | <i>County</i> | <i>Climatic Data</i> | <i>Source</i> | <i>Length of Data</i> |
|---------------------|---------------|----------------------|---------------|-----------------------|
| Sea-Tac | King | Cloud cover | EarthInfo | 01/1948 to 10/1996 |
| Olympia | Thurston | Cloud cover | EarthInfo | 01/1948 to 10/1995 |
| Stampede Pass | Kittitas | Cloud cover | EarthInfo | 01/1948 to 01/1994 |

Table 2: Locations and Sources of daily temperature observations

| <i>Station name</i> | <i>County</i> | <i>Climatic Data</i> | <i>Source</i> | <i>Length of Data</i> |
|---------------------|---------------|----------------------|---------------|-----------------------|
| Sea-Tac | King | Temp | NCDC | 10/1927 to 12/2005 |
| Landsburg | King | Temp | NCDC | 10/1927 to 10/2003 |
| Forks | Clallam | Temp | NCDC | 10/1927 to 6/2004 |
| Everett | Snohomish | Temp | NCDC | 10/1927 to 10/2003 |
| Centralia | Lewis | Temp | NCDC | 10/1927 to 07/2004 |
| Olympia | Thurston | Temp | NCDC | 01/1948 to 07/2004 |
| Leavenworth | Chelan | Temp | NCDC | 05/1914 to 06/2007 |
| Plain | Chelan | Temp | NCDC | 04/1937 to 06/2007 |
| Stehekin | Chelan | Temp | NCDC | 01/1906 to 04/2007 |
| Wamtachee | Chelan | Temp | NCDC | 02/1877 to 06/2007 |
| Bickelton | Klickitat | Temp | NCDC | 06/1927 to 12/2006 |
| Dalles | Klickitat | Temp | NCDC | 06/1948 to 12/1980 |
| Goldendale | Klickitat | Temp | NCDC | 10/1905 to 01/2006 |
| Mt Adams | Klickitat | Temp | NCDC | 11/1909 to 04/2007 |
| Cle Elem | Kittitas | Temp | NCDC | 01/1899 to 11/2006 |
| Stampede Pass | Kittitas | Temp | NCDC | 01/1944 to 05/2007 |
| Moxee City | Yakima | Temp | NCDC | 04/1946 to 04/2007 |
| Sunnyside | Yakima | Temp | NCDC | 09/1894 to 04/2007 |
| Wapato | Yakima | Temp | NCDC | 10/1915 to 03/2007 |
| Yakima | Yakima | Temp | NCDC | 09/1946 to 05/2007 |

MULTI-MODEL

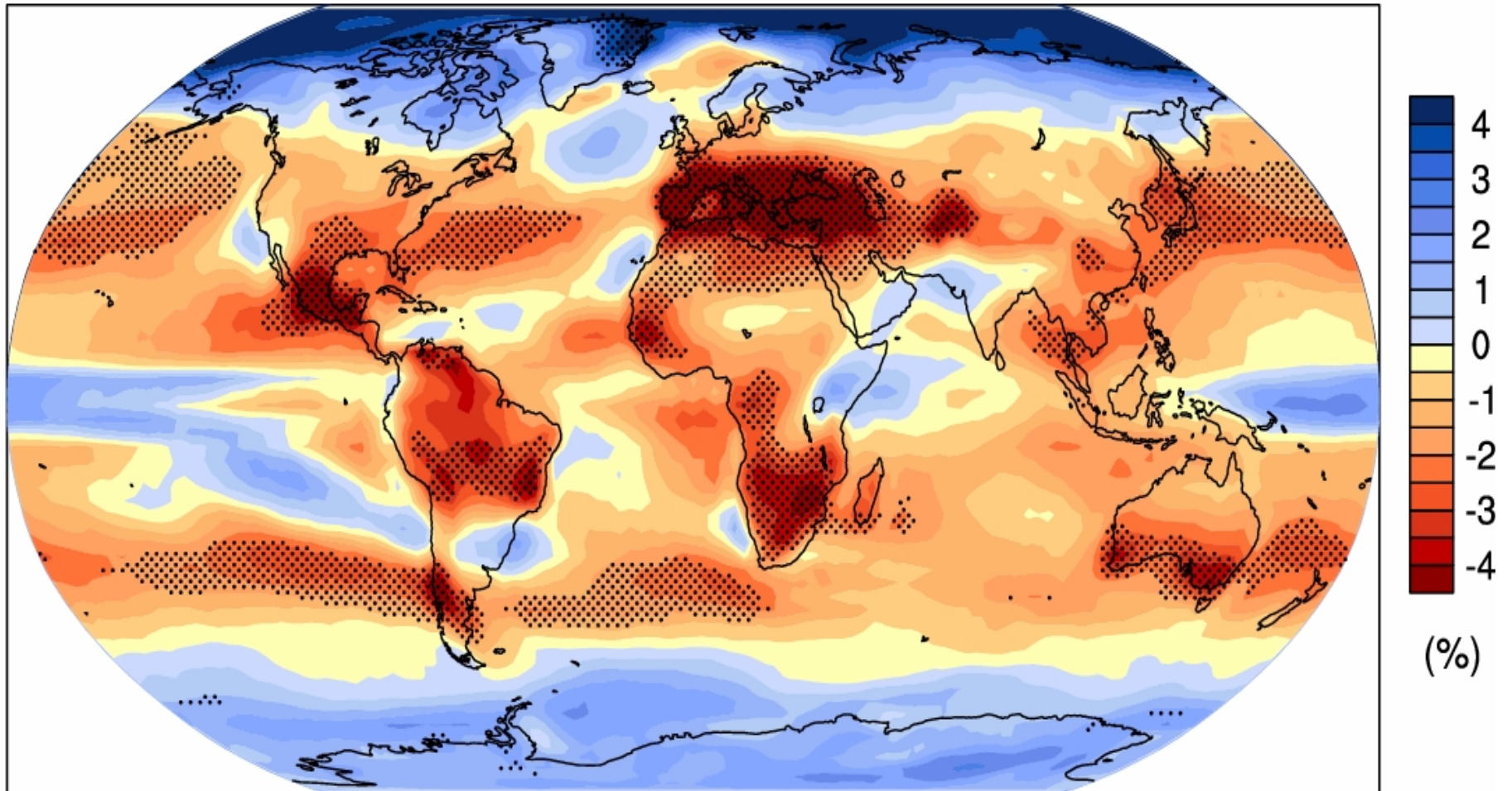


Figure 1: Projected changes in cloudiness of a multi-model forecast representing the change in total cloud area fraction of the ensemble mean i.e percent cover from all the models (IPCC WG1 AR4 Report, Chapter 10, Figure 10.10b)

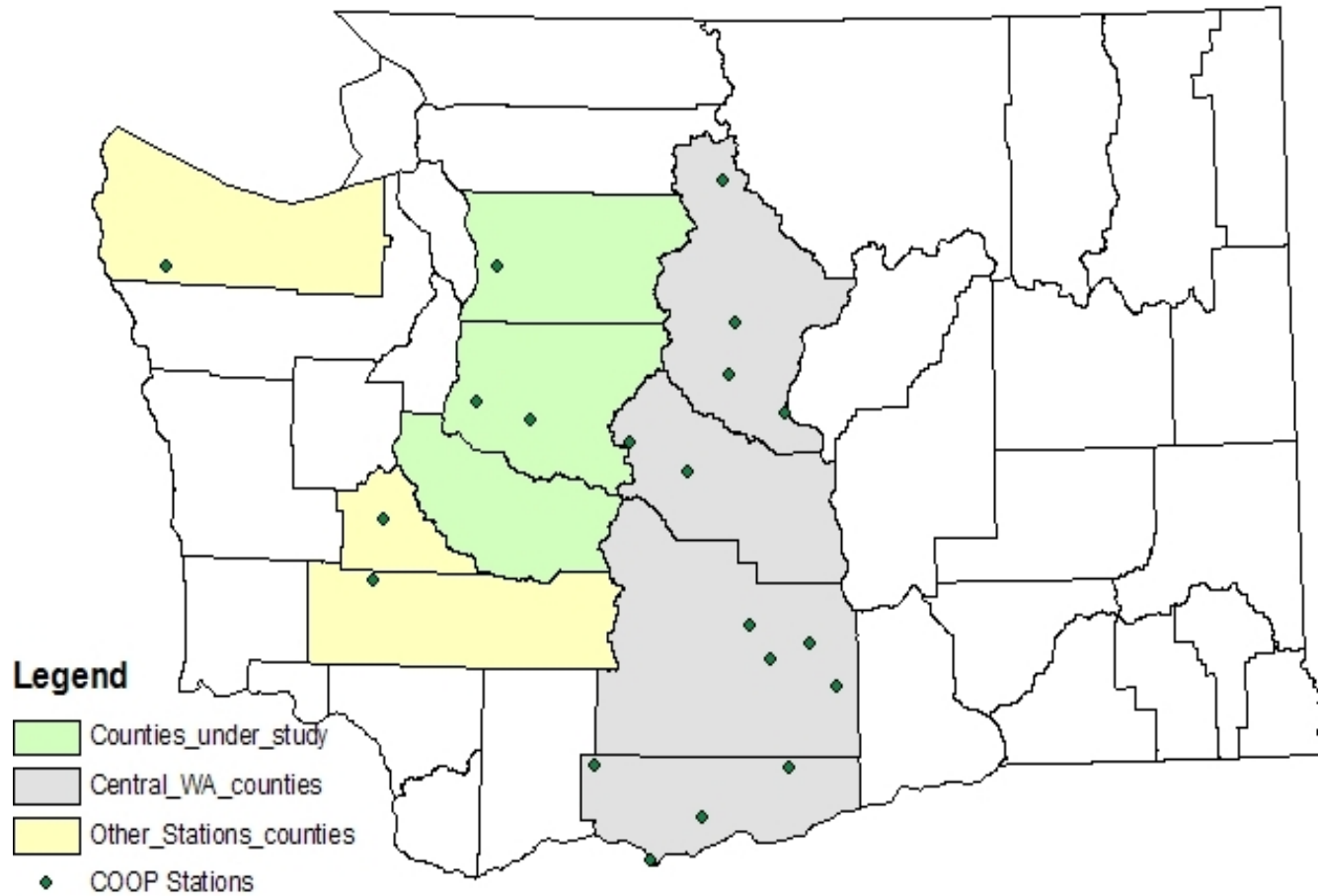


Figure 2: Location of stations in Washington State on which statistical analysis has been conducted

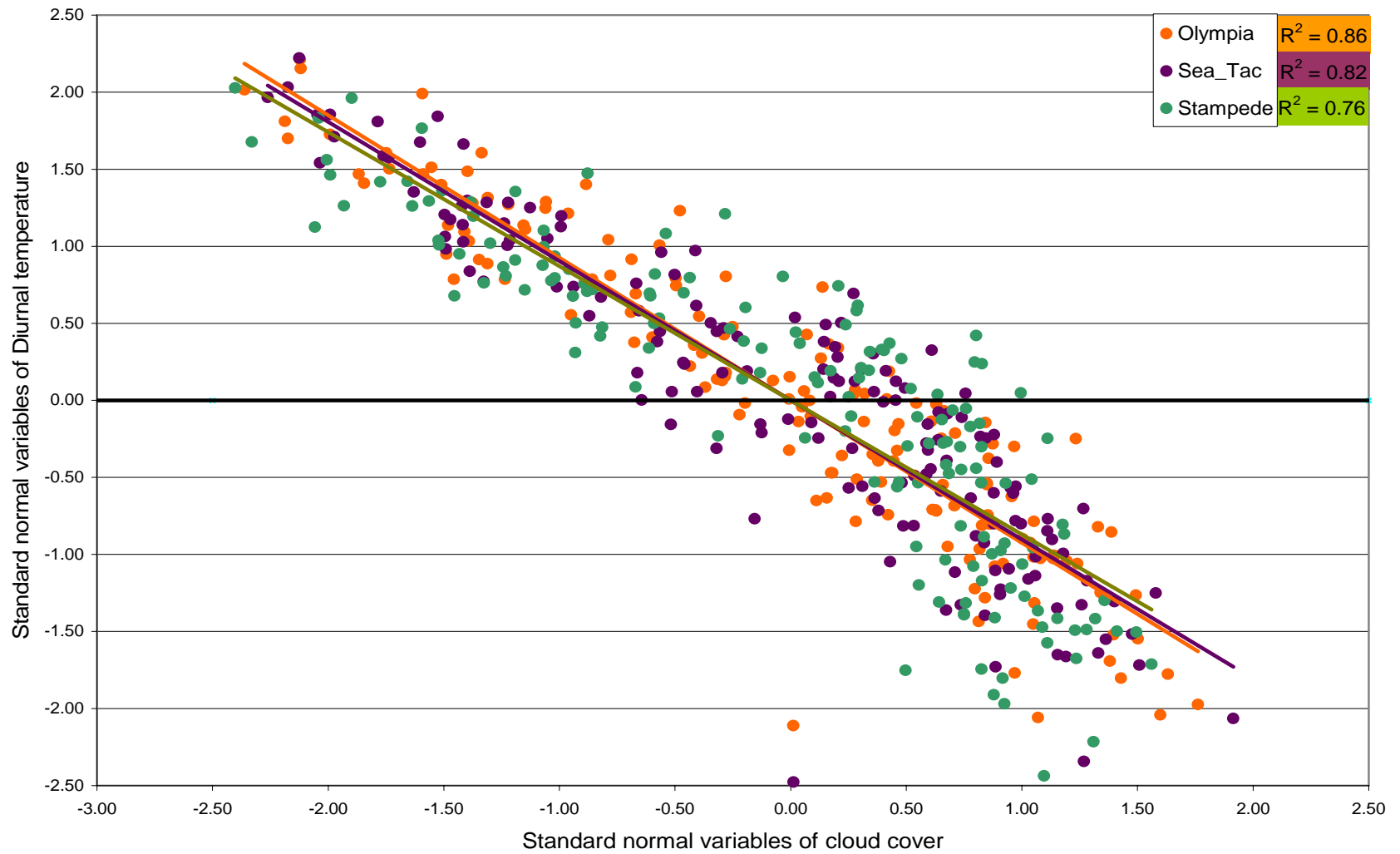


Figure 3: Relationship between standard normal variables of diurnal temperature variation and cloud cover for three stations in Western WA for a seasonal average of April through August for the years of 1948 to 1996

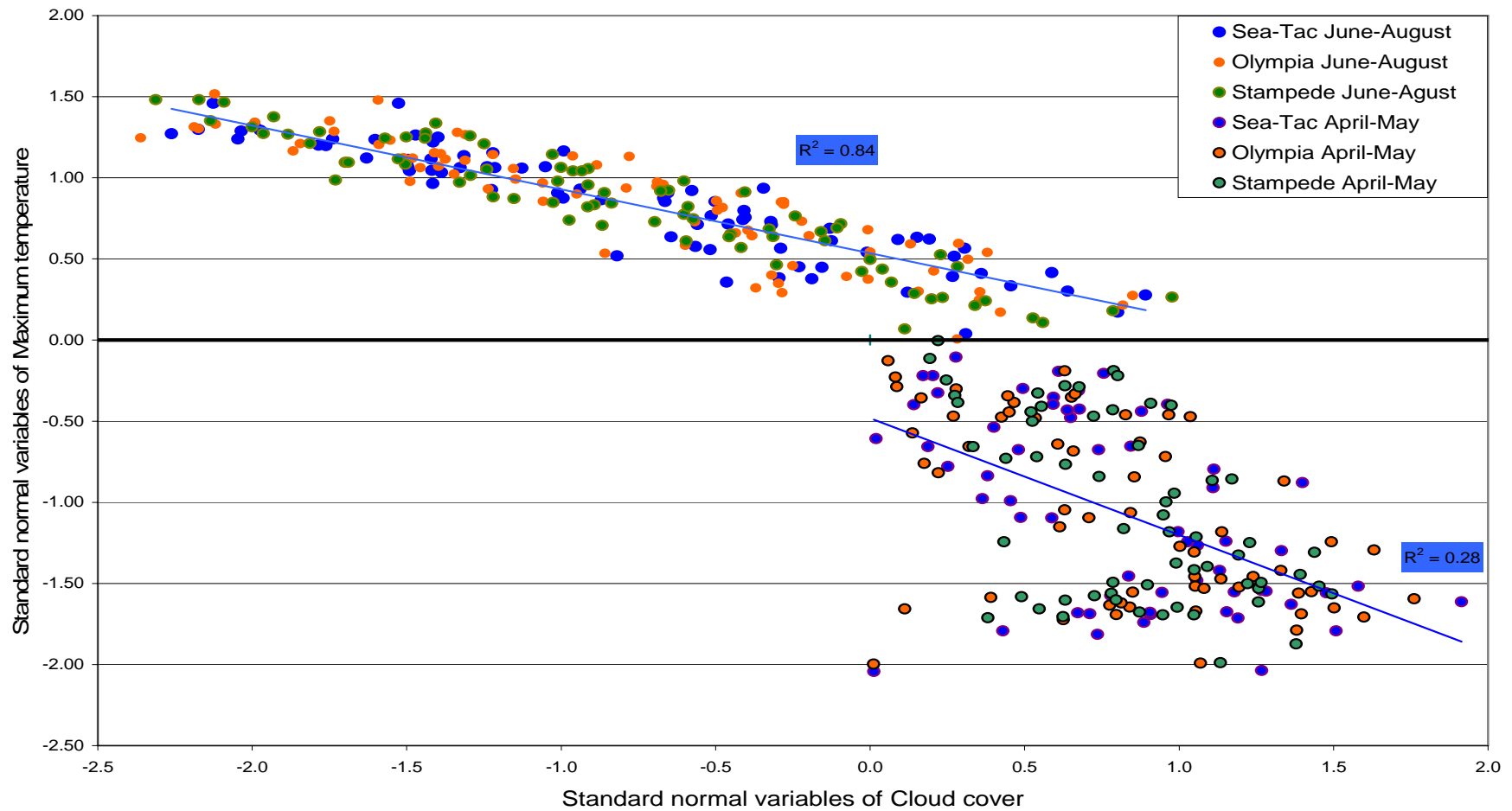


Figure 4: Relationship between standard normal variables of maximum temperatures and cloud cover regressed separately for April-May and June-August for three stations in Western WA, for a seasonal average of April through August for the years of 1948 to 1996

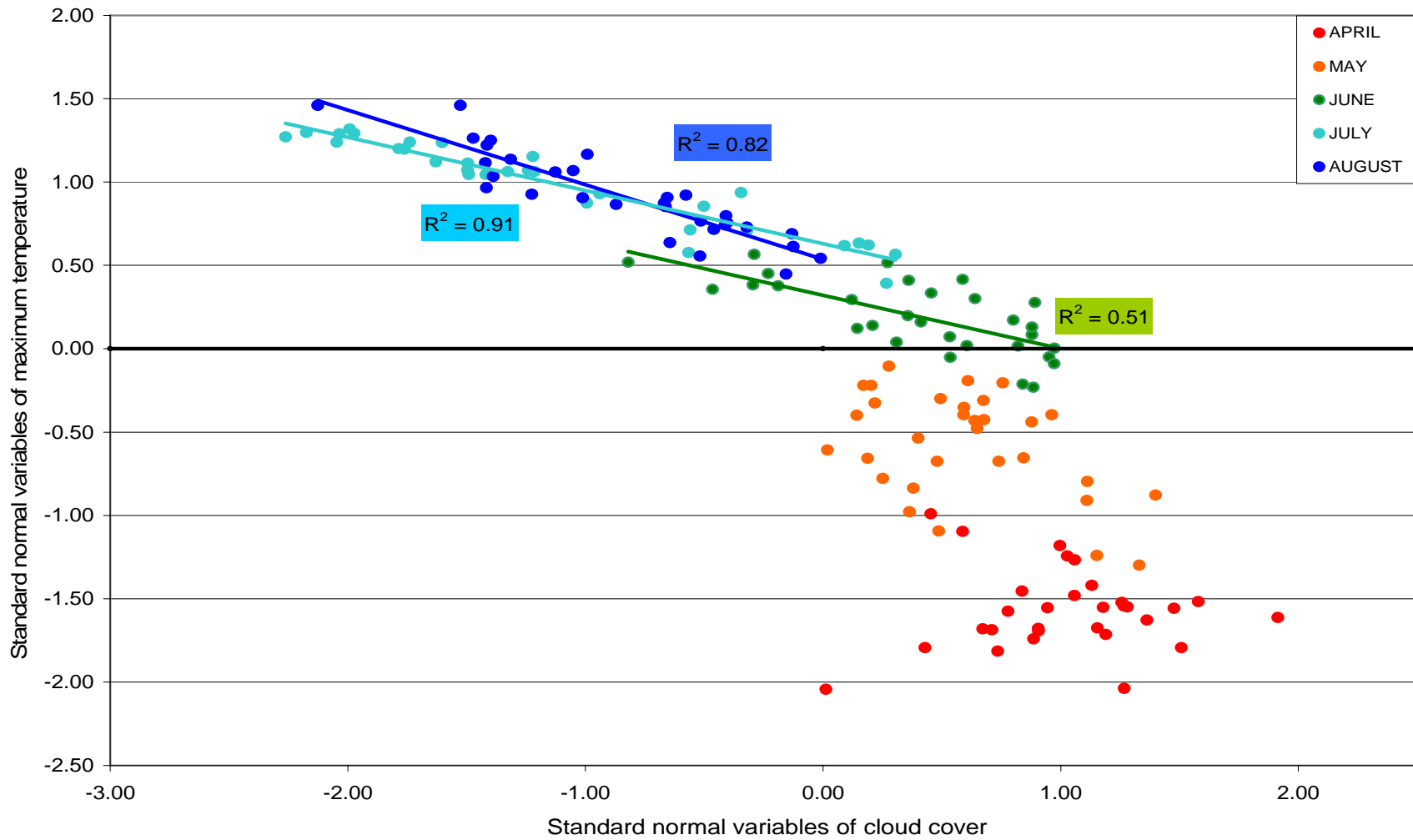


Figure 5: Relationship between standard normal variables of maximum temperatures and cloud cover, regressed for individual months for Sea-Tac station for a seasonal mean of April through August for the years of 1948 to 1996

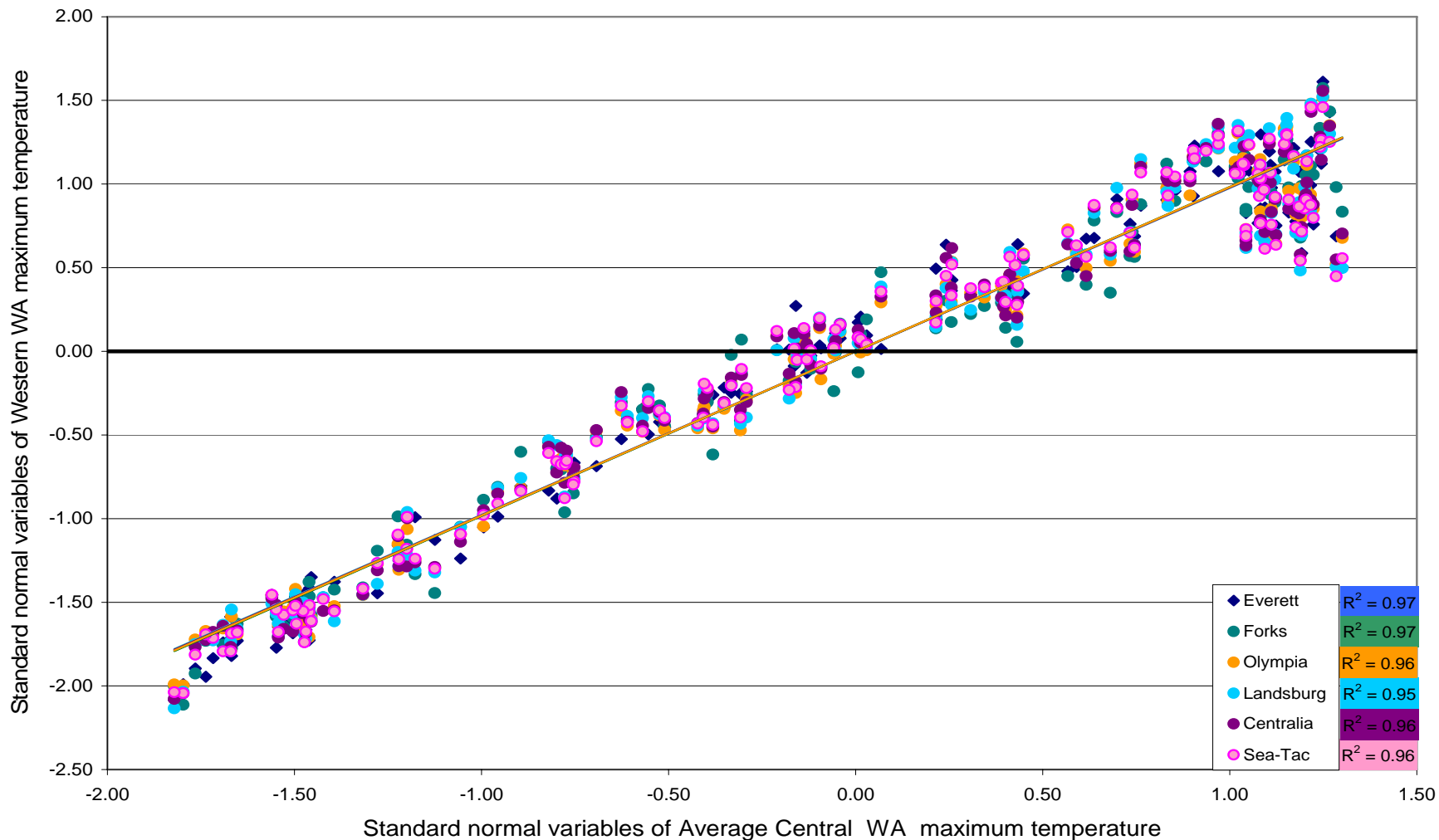


Figure 6: Relationship between standard normal variables of maximum temperatures of six stations in Western Washington and standard normal variables of average maximum temperature of Central Washington, for a seasonal mean of April through August for the years of 1948 to 1996

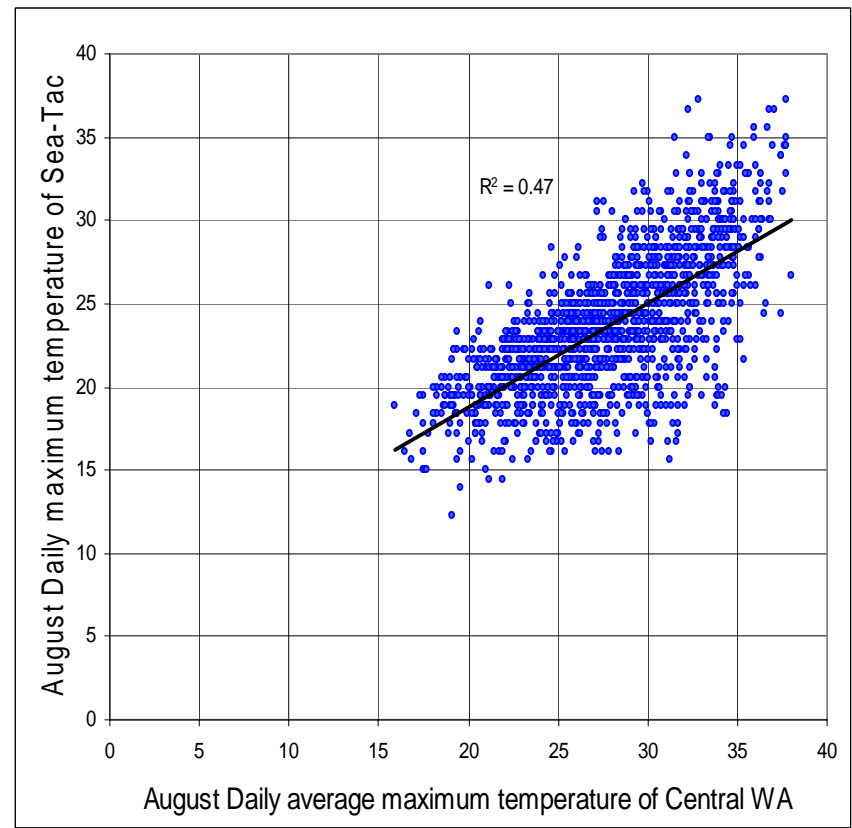
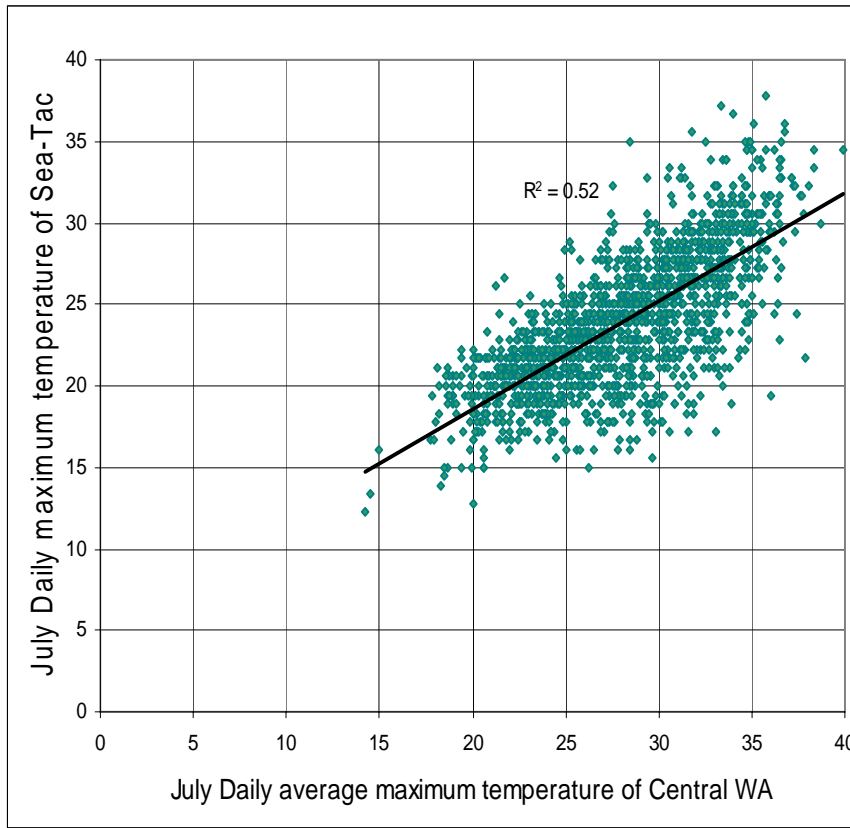


Figure 7: Relationship between daily observations of maximum Sea-Tac temperatures and daily averages of maximum Central WA temperatures for the months of July and August for the years of 1948 to 1996

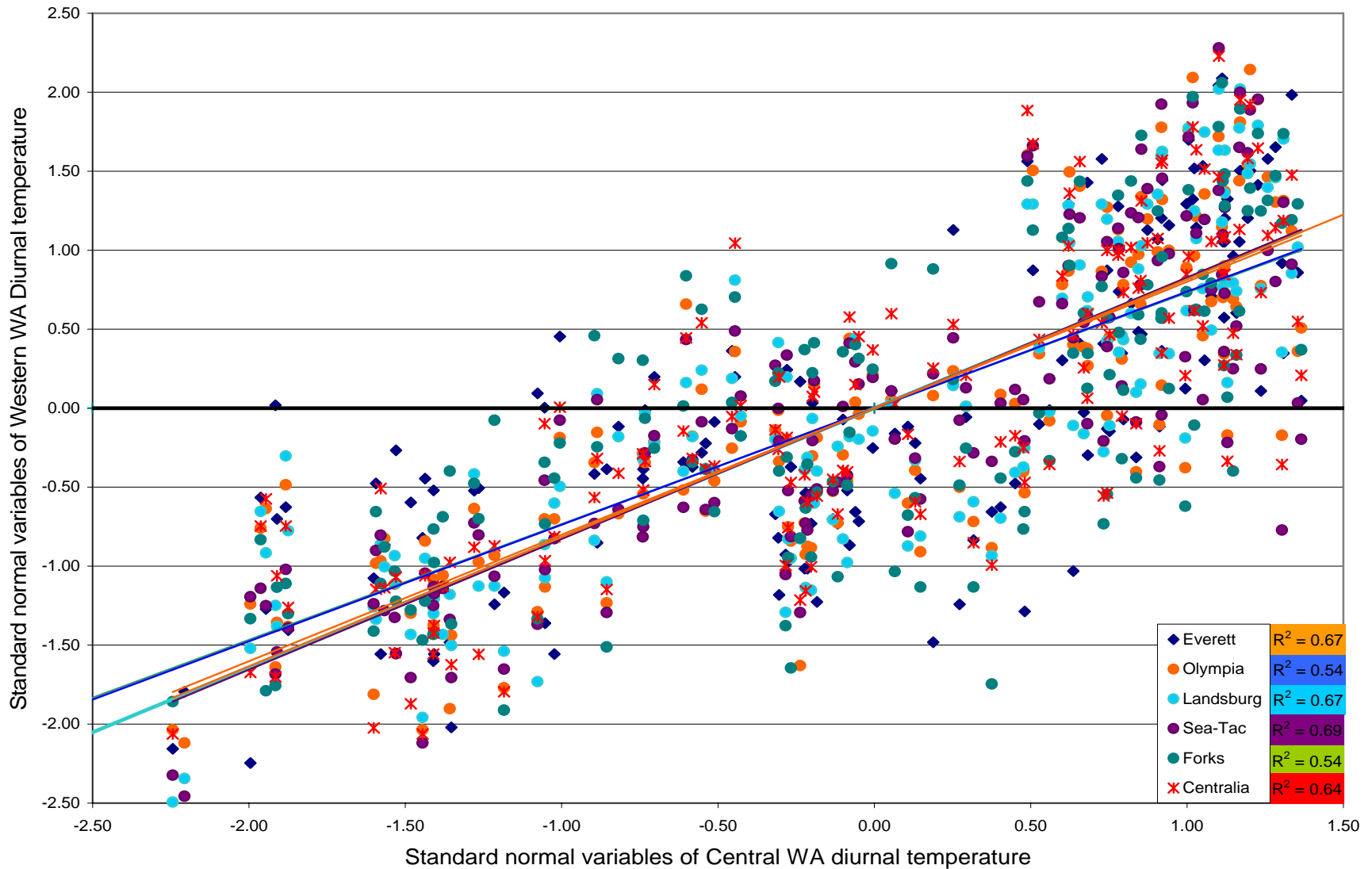


Figure 8: Relationship between standard normal variables of diurnal temperature variations of six stations in Western Washington and standard normal variables of average diurnal temperature variations of Central Washington, for a seasonal mean of April through August for the years of 1948 to 1996

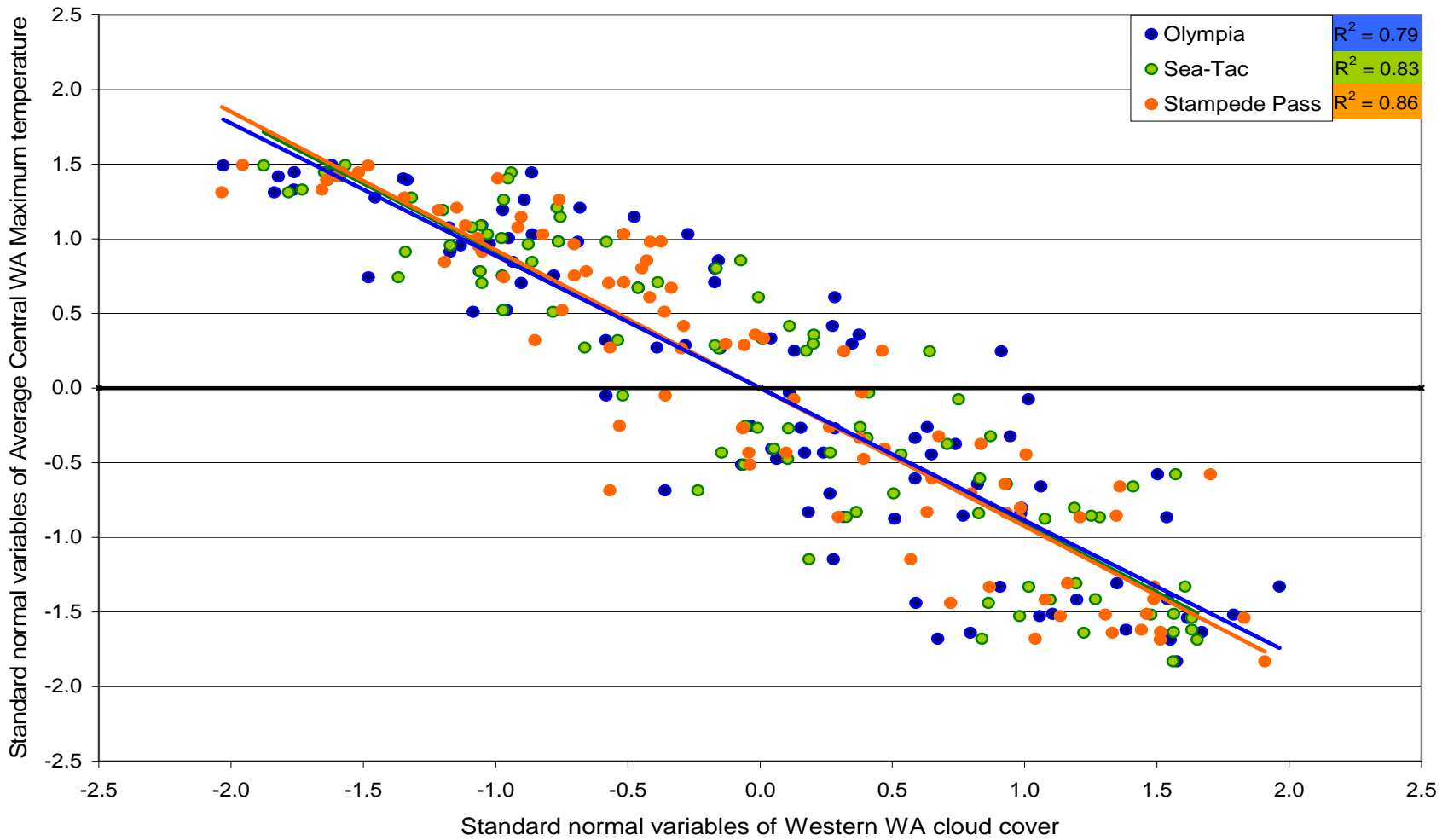


Figure 9: Relationship between standard normal variables of average maximum temperatures of Central WA and standard normal variables of cloud cover of three stations in Western Washington, for a seasonal mean of July through August for the years of 1948 to 1996

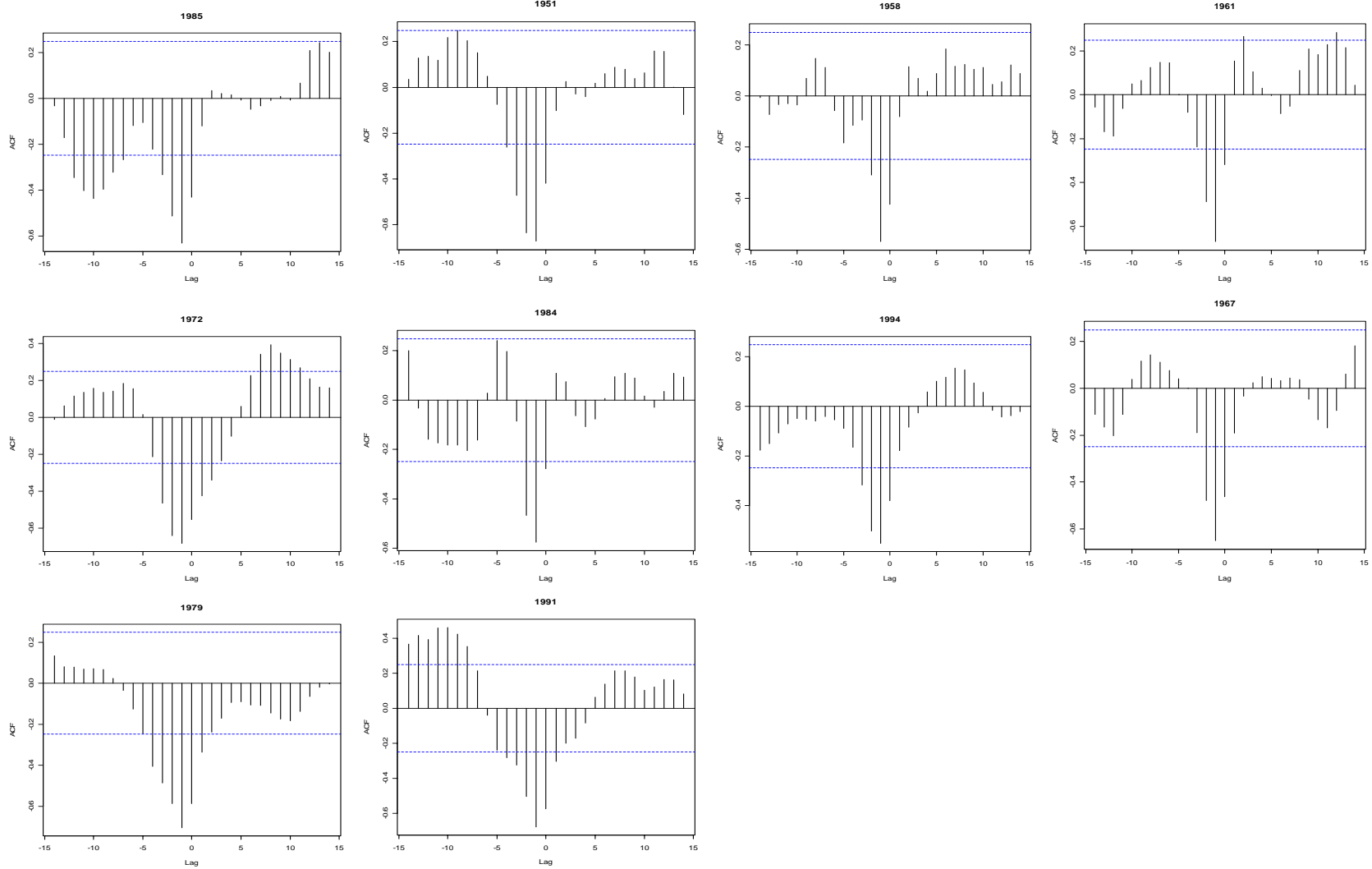


Figure 10: Cross covariance coefficient plots relating daily average maximum Central WA temperatures and daily cloud cover for Sea-Tac station in Western Washington for the hottest 11 hottest July and August for the years of 1948 to 1996

MULTI-MODEL

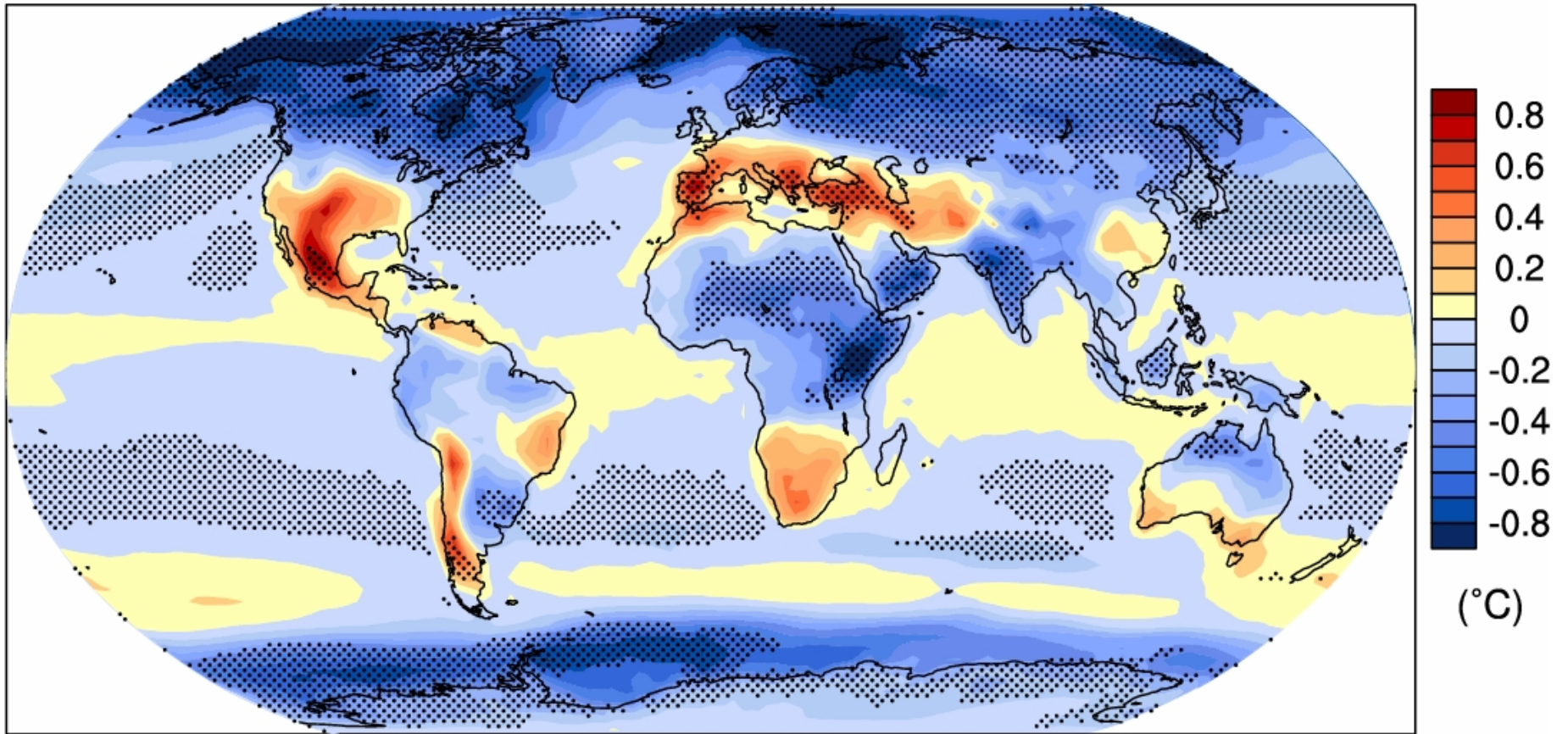


Figure 11: Projected changes in diurnal temperature ranges of a multi-model forecast (IPCC WG1 AR4 Report, Chapter 10, Figure 10.11b)