2021 PNW Heatwave Time Series Analysis: A Possible 'Recipe' for Heatwaves in Seattle

Mentor: Dr. Eric Salathé

Christopher McJunkin

University of Washington Bothell

Background

In the summer of 2021, a massive heatwave struck the Pacific Northwest. Temperature records broke across the region. An understanding of heatwave development can provide regional government and facilities with information to better prepare for these events.

Heatwaves are seen to grow in frequency according the WRF ensemble (figure 1), a collection of data comprised of many regional climate simulation models. Although they cover the mesoscale of the PNW, data in this paper is based off SeaTac using a 12-km grid spacing and assuming an RCP 8.5 scenario (Mass et al., 2021).

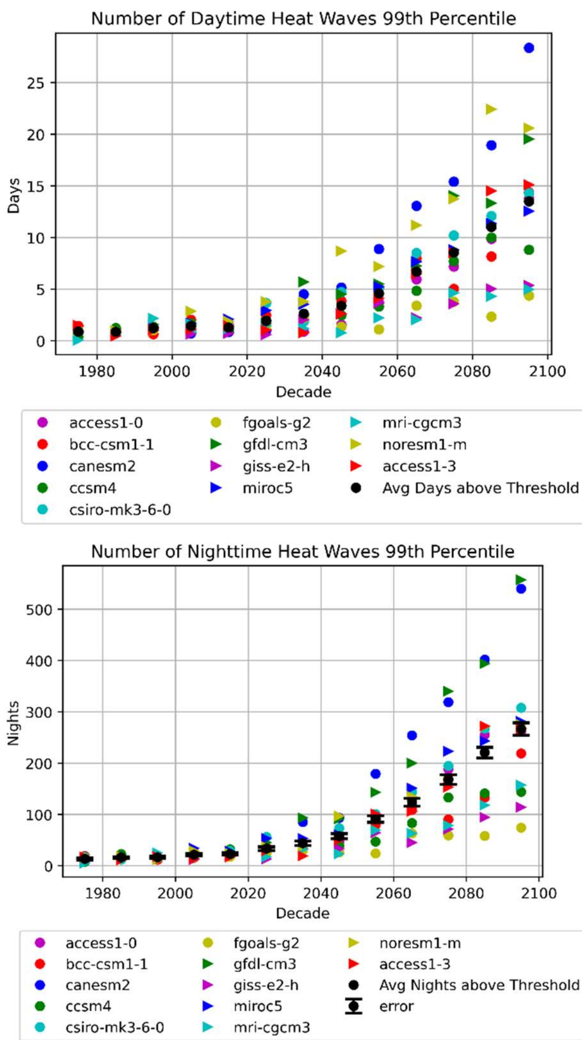

Figure 1: Number of heatwaves per model

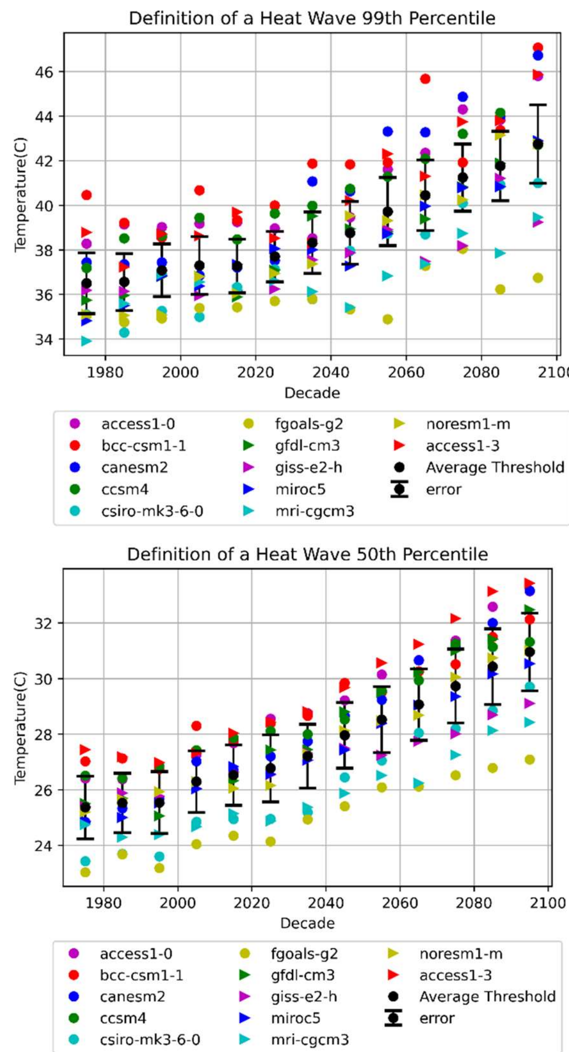

Figure 2: Changes over time of the 99th and 50th percentile temperatures in heatwaves

The definition used for heatwaves is described to be a three-day event that exceeds the 99th percentile threshold (Bumbaco et al., 2013). Analysis over a summer REU program utilized this definition.

During the REU, heatwave temperatures were found to grow in the WRF ensemble alongside how often they occur. An observed historic threshold from 1970 to 1999 was used to compare 99th percentiles in the WRF ensemble per summer (June – September). The historic threshold is 33°C. In context of the PNW 2021 heatwave, according to the daytime 99th percentile thresholds of the WRF ensemble, SeaTac should expect a heatwave 37°C ± 1°C. In contrast, the heatwave in SeaTac was, at the highest, 42°C.

Data Collection/Methods

Time series data was collected from Weather Underground's stations from municipal and international airports (KCLS, KHQM, KPDX, KRLD, CYVR, KSEA, and KEAT) between the dates of 6/16/2021 0:00 and 7/10/2021 23:00. Each time series for each station was interpolated to produce a reliable FFT due to some missing data present in some stations.

The NOAA HYSPLIT trajectory model supplied back trajectories from Seattle and Portland locations. HYSPLIT processed a 72-hour period between 8:00 UTC 6/26/2021 and 8:00 UTC 6/29/2021. Back trajectories boundary heights were set to 500 meters to avoid anomalies present in the Atmospheric Boundary Layer. Temperature data and elevation data reported from HYSPLIT was used to determine heat contribution in an idealized system examined later in this paper.

Results

Qualitatively, a heatwave signal can be seen in all stations from their respective time series but remains hidden within the diurnal cycle (figure 3).

A 32-hour cycle filter was found to best bring out the heatwave signal present within the time series

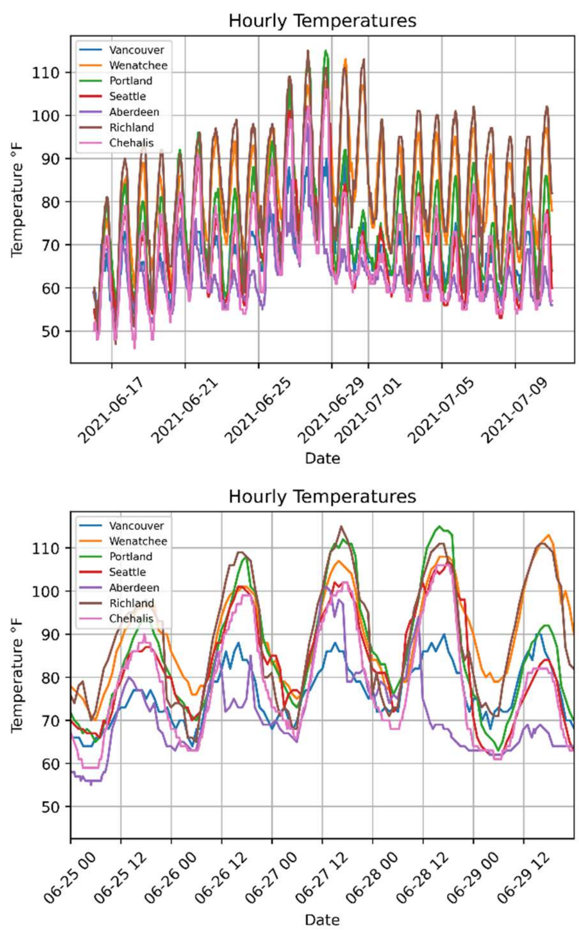

Figure 3: Above – Time series of heatwave over all stations. A distinct hump can be found during the dates of the heatwave. Below – A zoom in on the station data within the dates of the heatwave experienced in Seattle/Portland

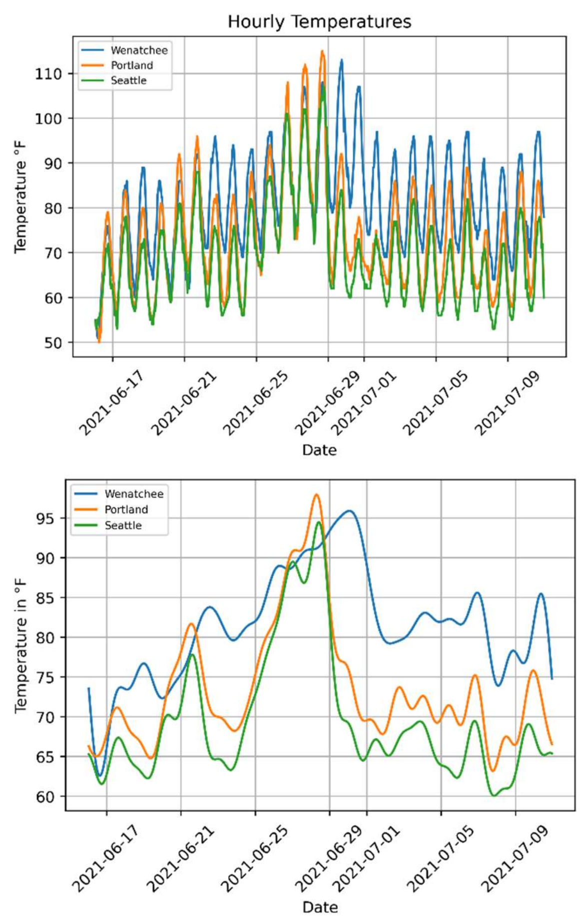

Figure 4: Above – Time series of heatwave with only Wenatchee, Portland, and Seattle stations. Below – Fourier transform of the above time series, revealing a prominent heatwave signal.

(figure 4). In addition to the growing temperatures, another interesting feature revealed by the Fourier transform is cool temperature relief from the heatwave in places like Portland and Seattle. The Fourier transform hinted at a possible timing of the heatwave, where Eastern Washington was hit with hotter air before cities West of the Cascades (Wang & Ullrich, 2018).

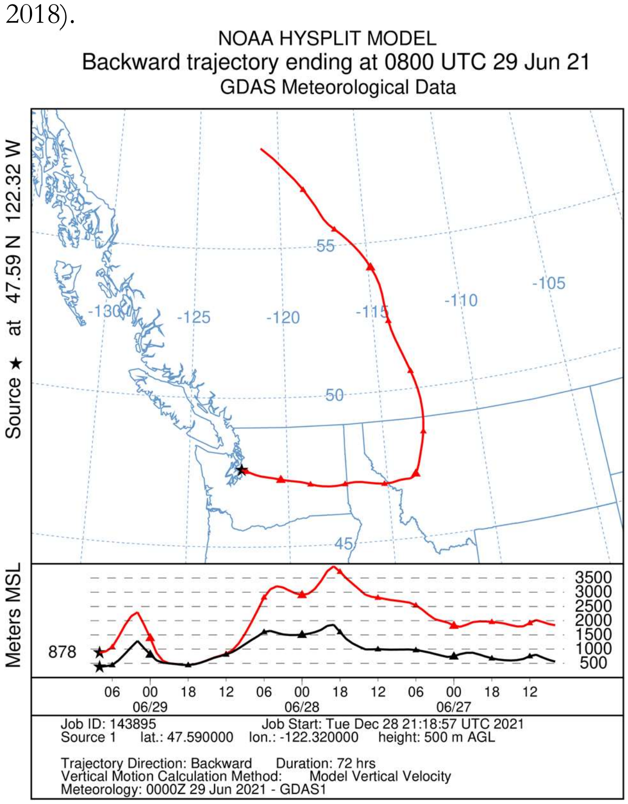

Figure 5: HYSPLIT back trajectory. In the graph below the trajectory, the black line is terrain height above sea-level, while the red line is the height above terrain. The trajectory shows the air parcel beginning in high elevations in Alberta and continuing with the terrain until entering the Idaho – Montana border.

The HYSPLIT model does suggest the air did travel into Eastern Washington before reaching the Western cities, and furthermore suggests it came from high elevations above Alberta. The air at high elevations brought down to city elevations could help describe how the heatwave broke records. The back trajectory reveals elevations between ~2 km and ~3.5 km before crossing the US-Canadian border. The ambient temperatures reported through HYSPLIT at these elevations at the time is ≈ -3°C.

By using the following equation,

$$\Delta T = (\Delta q - g\Delta z)/Cp \quad (1)$$

one can determine how much warming a parcel of air can experience, where Δq is the amount of heat added or taken out of the parcel, Δz is the change of elevation, g is the gravitational acceleration 9.8 m s^{-2}, and C_p is the heat capacity of air, assuming constant pressure.

Assuming dry air and adiabatic process, C_p = 1004 J K^{-1} kg^{-1}, and $\Delta q = 0$ J. Therefore, we can rearrange equation 1 to

$$\frac{\Delta T}{\Delta z} \approx \frac{dT}{dz} = -\frac{g}{Cp} = -9.8\ \frac{K}{km}$$

Using -9.8 K km^{-1}, a change in elevation Δz = 3.5 km gives a warming of 34°C to a parcel assumed at −3°C.

More realistically, the scenario is diabatic. Taking equation 1 and solving for Δq by using HYSPLIT ambient temperature, the range of Δq varied between ±3000 J. Using −3000 J and 3000 J as boundaries for Δq, ΔT can be expected to be in the range of 31°C and 37°C from 3.5 km.

The WRF ensemble 50th percentile for 2021 gives temperature ranges of 25°C−28°C. By using the change in temperature from the 50th percentile to the 99th percentile as ΔT gives a Δz of 0.8 km to 1.3 km under adiabatic conditions. But assuming Δq takes on a value range observed in the 2021 PNW heatwave, Δz values are expected to be from 1.0 km to 1.6 km.

Discussion

This analysis assumes the parcel never changes pressure, and Δq supplied by HYSPLIT is only specific to the dates ran in the model. Though the actual heatwave system is much more dynamic in changing pressures and volumes, the analysis presents a possible snapshot look at how heatwaves evolve and contribute to the PNW.

Heat energy Δq also has a variety of influences ranging from convection and conduction to photon absorption from the earth and Sun as well as the latent heat of water vapor being compressed or evaporating.

The overall picture of creating a heatwave from this analysis suggests taking air parcels from high elevations to lower elevations to convert its potential energy. Furthermore, due do the desert like climate of Eastern Washington, the parcel could be scrubbed across the region to contribute to Δq. Finally, pushing parcels over the Cascade mountain range from the elevation of the Washington Plateau will create further warming due to the difference in elevation between the plateau and lowland areas West of the mountains.

When looking at the Fourier transformed time series, a question of timing is prompted. Temperatures in Wenatchee continued to grow after for the next four days after the heatwave relief is seen in figure 4. The NOAA HYSPLIT model reinforces the idea that air parcels traveled from East to West relative to the region e.g., over the Cascade mountain range. Station temperatures overlayed with wind data may allow for a clearer analysis of heatwave evolution.

The same method can be applied to other historically observed heatwaves and determine if there is a suggestion that heatwaves are caused from higher elevation air parcels being driven over the plateau and over the Cascades. From there, a heatwave pattern may be identified. Using that heatwave pattern, heatwave events found in the WRF ensemble can be compared to the pattern to examine the impact climate change may have on future heatwaves.

Acknowledgements

I would like to thank my mentor, Dr. Salathé, Satveer Sandhu, Adrienne Beggs, and Cliff Mass as well as NOAA Air Resources Laboratory and Weather Underground and its stations at CYVR, KCLS, KEAT, KHQM, KPDX, KRLD, KSEA.

Bibliography

Brewer, M. C., & Mass, C. F. (2016). Projected Changes in Heat Extremes and Associated Synoptic- and Mesoscale Conditions over the Northwest United States. In Journal of Climate (Vol. 29, Issue 17, pp. 6383–6400). American Meteorological Society. https://doi.org/10.1175/jcli-d-15-0641.1

Bumbaco, K. A., Dello, K. D., & Bond, N. A. (2013). History of Pacific Northwest Heat Waves: Synoptic Pattern and Trends. In Journal of Applied Meteorology and Climatology (Vol. 52, Issue 7, pp. 1618–1631). American Meteorological Society. https://doi.org/10.1175/jamc-d-12-094.1

Isaksen, T. B., Yost, M., Hom, E., & Fenske, R. (2014). Projected health impacts of heat events in Washington State associated with climate change. In Reviews on Environmental Health (Vol. 29, Issues 1–2). Walter de Gruyter GmbH. https://doi.org/10.1515/reveh-2014-0029

Lovett, R. A. (2013). Air-movement pattern portends US heatwaves. In Nature. Springer Science and Business Media LLC. https://doi.org/10.1038/nature.2013.14033

Mass, C. F., Salathé, E. P., Jr., Steed, R., Baars, J. (2021). The Mesoscale Response to Global Warming over the Pacific Northwest Evaluated Using a Regional Climate Model Ensemble. (2021). In Journal of Climate (pp. 1–56). American Meteorological Society. https://doi.org/10.1175/jcli-d-21-0061.1

McKinnon, K. A., A. Rhines, M. P. Tingley, and P. Huybers (2016), The changing shape of Northern Hemisphere summer temperature distributions, J. Geophys. Res. Atmos., 121, 8849–8868, doi:10.1002/2016JD025292.

Rolph, G., Stein, A., and Stunder, B., (2017). Real-time Environmental Applications and Display sYstem: READY. Environmental Modelling & Software, 95, 210-228, https://doi.org/10.1016/j.envsoft.2017.06.025

Salathé, E. P., Jr., Leung, L. R., Qian, Y., & Zhang, Y. (2010). Regional climate model projections for the State of Washington. In Climatic Change (Vol. 102, Issues 1–2, pp. 51–75). Springer Science and Business Media LLC. https://doi.org/10.1007/s10584-010-9849-y

Schramm, P. J., Vaidyanathan, A., Radhakrishnan, L., Gates, A., Hartnett, K., & Breysse, P. (2021). Heat-Related Emergency Department Visits During the Northwestern Heat Wave — United States, June 2021. In MMWR. Morbidity and Mortality Weekly Report (Vol. 70, Issue 29). Centers for Disease Control MMWR Office. https://doi.org/10.15585/mmwr.mm7029e1

Stein, A.F., Draxler, R.R, Rolph, G.D., Stunder, B.J.B., Cohen, M.D., and Ngan, F., (2015). NOAA's HYSPLIT atmospheric transport and dispersion modeling system, Bull. Amer. Meteor. Soc., 96, 2059-2077, http://dx.doi.org/10.1175/BAMS-D-14-00110.1

Wang, M., & Ullrich, P. (2018). Marine Air Penetration in California's Central Valley: Meteorological Drivers and the Impact of Climate Change. In Journal of Applied Meteorology and Climatology (Vol. 57, Issue 1, pp. 137–154). American Meteorological Society. https://doi.org/10.1175/jamc-d-17-0089.1

Chehalis, WA Weather History | Weather Underground [Weather Report]. Retrieved from https://www.wunderground.com/history/daily/us/wa/chehalis/KCLS/

Hoquiam, WA Weather History | Weather Underground [Weather Report]. Retrieved from https://www.wunderground.com/history/daily/us/wa/hoquiam/KHQM/

Portland, OR Weather History | Weather Underground [Weather Report]. Retrieved from https://www.wunderground.com/history/daily/us/or/portland/KPDX/

Richland, WA Weather History | Weather Underground [Weather Report]. Retrieved from https://www.wunderground.com/history/daily/us/wa/richland/KRLD/date/

Richmond, Canada Weather History | Weather Underground [Weather Report]. Retrieved from https://www.wunderground.com/history/daily/ca/richmond/CYVR/

SeaTac, WA Weather History | Weather Underground [Weather Report]. Retrieved from https://www.wunderground.com/history/daily/us/wa/seatac/KSEA

Wenatchee, WA Weather History | Weather Underground [Weather Report]. Retrieved from https://www.wunderground.com/history/daily/us/wa/wenatchee/KEAT/