Spring 5-2021

Analysis of Extreme Precipitation and Identification of Tropical Storms in the Near-Hawaii Region

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Recommended Citation
Odstrchel, Brooke, "Analysis of Extreme Precipitation and Identification of Tropical Storms in the Near-Hawaii Region" (2021). *Atmospheric & Environmental Sciences.* 23.
https://scholarsarchive.library.albany.edu/honorscollege_daes/23

Analysis of Extreme Precipitation and Identification of Tropical Storms in the Near-Hawaii Region

An honors thesis presented to the
Department of Atmospheric and Environmental Science,
University at Albany, State University of New York
in partial fulfillment of the requirements
for graduation with Honors in Atmospheric Science
and
graduation from The Honors College

Brooke Odstrchel

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May 2021

Abstract

The Hawaiian island are chain of volcanic island with unique location, climate, and weather patterns that are very different from the mainland united states. Various synoptic weather patterns, including cold fronts, tropical cyclones, Kona Lows, and trade winds all influence rainfall across the region. Unlike other areas, Hawaii has not been studied in-depth by climate models, in order to further identify tropical cyclones and extreme precipitation events.

Running both historical and future WRF ensemble runs allow for a close analyzation of extreme precipitation events over the entirety of the Hawai'i islands. Both the frequency and intensity of the top extreme rainfall events are observed throughout a set of various parameters, including precipitation maximum and surface pressure. The dry summer season and the wet winter seasons are divided into four seasonal groupings (SON, DJF, MAM, JJA), to get a better sense of how extreme rainfall in changing in future climate ensemble runs. From this it is observed that frequent and intense tropical systems over Hawaii are in the future, along with extreme amounts of rainfall, over the entire island not just the mountain regions, in a single day. The climate of the Hawai'i Islands is changing in the future, in terms of rainfall, and a deeper look at the synoptic weather patterns and the extreme rainfall that are produced give insight to just how so.

Keywords: *Hawaii, Synoptic Weather, Extreme Rainfall, Tropical Cyclones*

Acknowledgements

Many People have helped me throughout my research and writing my thesis this past year. I would like to give a big thanks to Katrina Fandrich for providing helpful insights for approaching writing my thesis and for providing me with feedback throughout my research process. I would also like to give a big thanks to Professor Elison-Timm as he was instrumental in guiding me throughout my entire research process and answered any question I may have had. He was also very helpful guiding me throughout my undergraduate career and throughout the graduate school process- Thank you!

I would also like to thank all of my other professors who have supported me throughout my undergraduate career, especially Ross Lazear and Kevin Tyle, who were amazing professors and answered any questions I had, whether or not they were my professor at the time.

Finally, thanks to my family and friends for supporting me, throughout my life and entire college career. You guys made my dreams possible and were my biggest cheerleaders along the way. None of this would’ve been possible without you.

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Introduction

Background

The Hawaiian Islands region has an intriguing geographic location, climate and topography that is quite interesting for climate modeling that has yet to be studied in depth, compared to other regions in the world. Hawai'i is a chain of volcanic islands on a hot spot sitting in the Central Pacific Ocean, formed million so years ago through the drift of the tectonic plates.by volcanoes erupting and cooling on the ocean surface. Located within the easterly trades in the subtropical North Pacific the islands climate has distinct windward and leeward climate gradients, where the windward side of the mountains receives significantly more rainfall, while the region in the leeward side is generally drier (with in parts desert like conditions) (Giambelluca et al., 2013). Thus, higher annual rainfall amounts are found on the windward slopes and lower annual rainfall amounts on the leeward slopes Hawaii maintains warm temperatures year-round due to the moderating ocean effects, but comes at the price of weather and climate related risks, such as wind damage from tropical cyclones, coastal flooding and erosion, flash floods and mudslides. While the trade winds play a role in Hawaii's precipitation, interannual rainfall variability is strongly influenced by the El Nino-Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Chu & Chen 2005). The ENSO cycle, the most dominant mode of natural climate variability, fluctuating on a 2-8-year cycle. Hawaii tends to be drier during El Nino(+PDO) events and wet during La Nina(-PDO) events, with the negative PDO phase being correlated with winter Hawaiian rainfall (Fandrich, 2020).

Synoptic Weather Patterns

While trade-wind orographic rainfall is the most frequent rainfall pattern overall here are four main types of synoptic weather situations that contribute to the year-round rainfall events in Hawaii (Longman, 2021). These atmospheric disturbances include cold fronts, Kona lows, tropical cyclones, and upper tropospheric disturbances (Longman, 2021). These synoptic scenarios can be categorized into two different hydrologcial seasons: extra tropical disturbances, cold fronts and Kona Lows occurring in the wet winter months, from November to April, while tropical cyclones and trade winds influencing rainfall in the dry summer months from May to October. **Figure 1** and **Figure 2**, respectively from Longman's recently published paper, depicts these different synoptic patterns that produce rainfall in Hawaii and the occurrence off each disturbance type. Both of these figures allow a better understanding of what exactly Hawaii's weather and climate patterns are and what synoptic patterns produce extreme and non-extreme rainfall, as it is not the same as the continental United States. **Figure 1** illustrates the how the synoptic setup would look like in a typical scenario of the islands, while **Figure 2** shows the frequency of each type of atmospheric disturbance sorted by which month each disturbance occurs in regard to producing rainfall in Hawaii. Tropical cyclones dominate the dry summer months, while fronts, upper-level lows, and Kona lows dominated the wet winter months.

WRF Model (downscaling) and Objectives

Looking at future climate change, global climate models begin to do a better job in reproducing these weather systems that are seen to emerge over Hawaii than they previously did. However, the regional rainfall changes over the islands still cannot be resolved. Thus, dynamical downscaling is used and is one such method is to apply downscaling to regional climate models.

This method is tested and used throughout the entirety of the analysis of extreme precipitation over Hawaii in both the historical and future model runs, to better understand what climate change will bring about.

Currently, there are a few main goals and questions that drive this research project of extreme tropical storm systems and precipitation over the Hawaiian Islands. The overarching goal is to identify extreme precipitation events in the WRF model simulations, using threshold-based event detection methods for the Hawaiian Island's. The second research objective is to analyze weather conditions, such as pressure, wind, humidity, temperature, and rainfall roughly 3 to 5 days leading up to an extreme event. The third research objective is to use animation plots of daily weather patterns to visually identify tropical storms in near the Hawaiian Island into WRF simulation models. Furthermore, a fourth research objective is to obtain characteristic measures of the intensity of tropical storm systems, wind and rainfall maximums over land, and combine all of that data into an excel spread sheet. Continuing off of this would be to develop a variety of time series of minimum pressure over the ocean, precipitation maximum over land, and wind to see if tropical storm systems can be detected in time series rather than visually in animated plots. The final research question to be examined, along with the general tropical storm and extreme precipitation over the Hawaiian Island clime region, along with how to proceed in answering it, is as follow:

1) Are there significant differences in extreme precipitation intensity or in tropical storm frequency between present day and future climate simulations?
    a. Comparing observed recent extreme events to study the meteorological developments leading to local precipitation extremes with simulated events in WRF ensemble simulations for present day and future climate

b. Develop semi-automated analysis method that allows to detect extreme events in the ensemble model simulations
c. Apply statistical methods to summarize the frequency and intensity of the extreme events and to compare the statistics between present and future climate simulations

Data and Methods

WRF Simulations and Map Analysis

The WRF model was given conditions, both weather and climate, from the CESM large ensemble situations, a global climate model. In this project, each model simulation with WRF is given by weather and climate variability from CESM model simulation, with the following statements briefly describing each of the simulations used (Fandrich, 2020). The WRF Model is integrated 10 times for the "present day" climate simulation of the Hawaiian Islands from 1996-2005. It is integrated again another 10 times for the future climate of Hawaii for the year 2026-2035 (Fandrich, 2020). For both the present and future climate, the WRF model is integrated under both positive and negative PDO conditions. While the WRF model is also integrated another 10 times under neutral PDO conditions, data from those simulations are not used throughout this research project (Fandrich, 2020). Some years in the WRF dataset have missing values in the daily mean rainfall over Hawaii. The data used in this research project are a total of 20 ten-year simulations grouped into four categories: positive and negative PDO ensemble runs for the 1996-2005 time period and the 2026-2035 future time period. In total almost 200 model years are available for the data analysis.

Identification of Extreme Weather Events

Using the WRF simulation data and subsequent Python programming scripts, a daily mean rainfall rate image for every year and both PDO’s can be made. To do so, Jupyter Lab, the Linux cluster that stores the WRF data, and Python programming can be used to create these images of daily mean surface pressure and daily rainfall amounts for the model domain. Therefore, this creates 365 images for every year, both positive and negative PDO, for both the present and future climates. After all of the images for both present day and future climate of Hawaii are made, an animation script can be run, combining all of the images into one movie per year. This makes it easier to shift through the images to find extreme weather events. All of the rainfall rates over the Hawaiian Islands are in one movie file, that can be paused at any time and sifted through much faster than having to open each individual image in their yearly folders. Once all of the “movie” files for each year and WRF simulation are made, each one is then played through carefully, multiple times, to see the daily mean rain rate of Hawaii. Sifting through each video allows me to look for patterns in rainfall or the synoptic environment, to see if there is a tropical disturbance near or passing through the Hawaiian Islands. If there is an “exciting” pattern, one that shows a potential tropical event or severe rainfall, it is then recorded and the image is screenshotted to make note of the day, PDO type, ensemble run, present or future climate, and year. Typically, the late summer months through November showcase some type of tropical disturbance or significant rainfall over Hawaii, while January through April showcases much less rainfall over the islands. While this approach can be used to identify a few outstanding events, this method is neither objective nor reproducible; a different researcher would apply their own expert judgement based on prior experience and expertise. Therefore, I developed and tested alternative, quantitative metrics that could allow us to detect high impact weather events in a reproducible way. To this end, a set of statistical parameters were extracted from the daily model output, with the main indices and their use are described as seen in Table 1.

Extreme Index and Seasonal Analysis

The extreme index analysis from all of the WRF simulations comprises of applying Python scripts to combine the previous time index series of both the historical and future simulations. In order to improve the detection of daily extreme weather situations in the daily model data output, I developed index time series with daily values of various meteorologically relevant variables: daily maximum precipitation (pmax) over land, daily minimum surface pressure over ocean (psfcmin), daily precipitation maximum over ocean (pomax), daily precipitation total over land (ptotal), and wind maximum (wmax) **(Table 1).** Then each variable in both historical and future ensemble runs are sorted and ranked in correlation to surface pressure minimum(psfcmin). This yields four different tables with variables ranked in relation the lowest psfcmin for each historical/future positive/negative PDO ensemble run, along with four additional index tables showing the ranking of each variable in regards to psfcmin. In addition, the Python scripts are updated to sort and rank all of the time index series to distinguish the seasons by four groups: December-January-February (DJF), March-April-May (MAM), June-July-August (JJA), and September-October-November (SON). These four variables are then added to the Excel sheets of ranked variables, in order to determine when, seasonally, these extreme rainfall events are occurring in Hawaii. From there, various boxplots and histograms are made for each of the different historical and future WRF PDO ensemble runs, looking specifically at psfcmin and precipitation maximum over land (pmax). Once the ranked data tables have been obtained a comparison is conducted with the top ranked index values grouped into present and future and postive and negative PDO phases. This histograms and boxplots give insight into possible shifts in the the distributions in association with these factors. This method allows for comparison and searching of patterns between alike historical and future PDO runs, how the psfcmin and pmax variables change over time in Hawaii, throughout the seasons, and if any are tropical cyclone induced events. This analysis could potentially lead to conclusions about seasons favored to produce extreme rainfall, tropical cyclones, and how events change overtime, and if they meet our expectations or fail to do so.

Results

Future Scenario of Extreme Rainfall

While running various WRF simulations, one of the key features that was looked for was evidence of tropical cyclone induced rainfall in either historical, or future ensemble runs. One notable event was identified in the future scenario simulation (with negative PDO phase) in June (06/29/2029, in WRF ensemble run #1). This day had been identified using the the ranking of the index for precipitation over land. The maximum daily precipitation total of 1025.19mm occurred on that specific day. The weather pattern showed a surface pressure of 993hpa over the ocean. **Figure 3** shows a sequence of this event over the course of a 6 day period. It is quite evident that a cyclonic circulation structure is located south of the islands and thus this is a tropical cyclone induced extreme rainfall event. A deep tropical moisture source is fueling such an event during Hawaii’s dry season making the region very wet as the rainfall spans a huge area instead of it normally being localized, making this a so-called “freak” event. The whole domain that was plotted of the Hawaiian Island was under heavy rainfall, which is very different from what occurs today in Hawaii.

Seasonal Analysis of Extreme Rainfall Events

Winter Weather Extremes

Although there was a significant amount of data to comb through, there have indeed been significant rainfall events and even some tropical storm/cyclone disturbances over the Hawaiian Islands region. The windward sides of the Hawaiian Islands consistently have higher and almost daily rainfall totals, compared to the leeward side of the islands. Late January seems to bring about frontal passage driven rain events, with multiple years showing the passages of a front line of storms through Hawaii. **Figure 4** showcases the daily mean rate for the positive PDO WRF 6 run on 01/23/2000, where we see such a line of storms move through the Hawaiian Region. This image illustrates, to a degree that the windward side of the island receive rainfall amounts localized of over 200mm, while the leeward side receives 0-15mm. **Figure 5** shows another example from the WRF 8 model simulation (historical positive PDO run, year 2005). It illustrates a more accurate representation of which sides of the island receive more rainfall, with higher localized amounts on the east/windward side and less on the left/leeward side. The eastern side of the Hawaiian Islands receives over 500mm of rainfall, while the western side receives the bare minimum.

Tropical Cyclone Extremes

More importantly, there have been tropical cyclones/storms that have been discovered in these animated plots of daily mean rainfall. **Figure 6** is one such example, with its origins are the positive PDO WRF 9 2001 model simulation. Here we see the clear passage of a tropical cyclone straight through the Hawaiian island, which can be proven from the structure of the storm, high rainfall amounts, and low pressure over land/ocean. The animation plot reveals one of the few tropical cyclones that have passed throughout the Hawaiian Island region in an almost perfect way. In addition, **Figure 7**, from the positive PDO WRF 6 2000 model simulation, also potentially illustrates the passage of a tropical storm or depression in this case over the Hawaiian island. It seems to be that while there is the structure of the rainfall and isobars to indicate a tropical disturbance, it has been severely weakened by the time it reached Hawaii. This event still brought significant rainfall to the Hawaiian Island regions, with localized amounts of over 100mm per day in some areas, with minimal amounts of at least 1mm of rainfall.

While those are instances of tropical cyclones or disturbances passing directly through the Hawaiian Islands, **Figure 8** is an example that does not pass directly through the Hawaiian Islands. **Figure 8** shows an event from a model simulation of the positive PDO WRF9 2001 run in which a tropical disturbance is passing through the main Hawaiian Island and to the south of it. Over the course of three days, September 25th through the 27th, it can be seen what looks potentially like some outer rain bands passing through part of the Hawaiian Islands, while the majority of the storm remains south of the Hawaiian Island region and therefore undetectable, via the pmax and psfcmin indices. While most of these tropical disturbance events seem to occur between August to November, the model simulation for PDO positive WRF 10 2001, **Figure 9** showcased a major rainfall event over the Hawaiian region in the middle of December, that lasted from 13th up until the 19th. While it is not clear if this is a tropical disturbance, as the wind field potentially indicates this, this day marks a high intensity event in terms of rainfall amounts, which were over 250mm, pushing close to 400mm in a single day. The shape of the storm could indicate that this is some sort of remnant of a tropical storm, very late in the season, but perhaps not a full-on tropical cyclone, as the storm is not symmetrical. This event brought unusual heavy rainfall over the course of several days, impacting all of the Hawaiian Islands greatly and not just the regions that favor heavy rainfall.

Statistical Analysis

Historical vs. Future Negative PDO

The first part of the statistical analysis of the multiple sorted and ranked data tables that were created involves comparing the historical and the future negative PDO ensemble runs of the both the psfcmin and pmax variables. To accurately get a sense of the variables that are involved in extreme rainfall events, the top fifty values in each seasonal grouping are plotted in box plots to see how they change between PDO ensemble runs and over time in general. The top 50 lowest surface pressure minimums over ocean (psfcmin), which are values typically associated with the synoptic patterns for extreme rainfall (such as tropical cyclones or Kona Lows), are plotted in two box plots in **Figure 10**. The lowest surface pressures are compared historically and seasonally, in order to observe where low pressure events may be correlated with extreme rainfall. Beginning with the SON months in **Figure 10** (left), this seasonal grouping has the second largest amount of lowest psfcmin values, with the DJF grouping seeming having slightly more of the lowest psfcmin values overall. This is the same for the SON plot for the future runs shown on the graph on the right in **Figure 10**. The historical SON values have a median just above 990 hPa, with the box plot being skewed towards the higher values and with a few outliers, that do not fit within the quartiles, around 987 hPa. However, the future SON psfcmin values are more disperse and less skewed than the historical run, with one outlier around 985 hPa and the median at 990 hPa. Moving on to the DJF grouping, the historical psfcmin values are very diverse, with the median around 987.5 hPa, but the graph overall is skewed to the higher surface pressure values. Comparatively, in the future ensemble runs, the DJF psfcmin values are less disperse and less skewed to higher psfcmin values, as the boxplot is shifts downwards, to accommodate for lower surface pressure outliers that previously did not exist. Both the historical and future MAM psfcmin values are less disperse, with the low surface pressure values not being observed in the future run and the medians being roughly the same around 992 hPa. Finally, looking at the JJA psfcmin values in **Figure 10** shows that the future ensemble runs produce not very many events with low surface pressure values, as the historical boxplot (left) is slightly more disperse than the future and the boxplot is not as compact as its companion graph. Overall, comparing the lowest surface pressure values between the negative historical and future PDO runs illustrates that lower pressure values are favored more towards the DJF and SON seasonal groupings in both runs, while the MAM and JJA low surface pressure values are not as prominent in future ensemble runs. This is quite different than expected, as low surface pressures, in the summer and late spring, are typically associated with tropical cyclone activity which can cause extreme rainfall in the region. This could potentially indicate a bias in the storm systems in the CESM climate model, that drives the WRF model simulations.

The next variable observed and compared by historical versus future is the precipitation maximum over land (pmax) between the four different seasonal groupings. **Figure 11** illustrates the historical (left) vs future (right) boxplots of the top fifty highest pmax values from the ensemble runs. Beginning with the historical SON grouping, the boxplot is quite dispersed, with values skewed to lower pmax values of around 600 mm over a one-day period. There are a few outliers that don’t fit the distribution around 900mm. Comparatively, the future SON pmax values are slightly less disperse than the historical, but the boxplot is skewed towards the higher values, as the largest non-outlier value being around 900 mm. However, as not seen in the historical run, there is a massive outlier of roughly 1500mm of rainfall observed over one day in Hawaii, which was not seen collectively across the seasons in the historical ensemble runs. This is a theme that is depicted throughout the future precipitation maximum values; there is more recordings of extreme rainfall events of over 1000mm in one single day shown in the boxplots, as outliers and as a part of the distribution, which was not seen prior in the historical ensemble run. Continuing on to the DJF historical group, the values are dispersed with very few outliers around 700mm, with a relative un skewed plot with a median just below 50mm. In the future boxplot of DJF, the pmax values are greater, as outliers are seen at just around 1000mm, along with the data being slightly skewed to the higher values, as the difference in medians indicates a greater pmax value difference between historical and future runs. For the historical MAM grouping, the pmax values are disperse and skewed to higher values, but the highest value in the plot is around 750mm and the outliers only being just above that at around 800-900mm. This differs from the future MAM grouping, as while its less disperse, the box plot is skewed to much higher pmax values, with the maximum value within the plot being above 800mm and outliers reaching values of 1200mm. Finally, looking at the historical JJA grouping, the plot is dispersed but skewed to lower values, with a median of 500mm and no outliers at all. But looking at the future JJA grouping, while the plot is skewed to lower values, the largest value is 800mm, compared to 700mm, with outliers of over 1000mm. In general, **Figure 11** illustrates the future seasonal groupings, while less disperse boxplots, yield precipitation maximum values greater than historical run, with more consistent recording of extreme rainfall greater than 1000mm in one day. This extreme rainfall is more common in the wet winter months of SON and DJF. The summer dry months tend to receive more heavy rainfall in the future ensemble runs but still less rainfall than the other main seasons.

Historical vs. Future Positive PDO

The second part of the statistical analysis compares the positive historical and future PDO WRF ensemble runs for the psfcmin and pmax variables. As displayed in **Figure 12**, the historical (left) and future (right) four different seasonal groupings boxplots of the top fifty lowest surface pressure minimum values. Starting with the historical SON plot, the pmax values are skewed to higher pressure vales, with the median around 990 and the highest value at 992. The data is mostly dispersed, with a few outliers around 980 hPa, which could be indicative of a an extreme rainfall event, potentially a tropical cyclone. Looking at the future SON plot, the pmax are less scattered comparatively, but even with the median being roughly the same as the historical plot, the data is skewed to lower pressure values, with a few outliers around 984 hPa. Moving forward to the historical DJF pressure, the data is skewed to higher pressure values, with one exception with an outlier at 983 hPa. The future DJF plot, while seems similar, is quite disperse and skewed towards lower psfcmin values, as more outliers are seen closer to 980 hPa. This is indictive of more lower pressure system moving through the Hawaiian Islands in the winter months in the future, but not as much in the summer ones. The MAM and JJA historical plots are skewed to higher psfcmin values than in respective wet winter month plots, with the medians being 992 and 996 hPa respectively. In both seasons the pressure values are less dispersive around the median, with very few data values for the JJA seasonal grouping, indicating that lower surface pressure values are not typically common nor seen in this seasonal grouping. Comparing these two graphs to the future MAM and JJA boxplots, the data is much more disperse but is still skewed to much higher-pressure values compared to the future SON and DJF groupings. The MAM data contains no outliers and is not skewed at all, with the lowest pressure being around 989 hPa and the median 991 hPa, which is slightly different from its historical pattern. However, the JJA plot still sees very few psfcmin data values and the few values plotted are towards the higher end, with the lowest, highest, and median value being between 995 and 997 hPa. This result is indicting that the JJA months tend to not see extreme low pressures still in the future, but more so than was illustrated in the historical ensemble run.

The precipitation maximum over land is presented in **Figure 13**, comparing the historical (left) and future (right) boxplots top fifty leading pmax values by the four seasonal groupings. Starting with the historical SON plot, the pmax values are disperse and slightly skewed to lower values, with a median of 650mm, the largest value at 1000mm, and an outlier of 1200mm. Comparing this to the future SON plot, while the data is skewed slightly to values around 700mm, in regards to the median, the larger values and outliers are upwards of 900 to 1100mm. these two plots are roughly the same, with the future SON plot having less total rainfall days below 600mm, where as we see in the historical plot low pmax values of roughly 500mm. The historical DJF graph shows a concentration at lower values, with the minimum pmax value being 350mm, the median 450mm, and the largest one around 650mm. Only one outlier is roughly 850mm. This is very different from the future DJF plot. Here, the pmax values are skewed to slightly more higher values than the historical plot, with a higher median closer to 500mm, the largest value around 750mm, and the lowest value around 400mm. There are several more significant outliers in this more disperse data set, ranging from 750 to 950mm, which is much greater and vastly different than seen in the historical graph. In addition, the MAM and JJA historical boxplots are skewed to lower values than their historical seasonal groupings and their future counterparts. This can be identified though lower medians of 500mm for MAM and

425mm for JJA, with decently disperse pmax values. While there are no outliers in the MAM plot, the JJA boxplot shows a few outliers with the more noteworthy ones reaching up to 800mm, which is still quite less than the historical SON and DJF plots. Comparing these two plots in, figure 13, to their future counterparts, the future MAM graph is slightly skewed to lower values, but has a much greater median at almost 600mm, a largest value at 725mm, and outliers reaching up to 100mm. Similarly, this is scene in the JJA graph as well, where there is a significant increase in median, 500mm, largest, 800mm, and smallest, 450mm, values, all of which are greater than the historical plot. The outliers depicted here range from 800 to 1000mm, indicative of potential tropical disturbances and a greater increase in extreme rainfall in the dry summer months from the historical ensemble runs.

Discussion and Conclusion

The intermediate results analyzing tropical storms and extreme precipitation over the Hawaiian Islands lead to some varying, and intriguing, conclusions. In today's world, we see headlines about localized record-breaking rainfall, such as the Kauai record breaking event, not this widespread extreme rainfall that this WRF ensemble run shows for the future. Notable observations such as those seen in Figure 3, that are vastly different from normal scenarios today, need to be accounted for, as it seems Hawaii's climate could see a drastic change in climate and extreme rainfall events that are very different from the past.

While tropical cyclones/storms do appear in the Hawaiian Island region in the simulations, they seem few and uncharacteristic compared with recent observed events. Most days receive a varying amount of rainfall some sort in the mountains, with the extremes ranging from roughly 400mm plus, and none on the leeward side. Random frontal passages, however, will bring some sort of rainfall to the region. The simulation results indicate that the majority of extreme precipitation events is cuased by non -tropical disturbances (consistent with historical observations and current climate, see Longman et al. 2021). This remains so for the near-term future simulations in the WRF simulations. This could be due to the ENSO cycle, frontal passage, or if something major is happening in the central/western Pacific Ocean. The statistical analysis illustrates that the median and inter-quartile ranges of the boxplots are close and show overlap. However, there is a tendency for the heaviest and extreme rainfall, greater than 800mm in a single day, to become more frequent and general in the future, regardless of the PDO run. The negative PDO runs tend to produce more of these extreme rainfall events, in comparison to the positive PDO run. While the surface pressure values don’t vary much between historical and future ensemble runs, there is a tendency of slightly lower surface pressures across in the future. The future ensemble runs lean towards higher rainfall extremes and lower pressures, especially in the fall and winter seasons, something that varies from the historical ensemble runs.

Although we do see such tropical storms make an appearance throughout the WRF model runs, it seems to be only under certain circumstances. While this research examined only two of a variety of variables, perhaps further research could be focused on some of the other variables. Instead of only examining the psfcmin and pmax variables, the wmax or q2 variables could be used to identify tropical cyclone and extreme precipitation events

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Appendix A

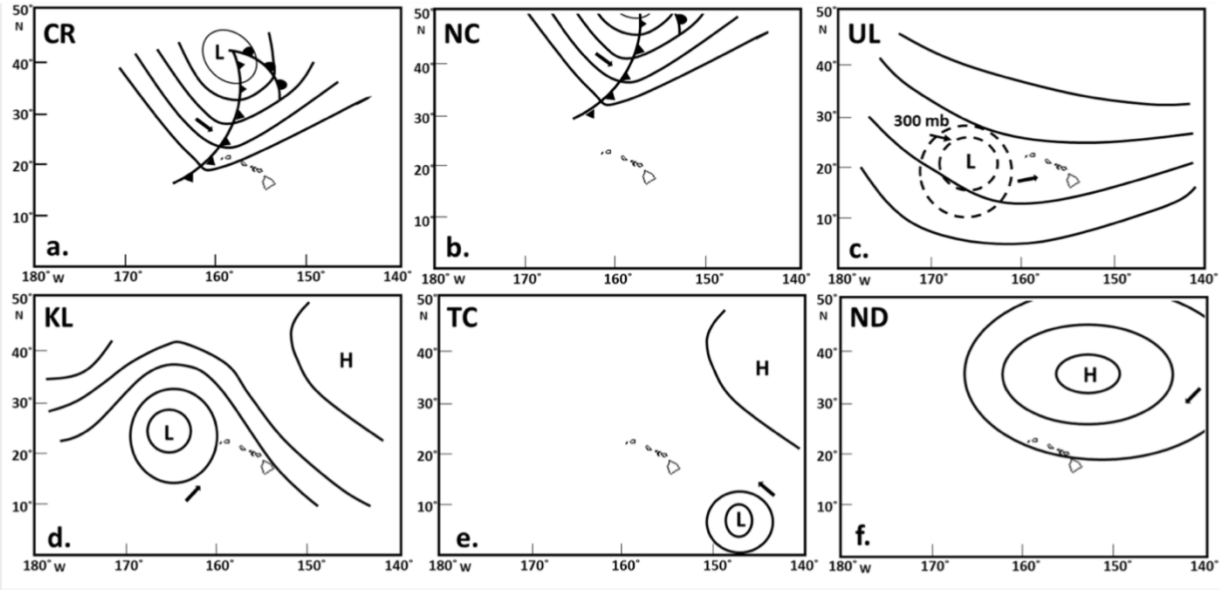

Figure 1. Schematics showing 6-types of synoptic patterns that produce rainfall in Hawaiʻi(a) crossing fronts; (b) non-crossing fronts; (c) upper level low pressure systems; (d) Kona storms; (e) Tropical Cyclones; 500 mb isobar are indicated with solid black line, wind direction are indicated by arrow.
[Figure 1 and caption adapted from Longman (2021)].

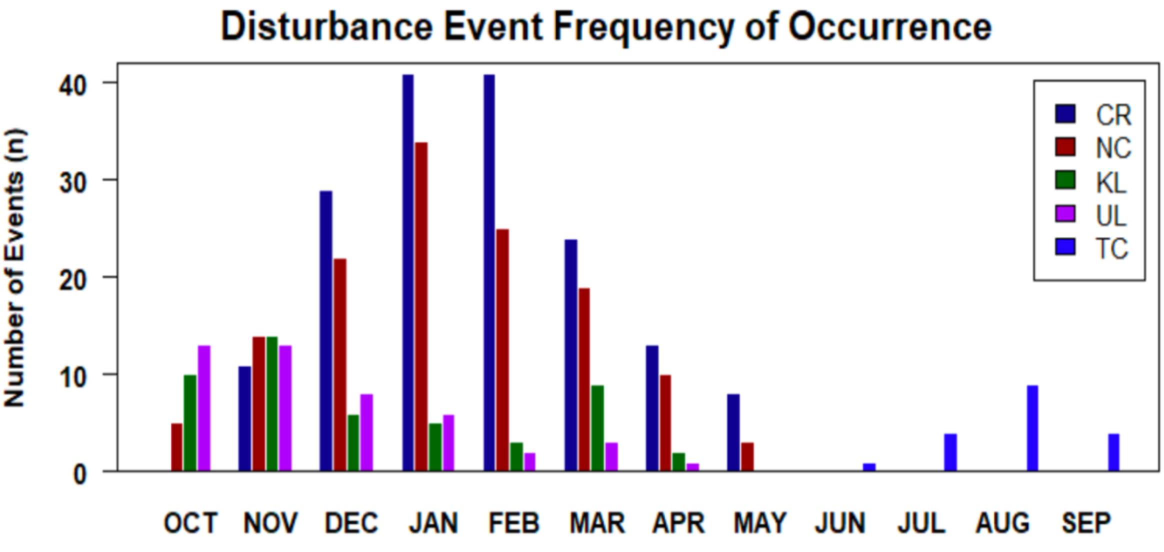

Figure 2: Frequency of occurrence for each disturbance type from 10/1/1990 to 09/31/2021; CR are crossing fronts; NC are non-crossing fronts; KL are Kona Storms; UL are upper-level lows and TC are tropical cyclones.
[Figure 2 and caption adapted from Longman (2021)].

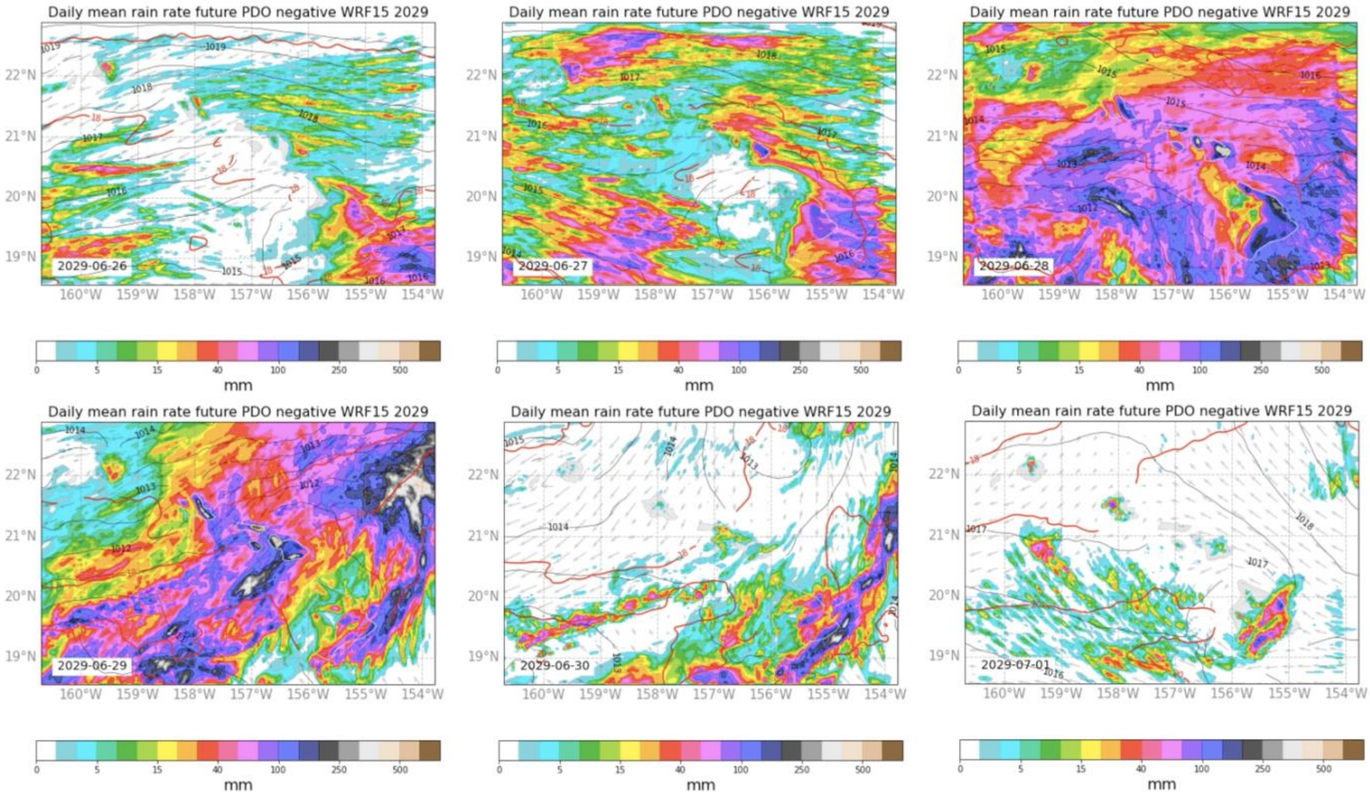

Figure 3: Six-day time lapse of the daily mean rate of rainfall from the future negative PDO WRF 15 2029 ensemble run, for June 26th through July 1st. Precipitation totals (mm), surface pressure (hPa), and wind vectors are illustrated in each individual map of the Hawaiian Islands.

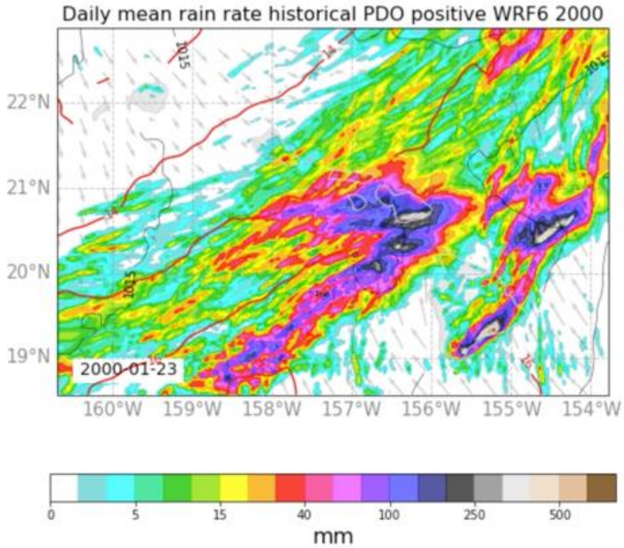

Figure 4: Mean daily rate of rainfall from the historical positive PDO WRF 6 ensemble run on January 23rd, 2000.

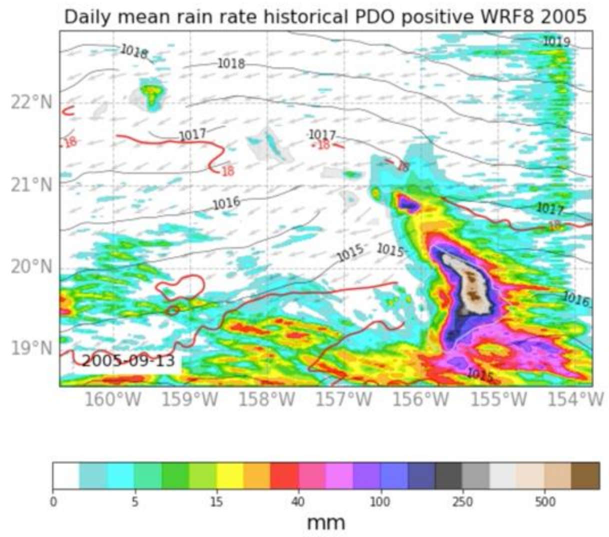

Figure 5: Mean daily rate of rainfall from the historical positive PDO WRF 8 ensemble run on September 13th, 2005

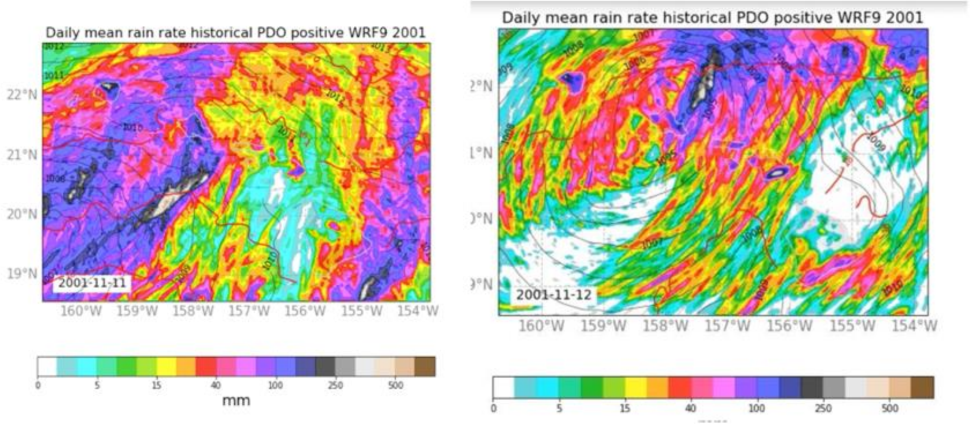

Figure 6: Mean daily rate of rainfall from the historical positive PDO WRF 9 ensemble run from November 11th to the 12th, 2001.

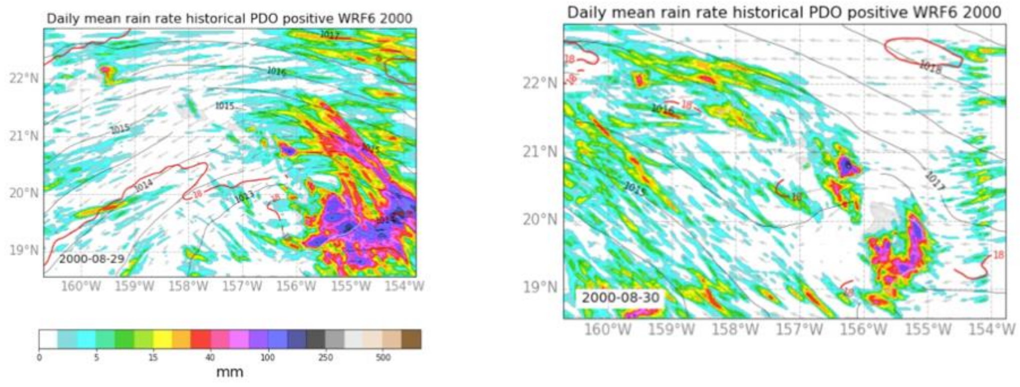

Figure 7: Mean daily rate of rainfall from the historical positive PDO WRF 6 ensemble run on August 29th to the 30th, 2000.

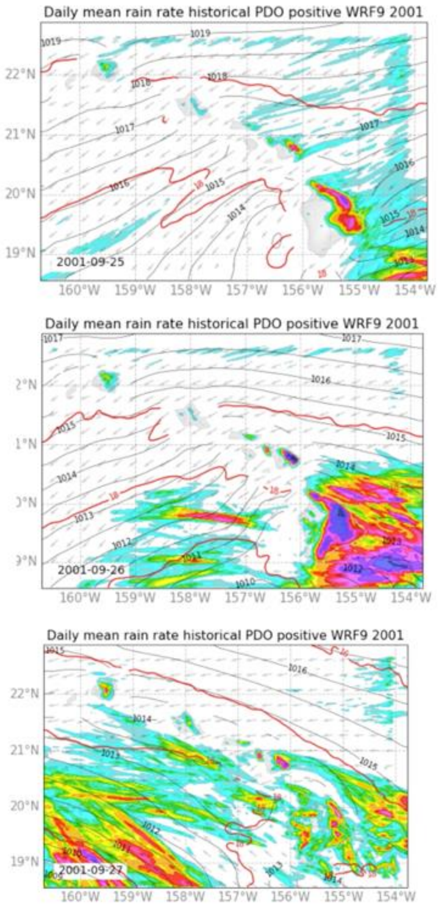

Figure 8: Mean daily rate of rainfall from the historical positive PDO WRF 9 ensemble run on September 25th-27th, 2001

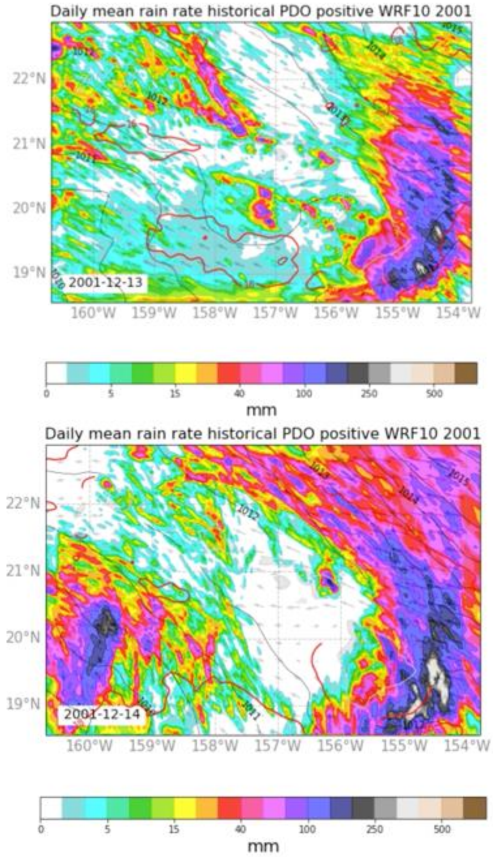

Figure 9: Mean daily rate of rainfall from the historical positive PDO WRF 10 ensemble run on December 12th-14th, 2001.

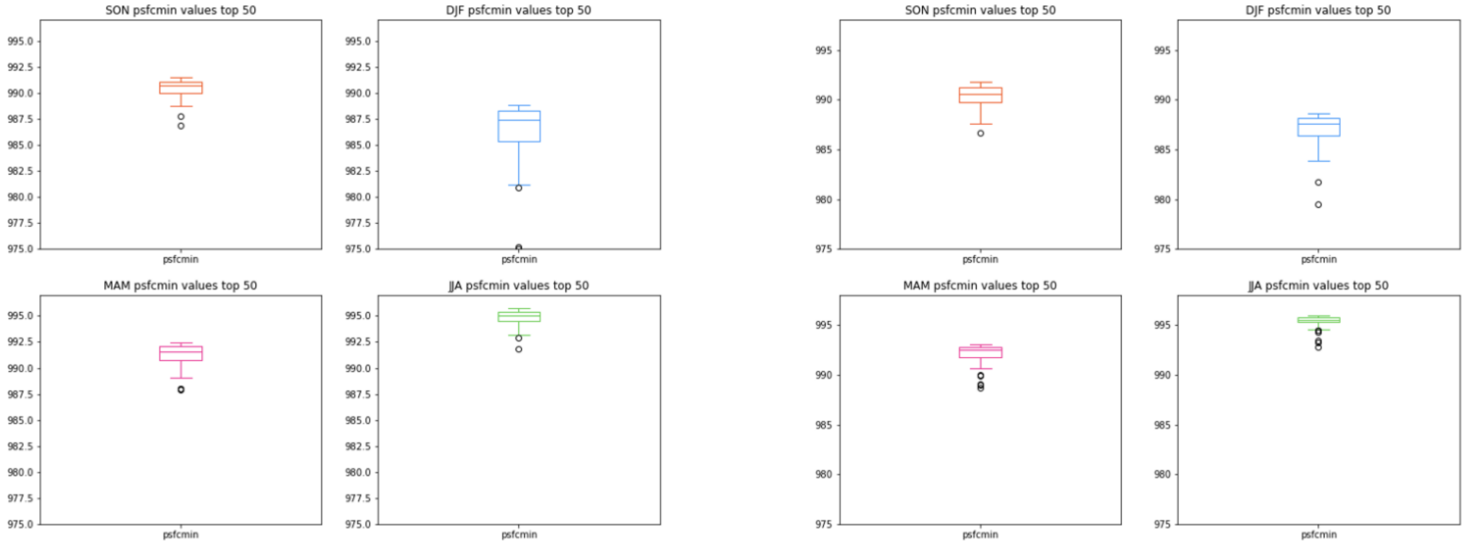

Figure 10: Box plots comparing Historical(left) versus Future(right) negative PDO WRF ensemble runs for the top 50 lowest surface pressure minimums over land. Orange is associated with SON, blue DJF, pink MAM, and green JJA seasonal groupings.

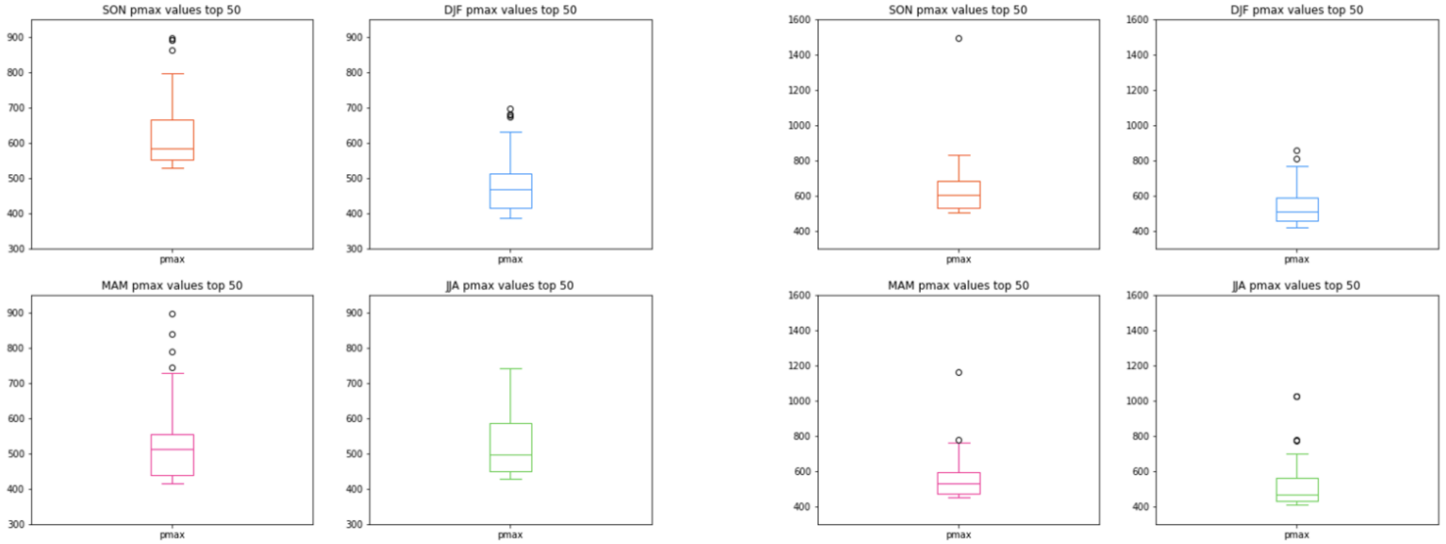

Figure 11: Box plots comparing Historical (left) and Future (right) negative PDO WRF ensemble runs for the top 50 highest precipitation maximums over land. Orange is associated with SON, blue DJF, pink MAM, and green JJA seasonal groupings.

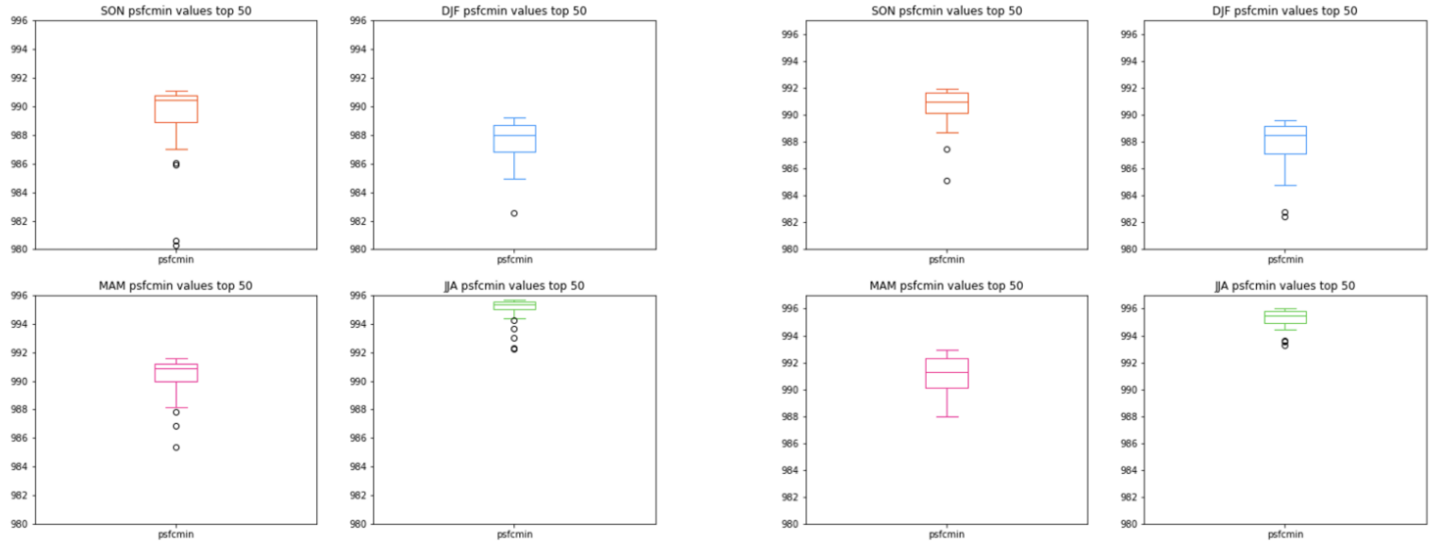

Figure 12: Box plots comparing Historical (left) and Future (right) positive PDO WRF ensemble runs for the top 50 lowest surface pressure minimums over land. Orange is associated with SON, blue DJF, pink MAM, and green JJA seasonal groupings.

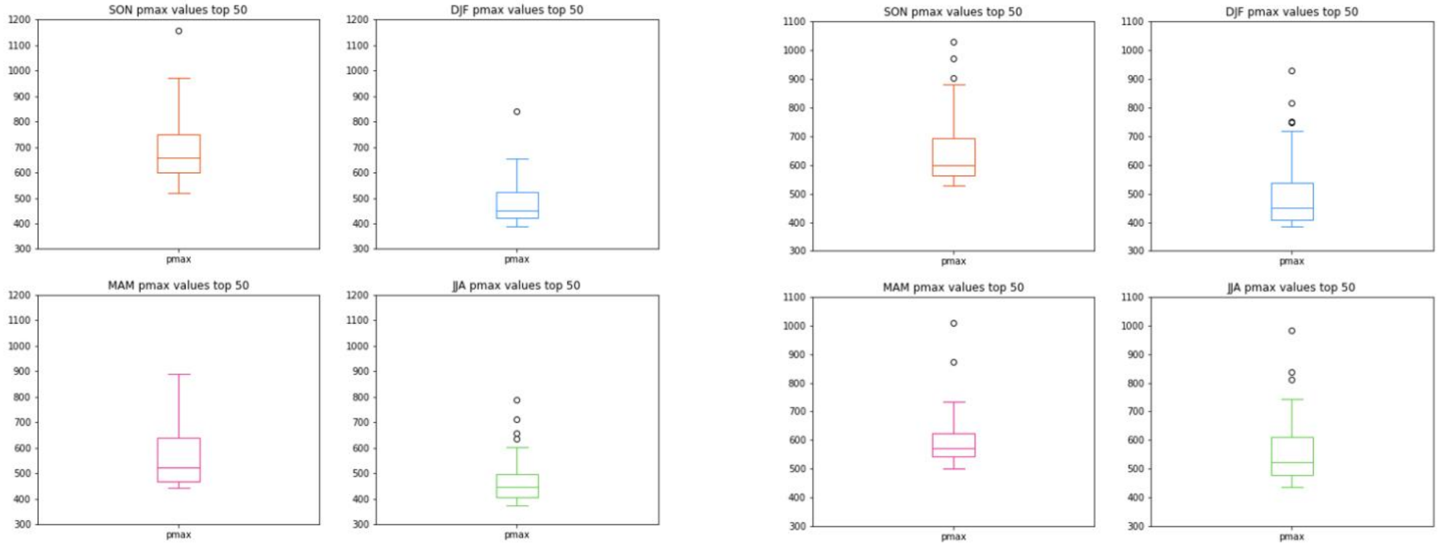

Figure 13: Box plots comparing Historical (left) and Future (right) positive PDO WRF ensemble runs for the top 50 highest precipitation maximums over land. Orange is associated with SON, blue DJF, pink MAM, and green JJA seasonal groupings.

Appendix B

Table 1

List of the Main Variables Used in Extreme Index and Seasonal Analysis

Variables	**Definition**
pmax	Precipitation minimum over land (single grid point's precipitation)
psfcmin	Surface pressure minimum over ocean grid points in the model domain
psfcvar	Surface pressure variance over ocean grid points
pomax	Precipitation maximum over ocean
ptotal	Precipitation total over land (sum)
wmax	Wind maximum (near surface, over ocean)