

On the Existence and Impacts of Summertime Northwest U.S. Weather Phenomena

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I. Abstract

The northwest U.S. experiences a variety of impactful weather phenomena in the summertime, most of which have received little to no attention in the literature. Specifically, the terrain of this region, its proximity to the Pacific Ocean, and commonly occurring configurations of high and low pressure systems result in complex wind circulations on many scales. Understanding the timing, intensity, and evolution of these circulations and their influence on other meteorological variables is crucial for aviation, wind energy, agriculture, and boating, among other applications. Fire managers must be familiar with the mesoscale meteorology of wildfire areas before making critical decisions that affect lives and property, and an understanding of wind circulations sheds light on regional variations in air quality and the transport of pollutants.

This work examines important northwest U.S. summertime weather phenomena, and also sets the stage for further research by utilizing the methods explained herein. A new method for analyzing the summer diurnal meteorology of the northwest U.S. is described and important findings regarding typical diurnal variations in wind, temperature and relative humidity are discussed. Low-level mesoscale nocturnal wind maxima were found to occur over many locations in the region, all reaching a maximum in wind near 2300 LDT (Local Daylight Time). Furthermore, it has been found that offshore (easterly) flow events (OFEs) that lead to the development of the West Coast thermal trough (WCTT) were shown to be highly correlated with warm and dry conditions in the summer, particularly west of the Cascades. Regional climate models suggest that summertime offshore flow events will decrease in the future, though more downscaled climate runs are needed to further examine this question.

II. Background

Figure 1 shows typical near surface summertime conditions for the northwest U.S. using composites of WRF output at 12-km resolution for July-August 2009-2011. During this period, the eastern Pacific Ocean is dominated by the Pacific High, which produces northerly flow along the coast. Such northerly flow is particularly strong along the southern Oregon (Elliot and O'Brian 1977; Bielli et al. 2002) and northern California coasts (Zemba and Friehe 1987; Holt 1996; Burk and Thompson 1996; Taylor et al. 2008), with little change in strength during the day. As the heat low over the Great Basin strengthens during the day while high pressure is maintained offshore, the low-level geopotential height

gradient builds over the Cascades. The Cascades impede marine air from pushing eastward, making the interior substantially warmer than the western lowlands.

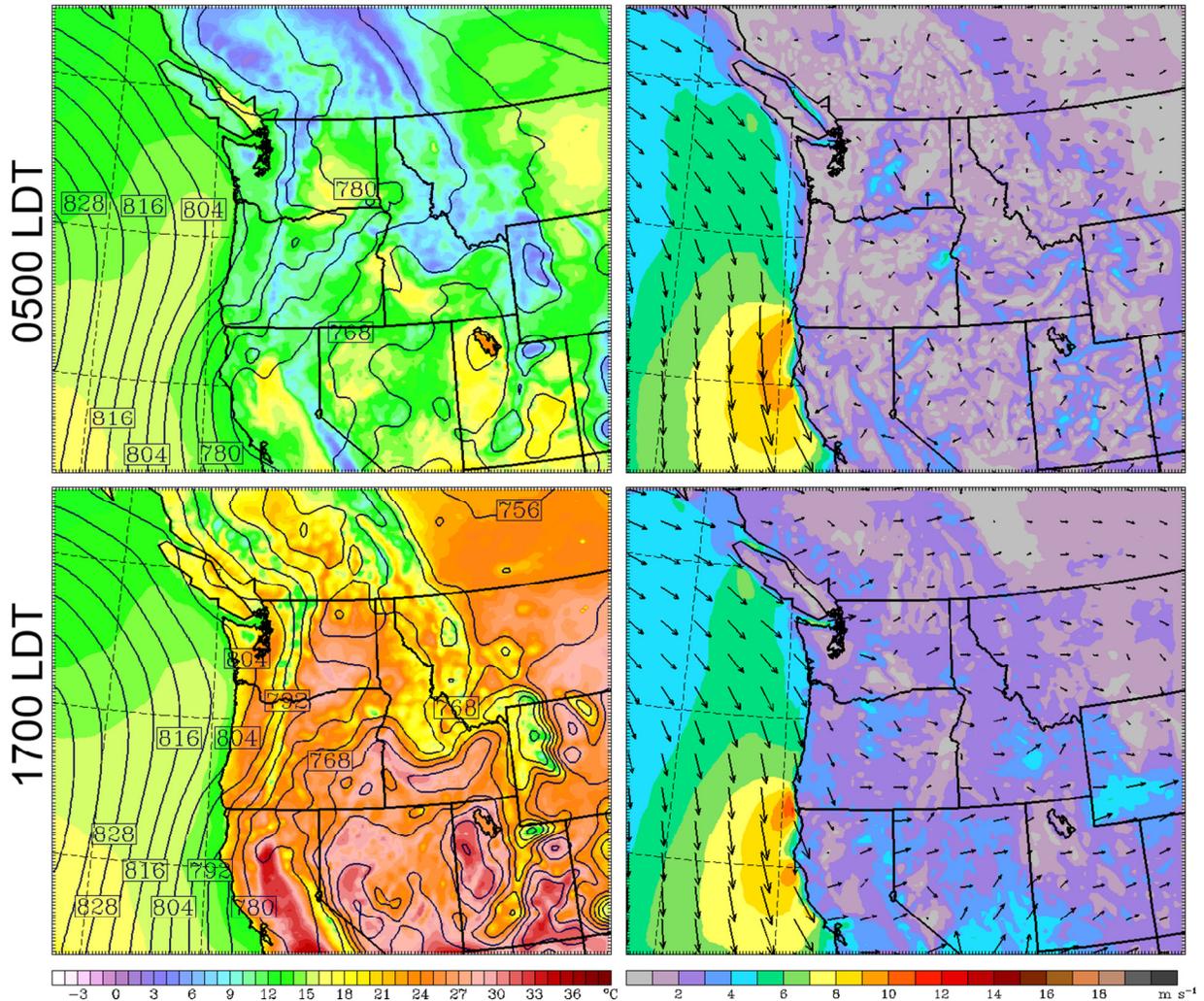


Figure 1: Average 925 hPa geopotential height (m, contours), temperature (°C, color shading) (left), and 10-m wind (vectors and color shading) (right) from WRF model output for July-August 2009-2011, from Brewer and Mass 2014.

Surface heating and its interaction with the variations in topography and land/sea contrasts result in complex diurnal circulations over the region. Some observational studies have described localized summertime wind phenomena, however, a comprehensive three-dimensional examination of diurnal winds over the region is lacking. This work has sought to ameliorate this by analyzing the three dimensional structure and temporal evolution of typical summertime diurnal circulations over the northwest U.S., as well as diurnal variations in temperature, pressure and moisture.

Before research on short-lived synoptic patterns such as WCTTs is done, this initial work will serve as a baseline for what to expect given the most persistent weather conditions across the northwest U.S. Once these normal summertime conditions are documented, it can be more clearly shown how various modes of variability differ from it.

Though the northwest U.S. is typically under a westerly flow regime with high pressure offshore and a thermal low inland, there are other transient

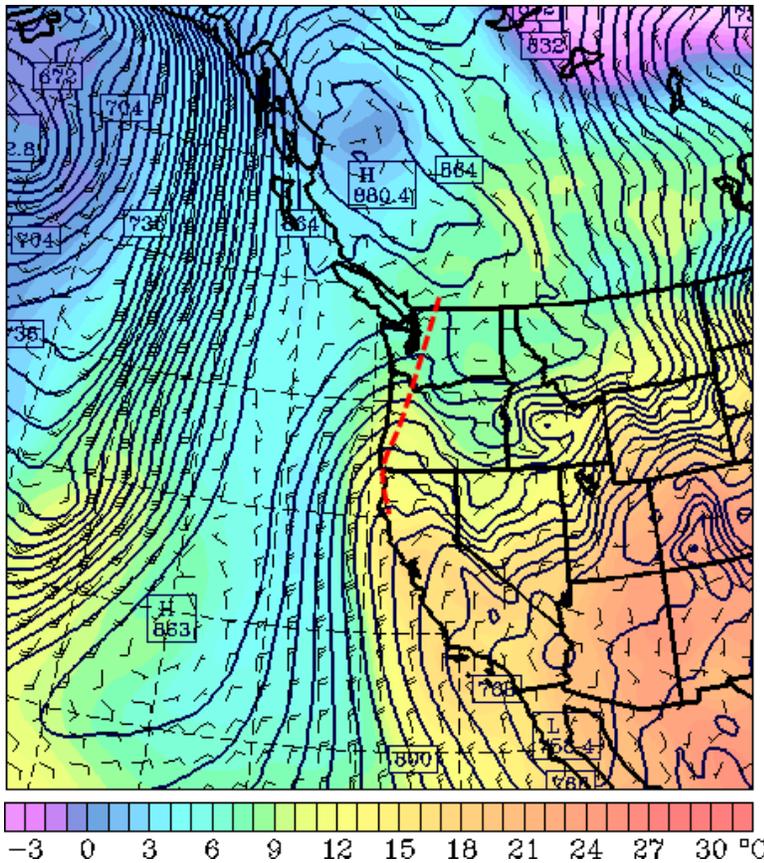


Figure 2: An OFE and associated WCTT at 1200 UTC 14 May 2007 showing 925 hPa geopotential height (m), temperature (°C, color shading), and wind (kt) from the 36-km WRF model (12-h forecast) from Brewer et. al 2012.

synoptic regimes that occur during the summer. Specifically, periods of low-level easterly (offshore) flow develop as upper-level ridges move over the region, high surface pressure builds inland, and a WCTT builds along the coast (Figure 2) (Mass et al. 1986; Chien et al. 1997; Brewer et al. 2012). These offshore flow events (OFEs) have profound impacts on regional temperatures, wind, and cloudiness, particularly during the warm season. Subsidence from a ridge aloft as well as downslope offshore flow on the western slopes of the Cascade, Coastal, and Siskiyou/Klamath Mountains suppresses cloud development and

precipitation along the West Coast, and brings abnormally hot and dry conditions to these regions. An extreme example of the conditions accompanying an OFE occurred on 29 July 2009 when Seattle-Tacoma Airport reached its all-time high of 103°F. As the synoptic-scale flow evolves, WCTTs often move eastward across the Cascades. Their passage brings a shift to westerly winds, increased cloud cover

and wind speed (known as an onshore or marine push), and a drop in temperature, thus signaling the end of a warm period (Mass et al. 1986).

As a result of wind shifts, above normal temperatures and low relative humidity, OFEs have a significant influence on the initiation and modulation of wildfires. This has been noted repeatedly in wildfire literature (Joy 1923; Dague 1934; Cramer 1957; Gisborne 1927; Cramer 1954; Colson 1957; Cramer 1957; Werth and Ochoa 1993; Rorig and Ferguson 1999; Saltenberger and Barker 1993). Several studies have found that OFEs influence air pollution in the Pacific Northwest (McKendry 1994; Barna et al. 2000; Ainslie and Steyn 2007). McKendry (1994) suggested that the OFEs inhibit the sea breeze, creating stagnation and reducing ventilation, and thus hinders the dispersal of photochemical pollutants such as ozone. Furthermore, the warm temperatures and sunny conditions associated with OFEs enhance photochemical production of ozone. WCTTs can have a large impact on wind energy generation since thermal trough movement across the Cascades can result in sudden increases and subsequent declines in wind energy (known in the industry as the ramp up/ramp down problem).

Although the OFEs and associated WCTT development has profound impacts on the West Coast in the summer, there are still important unanswered questions regarding historical and future trends. This work by the Student investigator (SI) Matt Brewer and the Principal Investigator (PI) Cliff Mass provides the first comprehensive documentation and analysis of this important western U.S. weather/climate feature and will set the stage for improved forecasts of its substantial lower-tropospheric effects.

III. Study Description and Location

As a way to describe typical summer synoptic/mesoscale conditions over the northwest U.S., NOAA/NWS Global Forecast System (GFS) model output at one degree latitude/longitude resolution was obtained for July and August 2009-2011. These data were averaged by hour, and the resulting files were used to initialize and provide boundary conditions to a high-resolution WRF (version 3.5) model run. An outer nest of 36-km grid spacing was used, along with three one-way nested domains of 12, 4, and 4/3 km grid spacing, all centered over the Pacific Northwest. The 4/3 km run was primarily used in this analysis (Figure 3). Thompson microphysics, RRTMG long-wave and short-wave radiation schemes, the Yonsei boundary layer scheme, 38 vertical full-sigma levels, MODIS land use,

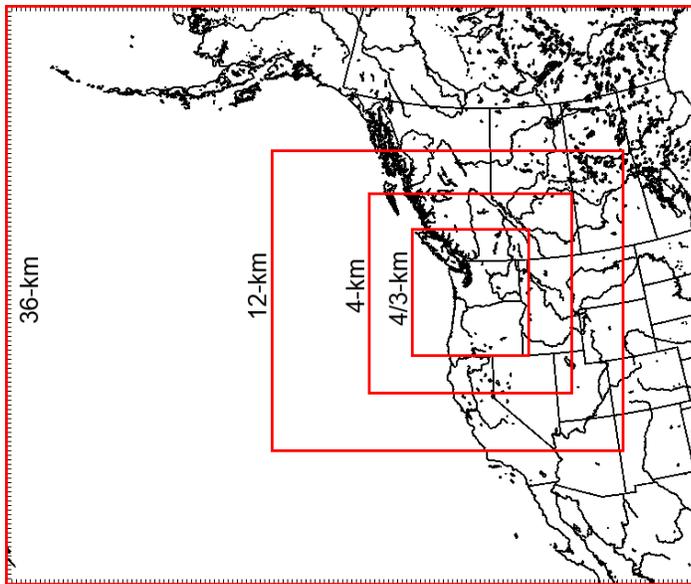


Figure 3: Domains for the WRF model simulations, from Brewer and Mass 2014.

and a model top of 50 hPa were used in this simulation. The Simplified Arakawa-Schubert cumulus parameterization was applied in the outer three domains, but no cumulus parameterization was used for the 4/3 km domain.

The model was initialized at 1700 Local Daylight Time (LDT), corresponding to 0000 UTC, and run for 48 hours. A 24-hr period from forecast hour 12 to 35 (0500 LDT to 0400 LDT) was used to describe the diurnal cycle over the region. The reason for initializing

the model at 1700 LDT is that if the model is initialized at night, the low-resolution GFS model that provides initial/boundary conditions will not resolve the thermal structures in the lower troposphere produced by surface heating the prior day. This is particularly true in the mountainous western U.S., where tight horizontal and vertical temperature gradients develop within terrain not resolved by the GFS.

The goal of the WRF model run is to simulate typical summer (July-August) diurnal wind, temperature, and moisture variations. In order to verify the accuracy of the model simulation, it was compared to high-quality aviation reporting station observations from around the region, from a subset of summer days with typical summer synoptic conditions. More information on the selection of this subset, as well as how the model performed in the verification can be found in Brewer and Mass 2014. Fourteen of the stations are from the Automated Surface Observing System (ASOS), while one station (CWQK) is from Environment Canada. Once this run was shown to closely simulate average summer conditions, it was used to describe the typical diurnal variations of temperature, moisture and winds.

Upon describing the most persistent weather conditions for the Pacific Northwest in summer, the next important step was to describe other modes of variability. Since WCTTs have substantial impacts on wildfires, air pollution, aviation, and renewable energy, it is of great interest to determine the historical

trends of WCTT frequency, intensity, and evolution, as well as future changes in those trends as the climate changes during the next century.

This work made use of the long-term, high-resolution WRF (V3.1) simulations produced by dynamically downscaling NCEP reanalysis and GCM grids. These Pacific Northwest-centric runs have been run at 36/12 km grid spacing, a resolution sufficient for realistically simulating OFE/WCTT events and the major orographically forced mesoscale circulations of the region. As shown in Brewer et al. (2012, 2013), the realistic simulation of the WCTT requires resolution of less than approximately 40 km, with roughly 12 km or better to simulate important mesoscale features. Recent CMIP-5 (Fifth phase of the Coupled Model Intercomparison Project) climate simulations only have horizontal resolutions of the order of 100-200 km and thus would be inadequate for appraising changes in OFE/WCTT frequency, structure, or intensity.

To analyze historical changes, downscaled WRF runs were used with initial and boundary conditions prescribed by the NCEP-DOE Reanalysis 2 for the period of 1950-2010. For studying future changes, several dynamically downscaled WRF model runs have been completed for Special Report Emission Scenarios (SRES) (A1B, A2) for a collection of IPCC CMIP-3 simulations driven by differing modeling systems (e.g., CCSM-3, ECHAM-5). These long-term simulations have been run for a century (1970-2070). Model physics for all runs include Thompson microphysics, Kain-Fritsch cumulus parameterization, YSU PBL, RRTM/Dhuria radiation, and the Noah LSM. Each long-term run was broken up into independent decades which ran without reinitialization for 11.3 years. Each decade was initialized at the end of the dry season 1.3 years prior to the beginning of the decade (eg. 01 Sep 1978 for 1980s decade) to permit the LSM to spin up soil moisture/temperature profiles and accumulate snow from zero. Grid nudging is applied to the outer domain throughout the simulations to endure continuity between the boundary conditions and the WRF model.

In the initial stages of this work, it was anticipated that the long-term changes in WCTT frequency, intensity, and evolution would be examined using the software for objectively finding WCTTs, as described in Brewer et al. (2012). However, it was determined that the software would be insufficient for use on the downscaled 12-km wrf runs. Therefore, it was decided to create software to track offshore flow along the crest of the Cascade Mountains, and analyze OFEs, since offshore flow and adiabatic warming are what drive the formation of WCTTs. This software was first applied to the 12-km WRF model grids produced by dynamically downscaling the NCEP reanalysis grids from 1950-2010, in order to

determine past changes in OFE events on a multi-decadal timescale. The OFE finding software was then applied to the climate runs to determine how OFEs may change under anthropogenic global warming. The results from each of the climate runs were compared to the downscaled NCEP reanalysis grids to ensure that the system is able to duplicate the occurrence of OFEs.

IV. Key Findings

A new method for analyzing summertime diurnal variations in wind, temperature, and moisture was tested and proven effective.

Typically, observations, reanalyses, or case studies of high resolution model runs are used to analyze diurnal modulations in various meteorological variables. Though these are useful tools, observations are primarily surface based and often sparsely located, the resolution of available reanalyses are too low for the complex terrain of the Northwest U.S., and choosing one or two representative case studies is a rather subjective endeavor.

The method for analyzing typical summertime weather conditions described in the last section is computationally inexpensive, and has been shown to match closely with observational averages of wind speed, direction, and temperature. Though moisture performed less well in the verification, it is expected that this will improve with improved physics and parameterizations within the model. This method has extraordinary application for locations all across the world when large-scale north-south temperature and pressure gradients are weak and where there is a dominant pattern of weather.

The initiation and temporal evolution of key near surface features were described.

Given their impacts across the region, it was necessary to describe the temporal evolution and three dimensional structures of the various circulations over the region. The northwesterly winds in the Strait of Juan de Fuca were shown to begin in the afternoon hours and intensify into the evening, reaching a maximum near 13 m s^{-1} near 2100-2200 LDT. The westerly flow east of Ellensburg on the eastern slopes of the Cascade Mountains was shown to reach a peak at

2300 LDT with a wind max of 11 m s^{-1} . The northerly flow offshore of the Oregon and Washington coasts was shown to have little diurnal variation, with persistent northerly flow all day and night.

Mesoscale nocturnal wind maxima, not previously mentioned in prior literature, were discussed.

The WRF simulations and confirming observations showed that evening wind maxima occur above the surface over the northern Willamette Valley and the Chehalis Gap, reaching maximum strength near 2300 LDT at approximately 975 hPa. These low-level wind maxima are reminiscent of low-level nocturnal jets/wind maxima that occur all over the world (Revelle and Nilsson 2008; Baas et al. 2009; Kairpot et al. 2009; Kumar 2012), and it has been shown that the WRF model can realistically simulate these wind phenomena (Storm and Basu 2010; Michelson et al. 2010; Colle and Novak 2010). During the day, horizontal winds often weaken in the boundary layer due to the vertical mixing of air slowed by surface drag. As the surface cools during the evening, a low-level inversion or stable layer forms, inhibiting vertical motion and decoupling the lower troposphere from the surface. Such decoupling from surface drag allows existing pressure/temperature gradients to accelerate air above the surface to form low-level wind maxima (Arya 2001); such evening gradients were evident in the simulations.

In the case of the well-documented low-level jet in the Great Plains, as well as other larger-scale nocturnal low-level jets over relatively flat terrain, there is a balance between friction, the Coriolis force, and the pressure gradient force within the boundary layer during the day. In the evening as the near-surface stable layer forms, the loss of drag results in an inertial oscillation that drives supergeostrophic low-level winds (Markowski and Richardson 2010). However, due to the smaller scale of the low-level wind features over the Willamette Valley and Chehalis Gap and their relative short longevity, the Coriolis force is small and thus accelerations of the wind are primarily due to the pressure gradient force.

Over the Oregon Plateau, the simulations indicated strong northerly flow during the evening. These winds are hardly noticeable at the surface, but are found immediately aloft (lowest 50 hPa) above the surface with wind speeds near $10\text{-}12 \text{ m s}^{-1}$. Such Oregon plateau northerlies are confirmed by observations at the tops of local mountain peaks. It appears that this northerly flow is driven by strong temperature/pressure gradients that develop during day. These gradients

are able to accelerate low-level flow during the evening when drag lessens as increased stability decouples the lower atmosphere from the surface.

A new way for objectively identifying offshore flow/WCTT events was utilized.

This method worked well for identifying offshore flow events, and it was shown that these events are highly correlated with warm and dry conditions west of the Cascades in the summer. This method is more versatile than the method for identifying WCTTs in Brewer 2012, in that it can be used in both low and high resolution models. Those who wish to explore offshore/downslope flow features in other part of the world may utilize this method as a way to identify those events.

Offshore flow events were shown to be highly correlated with temperature west of the Cascade Mountains.

Correlation does not prove causation, and the offshore flow is not *the* cause of warmer temperatures, but one of the causes of above normal temperatures under these weather conditions. Tracking offshore flow is a way to track the synoptic conditions that bring about heat waves over the region, namely the ridge aloft and higher surface pressure inland which drives offshore flow. The causes of above normal temperatures are subsidence warming from the ridge aloft and downslope flow, which contribute to the warming and cloud suppression, and offshore flow which keeps the marine air at bay.

Downscaled regional climate model runs suggest a decrease in offshore flow events in the future.

Both ECHAM5 and CCSM3 runs suggest decline in OFEs over the next century under anthropogenic global warming. There are two possible explanations for this. First, that increased thermally induced onshore flow in the summertime, due to a higher rate of warming inland, will more often overcome synoptically induced offshore flow. Second, changes in the synoptics, such as a decreased number of ridges, or ridges of shorter duration, will occur. In order to explore this question further, more downscaled runs from CMIP5 will be

produced where robustness in the result that OFEs will decrease in the future will be analyzed.

V. Management implications

From this work, important information on the summertime diurnal variations of winds, temperature, and moisture were described. Given the impacts of these variables on operations, the dissemination of this work to the operational community is essential. National Weather Service forecasters must be made aware of these wind features so they may properly forecast them and communicate this information to those who need it. Fire Managers and IMETs must be trained on these features given the dangerous impacts these wind and moisture variations can have on wildfires. Since wildfires commonly occur in this region, it is of particular interest for those in the fire community to be made aware of the low-level nocturnal wind maxima of northerly flow over the Oregon Plateau, as well as what synoptic conditions cause it to occur or not occur. Important wildfire-related decisions will be made based on the occurrence and intensity of these winds.

OFE events are another important phenomenon that has substantial impacts on wildfires, air pollution, energy consumption, etc. It appears that these events will be less frequent, as is suggested by ECHAM5 and CCSM3. However, the heat waves associated with them will be more intense, and thus preparations among the various entities impacted by these events will be necessary.

The SI has worked extensively with employees at the NWS as well as John Saltenberger (NWCC) and Dr. Brian Potter (PWFSL) to disseminate the findings of this work. John Saltenberger trains fire fighters in Pacific Northwest summer weather, and he will use the findings of this work in these courses. The SI has also presented multiple times in conferences, workshops, and informal meetings to publicize these findings.

VI. Relationship to other recent findings and ongoing work on this topic

As part of the Masters thesis of the SI, software was developed for objectively identifying WCTT events. Seasonal and diurnal climatologies were created using the North American Regional Reanalysis (NARR) of WCTTs extending over the northwest U.S. It was found that that WCTTs are most frequent along

the coast near the California/Oregon border, with weaker maxima west of the Cascade and coastal mountains. Over the coastal region, they occur most often during autumn, while east of the Cascade Mountains, the highest frequency is during summer. There is strong diurnal variability in WCTT frequency during the summer, with little diurnal variation in winter. Through compositing, the seasonal differences in WCTT evolution were described. This work can be found in Brewer et al. (2012).

A second part of the Masters thesis analyzed the physical mechanisms which lead to the formation of the WCTT on both the west and east side of the Cascade Mountains. A WCTT event in May 2007 was analyzed using the WRF model, in which it was found that vertical advection of potential temperature is the primary driver of local warming and WCTT formation west of the Cascades. The downslope flow that drives this warming is forced by easterly flow associated with high pressure over British Columbia. When the WCTT forms on the east side of the Cascades, diabatic heating dominates, with warm advection playing a small role. This work has recently been published in *Monthly Weather Review* (Brewer et al. 2013).

VII. Future Work Needed

This work is part of a larger project to understand northwest summertime weather phenomena, and how they might change under anthropogenic global warming. Work has and will be done to understand the forcing mechanisms of the various diurnal circulations over the region. Specifically, an analysis of momentum and thermodynamic energy budgets will be done for each of the individual wind phenomena. Composites of weak and strong cases of these wind features can be done using the archived high-resolution WRF output from the University of Washington. Terrain experiments may also be performed.

Effort is also being made to understand how the larger scale synoptic conditions may change under anthropogenic global warming. Many papers have suggested that inland areas will warm more than over the ocean (Bakun 1990, Cayan et al. 2008, Salathe et al. 2008, Salathe et al. 2010), which would have important implications for West Coast summertime pressure/temperature gradients. It has been suggested that enhanced onshore flow from greater warming inland has led to warm season temperature declines over parts of California (Lebassi-Habtezion 2011), and may lead to less warming and enhanced cloud cover in spring over the northwest U.S. (Salathe et al. 2008). It has also

been suggested that high pressure systems over the eastern Pacific may intensify under global warming (Li et al. 2012, Salathe et al. 2008, Favre and Gershunov 2009). Several papers (Bakun 1990, Snyder et al. 2003, Merryfield 2009) have suggested that enhanced coastal upwelling may result from increases in interior warming and associated pressure declines, though Mote and Salathe (2010) showed that GCMs show little future change in alongshore wind stress in the 21st century.

Composites of GCM output for several vertical levels and meteorological fields during the summer season will be completed every 20 years from 1970 to 2070 in order to determine the changes in synoptic/mesoscale configurations in time. Among the questions that will be analyzed with these composites are: Is the general synoptic pressure/height pattern changing? How does the rate of warming compare between inland and over the ocean? Will the East Pacific high or the interior heat low change over the next century? How will synoptic cloudiness be altered in future years? Similar composites for the region will be completed using the high-resolution downscaled ECHAM5 and CCSM3 that were described in a previous section. An important question to be explored is whether there are changes in the mesoscale configurations over time that is not found in the GCMs. Comparisons between GCM and downscaled pressure/heights, temperature, wind, and cloudiness will be made during the next century. Future trends will be calculated for such fields as the coastal pressure gradient, mid- and lower-tropospheric temperature, and low-level relative humidity.

Deliverable Type	Description	Status
Conference	AMS Mountain Meteorology Conference	Complete
Conference	Pacific Northwest Climate Conference	Presentation on 9 Sep 2014
Workshop	NW Weather Workshop, Seattle, WA	Complete
Publication	Describes important summertime features over PNW	Complete (In Press)
Informal Meetings	Dissemination of findings to operational community	Complete

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