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07/25/2022

Rainforests In Hot Water:

Warming Oceans and Their Effect on Wildfires in the Temperate Rainforests of the Pacific Northwest.

Abstract

In an era of increasingly large and destructive wildfire seasons, it is important to understand how wildfire conditions have changed over time, which environmental factors have influenced these changes, and how these changes have affected specific biomes. This project examines how climate change has affected wildfires which occur in the dense and verdant temperate rainforest regions of the U.S. Pacific Northwest. It examines the size of burned areas of rainforest over time and assesses the correlation of burned area size to environmental factors such as average air temperature, ocean temperature, and number of days of precipitation per year. In this way I examine the central question of how climate change has affected the size and severity of wildfires which occur in these sensitive ecosystems. Large wildfires in the Pacific Northwest are often tied to extended periods of warmer and drier than average conditions. Periods of drought are likely to become more common in a warming world, which will likely result in larger and more severe wildfires, compared to the twentieth century. (4) Additionally, warmer sea surface temperature anomalies such as La Nina have proven to be predictive of severe wildfires in the western U.S. in general, and warmer sea surface temperatures in the North Pacific have a correlation to larger wildfires in the pacific northwest specifically (5). The results of this project

demonstrate the overall scale of wildfire within Pacific Northwest temperate forests over time and its correlation to air and sea surface temperatures. An understanding of how environmental factors influence wildfires in any given environment is critical for both researchers seeking to document natural processes, and land managers seeking to better forecast significant wildfire events in their regions. This study concludes that sea surface temperatures in the North Pacific have risen in a statistically significant manner during the period from 2000 to 2020. Additionally, the mean and median size of wildfires in the temperate rainforest regions of the U.S. Pacific Northwest have also increased in a statistically significant manner during this same period. This study finds a 48.09% correlation between annual mean sea surface temperature in the North Pacific and the annual median acreage of wildfires in Temperate rainforest. There is a 26.17% correlation between annual mean North pacific sea surface temperature and mean wildfire size in the rainforest. This study has also found a -32.55% correlation between annual precipitation in the Pacific Northwest and the median size of wildfires within the rainforests of the region. This demonstrates that years of decreased rain carry a higher risk of large wildfire, even in traditionally cool, damp regions of the west coast. Additionally, average annual temperature in the pacific northwest has a 25.60% correlation with median wildfire acreage in the rainforest during the study period, and a 25.37% correlation with the mean wildfire acreage during this period. This demonstrates that although local temperature is an important determinant of wildfire risk, other factors such as lower precipitation causing the drying of plant matter, and elevated sea surface temperatures affecting the maritime climate, play an outsize role in determining the severity of the annual fire season within temperate coastal rainforest environments.

Introduction

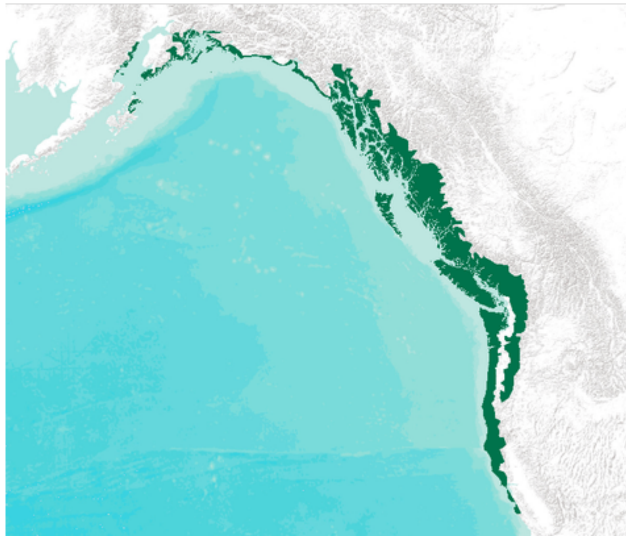
Increasingly hot, dry summers and warmer ocean temperatures are leading to an increasingly long, increasingly hazardous wildfire seasons in the American Pacific Northwest (4). This has led to an increasing level of direct threat by fire to rural and suburban communities directly adjacent to forested lands as well as indirect threats to urban centers caused by dense wildfire smoke and airborne particulates. The Pacific Northwest is naturally a cool, wet climate, with dense forests of old growth trees and high annual rainfall. Because of this, wildfires in western Oregon and Washington have typically been smaller than those observed in the warmer, drier climate of southern and central coastal regions of California (1). Although wildfires are a natural part of forest ecosystems throughout the Pacific Northwest, large uncontrolled wildfires, crown fires, and other destructive fire events have typically occurred under generally atypical circumstances such as drought and high wind (1). The resulting fires, although still large and high intensity, have been more limited in total area burned and shorter in duration than those that now occur regularly in California. Despite the relative difference in the scale and frequency of wildfires in this region, scientists, resource managers, and emergency responders alike have grown increasingly concerned that a warming climate, drier summers, warmer ocean temperatures, and the spread of insect parasites that leave areas of forest as little more than dry tinder are beginning to erode the advantages of the naturally less fire prone forests of the Pacific Northwest (4,8 ,17). Large wildfires in Washington State, Oregon, Idaho, and Montana have gained increasing attention in recent years, drawing in ever more of the precious and thinly spread firefighting infrastructure of the American West. (4,11) According to current climate projections based on historical data compiled through the late twentieth century to today, increasingly common drought conditions in the Western U.S. will have a drying affect on fuels within forested areas. This in turn will lead to increasingly long and hazardous wildfire seasons, with new fires igniting more easily among the highly flammable dry fuels available in high density forested areas (4, 20). Additionally, the decline of arctic sea ice and rising ocean temperatures in the North Pacific are diminishing the periods of cool, wet weather which makes the rainforests of the Pacific Northwest more resilient to large wildfires than other areas of the West Coast. (7)

This project tracks the changes in rainforest areas of the Pacific Northwest over time and assesses the size, scope and frequency of large uncontrolled burns and other destructive fire events. This information has been compared to average North Pacific sea surface temperature, average observed air temperature, and rainfall in these areas during the same period to determine the effect of local weather conditions on wildfire proliferation, and the degree to which climate affect the pattern of wildfires. I have utilized publicly available data from federal and state land management organizations including the Bureau of Land Management, the U.S. Forest Service, U.S. Geological Survey, and the Monitoring Trends in Burn Severity program for information on wildfire events over time in the Pacific Northwest. I have also utilized information from the NOAA's National Centers for Environmental Information to assess the oceanic and atmospheric temperatures in the U.S. Pacific Northwest region during the years which those fire events occurred.

The primary hypothesis of this research is that increasing ocean temperatures, increasing average ambient temperatures, and decreasing numbers of rainy days per year in the Pacific Northwest have a direct quantitative correlation with the size of wildfire events within temperate rainforest areas. The secondary hypothesis of this project is that the aforementioned factors are also correlated with an increase in the total number of large, high intensity, and uncontrolled fires that occur each year in high density old growth forests. To this end, the total acreage burned as well as the mean and median size of wildfires in rainforest areas each calendar year have been examined in order to assess the relative threat of large fires to areas capable of supporting rainforest habitat.

The study region for this project consists of the historically rainforested areas of Washington State, Oregon, and northern California. The Pacific Northwest's temperate rainforests are a unique and incredibly dense forest environment which stretches along the Pacific Coast of North America from northern California to southern Alaska. The rainforests within this region are incredibly verdant, with old growth hardwood trees, firs, lichens, mosses, and ferns dominating nearly every surface capable of supporting plant life. The temperate forests of this region even surpass their tropical counterparts in their overall density, which constitutes the largest contiguous biomass in the world (15). Temperate rainforests in the Pacific Northwest are characterized by their high annual rainfall (from 140 to 167 inches annually) and their moderate temperatures, which rarely exceed 80 degrees Fahrenheit even in summer. The forest floor contains not only a huge number of low ferns, mosses, and other undergrowth species, but large decaying "nurse logs", the fallen trunks of old growth trees, which can also serve as nurseries for further plant growth on the crowded forest floor (22) The moist climate of these rainforests creates an incredible density of plant life and fallen trees, which under normal weather conditions create a thriving ecosystem. Under drought conditions however, there is a danger that this density of uncharacteristically dry plant material can serve as fuel for intense wildfires. Dense forest environments with significant undergrowth, understory, and a dense canopy can often create some of the most dangerous wildfires, as there are continuous pathways of fuel for fire to move not only laterally across the ground, but also vertically from the understory into the canopy. Once a fire begins to travel within the canopy of a forest, it cannot be contained by traditional methods of wildland firefighting such as the cutting of fire lines by hand crews. This necessitates the use of heavy equipment to clear trees, creating a fire line wide enough to stop the spread. This type of operation is extremely expensive and hazardous, and cannot be conducted in mountainous, uneven terrain, where heavy machinery cannot operate. Additionally, canopy fires often create dangerous spot fires beyond the fire line, as burning leaf matter can easily be swept upwards by thermal updrafts and winds and deposited in other flammable material beyond where firefighters are operating. This can be incredibly dangerous for wildland firefighting crews, who can easily be surrounded by fire in this context and often must withdraw to safety. The inherent hazards of fighting wildfire within such densely forested terrain must be considered along with the hazards to sensitive biomes and the risk of massive wildfire spread when considering the negative effects of wildfire within dense temperate rainforests.

In this project, I will examine the temperate rainforest areas within the contiguous United States, this focus will allow me to compare data which has been compiled and shared by agencies cooperating under the auspices of the U.S. Federal Government, and the State Governments of the Pacific Northwest.



Total extent of the Pacific temperate rainforest biome, Conservation Biology Institute (24)

Courtesy of U.S. National Park Service, Olympic National Park (22)

Data and Methods

For this project I have analyzed data collected by U.S. Federal Government agencies involved in public land management, wildland firefighting, and climate and weather monitoring. I have also utilized data recorded by European Space Agency's Copernicus satellite, and shapefiles from the U.S. Based NGO, the Conservation Biology Institute.

My land-based data consists of 30m land cover raster data from the U.S. Geological Survey's National Land Cover Database (32) This data has been overlaid on a shapefile from the Conservation Biology Institute (24) describing the total land area capable of supporting the rainforest biome in the Pacific Northwest. This area contains multiple varieties of temperate rainforest ranging from cool to warm as well as various associated land cover types and biomes. Notably, the region contains areas of temperate to polar freshwater marsh, wet meadow, and shrubland concentrated along waterways as well as small meadows consisting of temperate & boreal grassland & shrubland. Additionally, the region is heavily logged, with large areas of land cover having been recently disturbed by logging activity. For the purposes of this project. These various associated land cover types within temperate forest areas have been included in my examination, as these associated areas of land cover are heavily intermixed, are subject to the same temperature and precipitation conditions. I have not examined the incidence of wildfire occurring in the more arid regions of Oregon, Washington, and Northern California outside the historically temperate rainforest areas of these states.

My wildfire dataset is drawn from the Monitoring Trends in Burn Severity program, organized by the U.S. Geological Survey, U.S. Forest Service, U.S. Department of the Interior, and U.S. Department of Agriculture. (28) This vector dataset contains shapefiles of all wildfires which have occurred in the United States from 1984 to 2020. For the purposes of this project, I have selected to examine only the wildfires which occurred from the year 2000 to 2020 and are within or overlap with the areas of rainforest habitat as designated by the Conservation Biology Institute. I have subdivided the wildfire dataset so that it can be examined on a year-by-year basis, and the total acreage burned as well as the mean and median size of wildfires which occur in rainforest habitat each calendar year can be established.

My Sea Surface temperature dataset is derived from observed data recorded by the European Space Agency's Copernicus Satellite. (35) The data is a 0.05° x 0.05° horizontal resolution raster dataset, which contains measurements taken for the entire global ocean, recorded on the first of every month with the temperature listed in Kelvin. I have downloaded monthly data for every year from 2000-2020 and selected a large sea study area of the Northeastern Pacific Ocean from the U.S Coast to the Ocean North of Hawaii and the Aleutian Islands. I selected this large area because it was necessary to capture the various ocean currents and seasonal movement of water which forms the marine climate for the western seaboard of the U.S. and to include the coastline of all temperate rainforest areas within U.S. territory. I have divided the sea surface temperature datasets by month and year and have collected average North Pacific sea surface temperatures for each year which I have examined alongside the yearly wildfire data. I have also converted the temperature measurements into Fahrenheit and Celsius. Additionally, I have created several map products in order to assess how spatial variations in surface temperature within different areas of the North Pacific have affected the incidence of wildfire. I have divided the study period into 5-year intervals and created a mean raster layer for each interval. I have divided the study period in this way in order to assess change over time in a more precise manner. I have then conducted a cell-by cell comparison of each year's raster layer to the mean raster values of the five-year interval. The maps produced by this process depict the spatial variability in annual sea surface temperature across different areas of the northern Pacific Ocean. A similar approach was taken by Yongqiang Liu in conducting his study on North Pacific warming and intense northwestern U.S. wildfires. Liu was able to use sea surface temperature raster data to link North Pacific sea surface temperature anomalies to particularly large and intense wildfire seasons throughout the northwestern region of the U.S. I was interested in using a similar technique to determine the effects of sea surface temperature anomalies, and overall warming due to climate change, on the wildfire situation within the cool damp climate of temperate rainforests in particular. (8)

In order to create a more detailed picture of the climate and weather conditions shaping the wildfire environment, I have also analyzed observed weather data from the National Oceanic and Atmospheric Administration's National Weather Forecast Offices. I have drawn Archival records of monthly and annual average temperatures and total rainfall, from four weather stations located within my study Area. Olympia Washington, Portland Oregon, Medford Oregon, and Eureka California. I have collected local monthly and annual mean temperatures and rainfall totals per year as well as created combined regional annual averages for examination alongside the wildfire and sea surface temperature data. (19) This will provide a fuller picture of the overall climate shaping the wildfire environment for each fire season.

Once I compiled the data on total acreage of rainforest lost, ocean temperatures, air temperatures and weather, I clipped the land data to include only the relevant study area and utilized the land cover dataset to focus on rainforest areas specifically. I compared the annual average of air and ocean temperatures in the study area for each year, as well as the annual total precipitation. I performed a linear regression analysis on each variable to assess its distribution over time and evaluate its level of statistical significance. I then performed a Mann Kendall Test of each variable in order to assess how each variable has changed over time, i.e. Whether the oceans have consistently warmed, and whether wildfires have consistently expanded in size and consistently burned more total acreage, etc. This technique has been utilized in similar studies such as the examination of spatio-temporal linkages between declining arctic sea-ice extent and increasing wildfire activity in the western United States by Knapp and Soule and is useful for demonstrating statistically significant changes in independent variables over an extended span of time (7). I also ran a Pearson Correlation Coefficient test to determine any correlation between these factors within the specified study period.

Results

In this section I will list the results of the various statistical and correlational tests I have conducted on North Pacific sea surface temperatures, climatological variables, and wildfire incidents in historically rainforested areas. I assessed the change over time of each of these variables independently, and then assessed the level of correlation between the variables in order to evaluate how these factors connect to the annual wildfire cycle within these sensitive ecosystems.

The first variable I examined was the annual mean sea surface temperature of the North Pacific. The linear model for mean sea surface temperature from 2000 to 2020 has a p-value of 0.00423. This value is statistically significant at the 0.05 level and indicates that the null hypothesis, that the changes in temperature are not statistically significant, can be rejected. Upon performing a Mann-Kendall trend test for change over time I observed that the p-value for the distribution of annual mean sea surface temperature is 0.046162. This value is also significant at the 0.05 level, further indicating that the average sea surface temperature has increased in a statistically significant manner during this period. (See figure 1). Additionally, I have created several map series depicting how the changes in sea surface temperatures have manifested spatially over the study period with both warm water and cool water anomalies tracked by calendar year (see map series 1 – 4).

Next, I analyzed mean wildfire size in rainforest areas during the study period. The linear model for mean wildfire size has a p-value of 0.02119. This value is statistically significant at the 0.05 level, and indicates that the null hypothesis, that increases in mean wildfire size are not statistically significant, can be rejected. Upon performing a Mann-Kendall trend test for change over time I observed that the p-value is 0.004108. This value is also significant at the 0.05 level, further indicating that the mean size of wildfires occurring in temperate rainforest areas has increased in a statistically significant manner during the study period (See figure 2). My most statistically significant variable in this study was median wildfire size. The linear model for this variable a p-value of 0.0006744. After performing a Mann-Kendall trend test I observed that the p-value for this distribution is 0.0003264 This value indicates that the median size of wildfires occurring in rainforest and cool temperate forest areas has increased in a statistically significant manner during the study period (See figure 3). The total acreage of rainforest area burned during the study period was also statistically significant, with a p-value of 0.02611. A Mann-Kendall trend test revealed that the p-value for this distribution is 0.0059974. This indicates that the total acreage of rainforest burned each year has increased in a statistically significant manner during the study period (See figure 4).

After analyzing each variable independently for statistically significant changes during the study period, I conducted several Pearson Correlation Coefficient tests to determine the level of correlation between the independent variables I have listed above. I have also compared the data to other weather variables such as annual average temperature and precipitation, obtained from NOAA data compiled by weather stations in the Pacific Northwest.

The strongest positive correlation I found in my study was between average annual North Pacific sea surface temperature and the median size of wildfires which occurred in temperate forest areas. The r value is 0.4809193, which corresponds to a 48.09% correlation between these variables. The next highest positive correlation I found in this study was between average annual North Pacific Sea Surface Temperature and the mean size of wildfires which occurred in temperate forest areas. The r value is 0.2617028, which corresponds to a 26.17% correlation between these variables. This result is generally similar to the r value for median wildfire size but there is a high degree of variability in the size of individual fires from year to year. In some years the largest fire is relatively close to the median size, and in others it is multiple times the acreage of the median. There is a weak positive correlation between average annual North Pacific Sea Surface Temperature and the total acreage of wildfires which occurred in temperate forest areas. The r value is 0.1638057, which corresponds to a 16.38% correlation between these variables. (See figure 5). As with the mean result, this statistic is greatly influenced by the variability in the size of individual fires from year to year. Although this study is focused specifically on the temperate rainforest areas of the Pacific Northwest, the results can be affected by wildfire events which spill over from drier more arid regions.

In this section of the results, I examined the relationship between fire size and other weather variables present in the Pacific Northwest during the study period. I examined the relationship between wildfire size, annual average temperature, and annual average precipitation. The data is derived from NOAA historical observations from Olympia Washington, Portland Oregon, Medford Oregon, and Eureka California. I have presented the variables which were demonstrated to have the strongest correlations in my results in figure 6.

The strongest negative correlation I found in my study was between the median size of wildfires which occurred in temperate forest areas and average annual precipitation across the Pacific Northwest coastal region. The r value is -0.3255965, which corresponds to a -32.55%

correlation between these variables. This demonstrates that drier years with less precipitation are correlated with larger wildfires within rainforest areas. (See figure 7)

Both Mean and Median fire size had an 25% correlation with annual average temperature in the Pacific Northwest. The r value of the median fire size was 0.2560154, which corresponds to a 25.60% correlation between these variables. The r value of the mean fire size was 0.2537997 which corresponds to a 25.37% correlation between these variables. Although temperature did have a noticeable correlation with the size of wildfire, this variable is less significant to the size and spread of fire than precipitation. This demonstrates that the drying of plant matter within the historically damp forests of the pacific coast plays a key role in the spread of fire within these environments.

Discussion

In my results I found that the mean sea surface temperature in the North Pacific is rising in a statistically significant manner, and that both the median and mean wildfire sizes are increasing within temperate rainforest regions over time. Additionally, I found that the overall increase in sea surface temperature is correlated with an increase in both the mean and median size of fires which occur in temperate rainforest areas along the U.S. Pacific coast. This is significant, as the temperate rainforests of the U.S. Pacific Northwest are among the most wildfire resistant biomes in the American West. These regions contain a vast amount of biomass, which has been more insulated to the effects of wildfire than other areas of the West due to its high annual precipitation and comparatively cool, moist, maritime climate. This moist temperate climate owes its existence to the Jet Stream which circulates East- West along the Pacific coast of North America. The jet stream varies in course seasonally, oscillating northward and southward depending on the time of year. During autumn, the jet stream reaches its northern apex, taking on the temperature of the air found above the surface of the icy northern Pacific. As winter approaches, the jet stream begins traveling southeast along the western coast of North America. The jet stream brings cold, moist, arctic sea air from the Gulf of Alaska to the U.S. Pacific Northwest, causing wind and rain in the region through February, when the jet stream bends northwards once more. (10) As mean sea surface temperatures rise, the cooling effect of the jet stream is reduced, due to the fact that the water it travels across is warmer. The diminishment of the cooling effect of the jet stream thus leaves the Pacific Northwest more susceptible to the warm dry conditions that fuel the growth of large wildfires.

In the article "*Long-term perspective on wildfires in the western USA"* Jenifer R. Marlon et al discuss the interaction of climatological, environmental, and anthropogenic factors which affect wildfire on a long-term basis "Fire regimes are primarily a product of climate, vegetation, topography, and human activities—factors that interact in a variety of ways and on a range of spatial and temporal scales. Climate influences fire at the broadest scales via the annual cycle, weather, and the distribution of vegetation (fuels)… On decadal-to-centennial scales, fire patterns have been linked to slow changes in ocean/atmosphere patterns associated with low-frequency variations in sea surface temperatures" (9) Although this study focuses on the long-term variations in wildfire patterns over a period of centuries, its principles can be observed even in a shorter-term study such as mine which focuses on a more limited period of just two decades. Wildfire conditions are influenced not just by local seasonal temperature variations or annual increases or decreases in precipitation, but by larger scale changes in climate, sea temperature, and weather patterns which span large swathes of the globe.

Further study of the relationship between sea surface temperature warming and wildfire patterns can be seen in the Article "*North Pacific warming and intense northwestern U.S. wildfires*" (8) written by Yongqiang Liu in 2006. In this Article, Liu closely examines the relationship between temperatures in different areas of the Pacific Ocean to Wildfire conditions in the continental U.S. Liu notes that tropical Pacific sea surface temperature anomalies such as La Nina have long been utilized as a predictor for Wildfires in the American Southwest and Southeast and seeks to determine a similar predictor for the Pacific Northwest. Liu laments the lack of previous studies on this topic, citing one study by Simard et al. in 1985 which found no statistically significant relationship between equatorial/tropical Pacific SST and wildfires in the Pacific Northwest. Liu's study examines the differences in temperature in various regions of the Pacific against historical wildfire data, finding that "warming in the North Pacific and cooling in the eastern tropical Pacific are closely related to intense Northwest wildfires." (8) Furthermore, Liu examines individual large scale fire events in the Pacific Northwest as compared to seasonal SST anomalies in the northern Pacific Ocean and determines that "the warming is more important than the cooling to the intense wildfires." (8) These findings are consistent with my results on how mean sea surface temperatures in the North Pacific Ocean affects the size and scope of wildfires within the temperate forests on the U.S. Pacific coast over time. Furthermore, my analysis of sea surface temperature anomalies in the North Pacific concurs with Liu's findings.

Another Article related closely to my study, "*Spatio-Temporal Linkages Between Declining Arctic Sea-Ice Extent and Increasing Wildfire Activity in the Western United States*" (7) published in June 2017 by P.A., Knapp and P.T., Soulé, establishes a strong negative relationship between the total area of arctic sea ice in the North Pacific and wildfire activity in the western U.S. overall, and the Pacific Northwest specifically. This article also links winter arctic sea ice extent with average summer temperature and precipitation in the Pacific Northwest. This link can be tied to the effects of the jet stream, with its seasonal north-south fluctuations bringing arctic sea air directly to the North American west coast during autumn and spring. When this air is colder and contains more moisture, the seasonal cool weather and rains of pacific northwest last longer, increasing the resiliency of coastal temperate forests to wildfire. This finding is consistent with my research, in which a rise in North Pacific sea surface temperature is linked to expanding wildfires in coastal temperate rainforests. Another significant point that Knapp and Soule make in their study is that although there may be a strong link between sea ice extent, temperature, and wildfire, this is not a direct correlation, but rather part of a more massive system of interconnected variables that set the conditions for fire weather. As global temperatures rise, entire weather and climate systems are altered, leading to sometimes unpredictable second and third order affects.

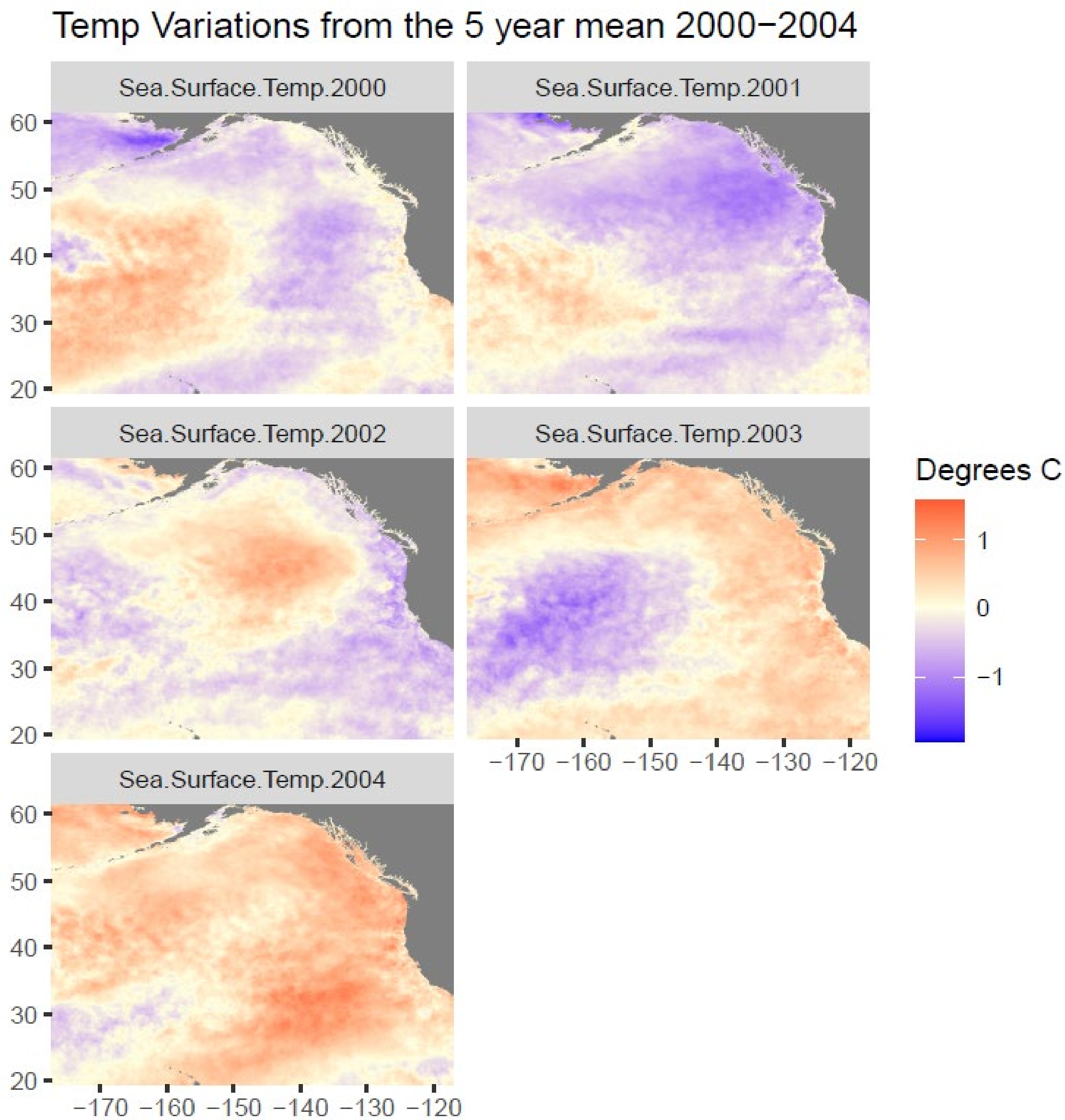
Conclusions

Wildfires pose an increasingly significant threat to sensitive ecosystems across the American west. The warming of the global climate, and its corresponding effect on sea surface temperature have a significant negative impact on the ability of Pacific temperate rainforests to resist the increasingly large, increasingly destructive wildfires now commonplace throughout American west. Temperate rainforests are a significant benefit to our climate overall, as their massive density of plant life absorb significant amounts of carbon dioxide from the atmosphere, which creates cleaner air and reduces the greenhouse effect. The greater the acreage of these forests that are lost to wildfire, the more the cooling and absorptive abilities of these ecosystems are reduced, which in turn further contributes to the runaway effects of climate change. This study, and those like it, demonstrate the interconnected effects of sea surface temperature warming in the northern Pacific Ocean, the decline of sea ice in the Arctic, and the increasing frequency of large destructive wildfires in the American West. My study has demonstrated a significant correlation between the annual mean sea surface temperature of the North Pacific with the mean and median size of wildfires in temperate rainforest areas of the Pacific Northwest each year. This shows that warmer seas result in individual wildfires being larger and more destructive than they have been in previous decades, particularly in the traditionally more wildfire resistant temperate rainforest. These findings are significant, in that they not only point to the need for reduced carbon emissions to mitigate climate warming, but also may be used in the prediction of wildfires and the analysis of annual wildfire risk within the Northwestern states. The rainforest environment has an incredibly dense concentration of biomass, which in sufficiently hot, dry conditions, can serve as fuel for particularly dangerous wildfire events. It is critical to understand the effects of a warming climate on wildfire risks, and the demands which am increasingly severe wildfire season places on the thinly stretched wildland firefighting resources of the American West. Organizations involved in wildland firefighting must be aware of the risks and demands of conducting a greater number of operations within temperate rainforest environments and must be able to establish plans and allocate resources accordingly. Additionally, from a scientific and ecological standpoint, it is critical to understand the increasing threat that wildfire poses to one of the most biologically diverse biomes in North America. The temperate rainforest ecosystem survives thanks to an interconnected system of compatible climate, weather, temperature, and precipitation. Much of this system originates within large atmospheric processes and weather patterns over the Pacific Ocean, which are in turn driven by ocean currents, temperature variations, and other oceanological processes. Each one of these processes are influenced in part by global temperature, the destabilization of which can have cascading effects throughout the entire system. Understanding the larger climatological and environmental factors which elevate wildfire risk in the Pacific Northwest is critical in making informed decisions in how to best combat wildfire and to preserve precious and sensitive rainforest ecosystems from destruction.

Map Series 1)

Spatial Variation of Sea Surface Temperature: 2000 – 2004

The following is a spatial analysis of the annual temperature variations in the North Pacific, based on a cell-by cell comparison to a raster of the mean values of the corresponding five-year interval. I have listed the mean, minimum, and maximum values of each raster below.



Map Series 1 Data)

<u>Annual mean, minimum, maximum temperature (degrees C):</u>

Annual Mean Sea Surface Temps 2000 – 2004:

```
> global(SST_Stack_2000_2004, fun = "mean", na.rm=T)
                              mean
Sea.Surface.Temp.2000 15.22798
Sea.Surface.Temp.2001 14.99947
Sea.Surface.Temp.2002 15.20666
Sea.Surface.Temp.2003 15.35857
Sea.Surface.Temp.2004 15.68502
```

Annual Minimum Sea Surface Temps 2000 – 2004:

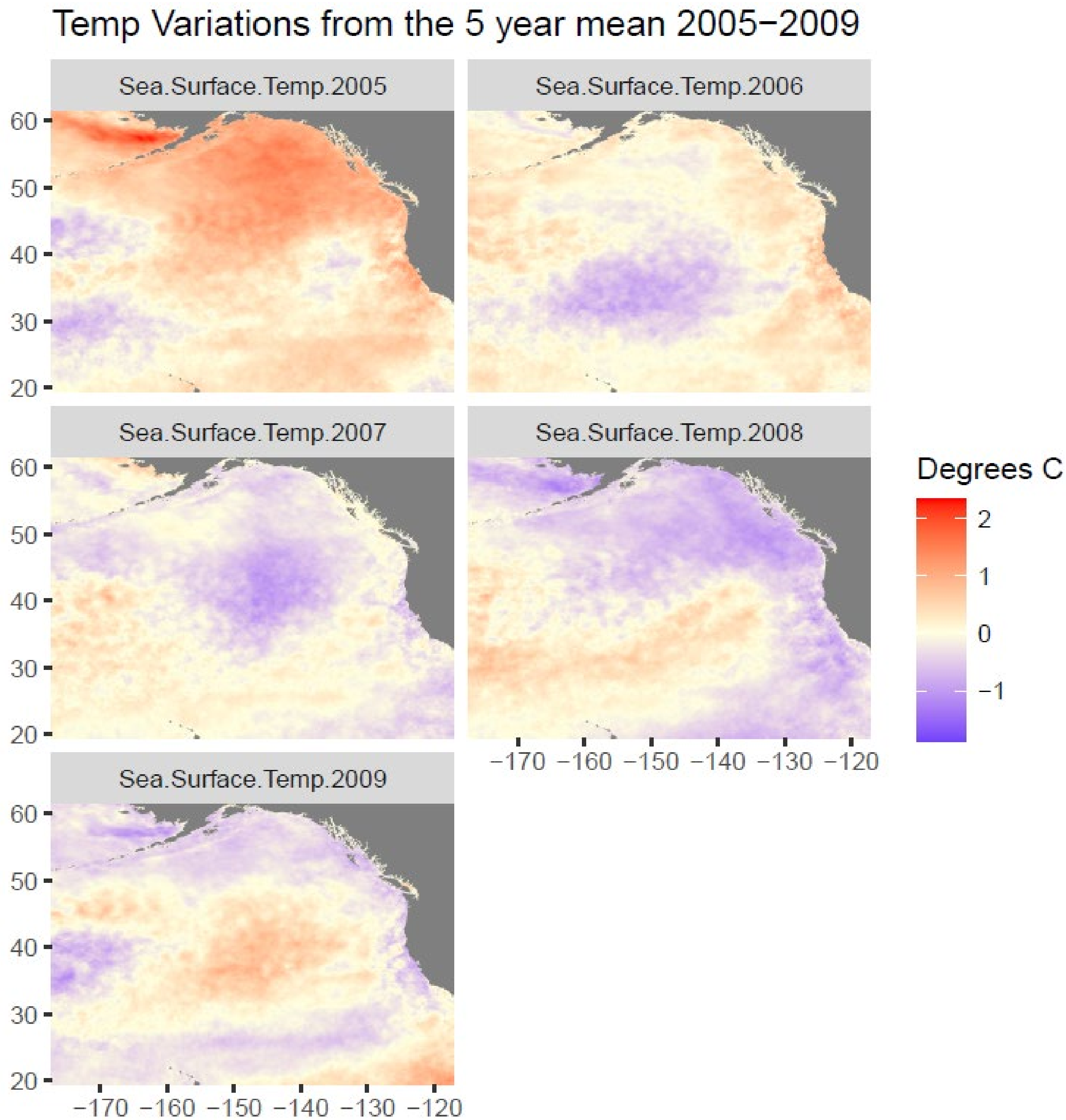
```
> global(SST_Stack_2000_2004, fun = "min", na.rm=T)
                                min
Sea.Surface.Temp.2000 0.1108337
Sea.Surface.Temp.2001 0.1108948
Sea.Surface.Temp.2002 0.1099792
Sea.Surface.Temp.2003 0.1116577
Sea.Surface.Temp.2004 0.1116577
```

Annual Maximum Sea Surface Temps 2000 – 2004:

```
> global(SST_Stack_2000_2004, fun = "max", na.rm=T)
                               max
Sea.Surface.Temp.2000 27.07665
Sea.Surface.Temp.2001 26.93453
Sea.Surface.Temp.2002 26.94500
Sea.Surface.Temp.2003 27.19500
Sea.Surface.Temp.2004 27.01916
```

Map Series 2)

<u>Spatial Variation of Sea Surface Temperature: 2005 – 2009</u>



Map Series 2 Data)

Annual mean, minimum, maximum temperature (degrees C):

Annual Mean Sea Surface Temps 2005 – 2009:

```
> global(SST_Stack_2005_2009, fun = "mean", na.rm=T)
                             mean
Sea.Surface.Temp.2005 15.69531
Sea.Surface.Temp.2006 15.28521
Sea.Surface.Temp.2007 15.13083
Sea.Surface.Temp.2008 15.06161
Sea.Surface.Temp.2009 15.20281
```

Annual Minimum Sea Surface Temps 2000 – 2004:

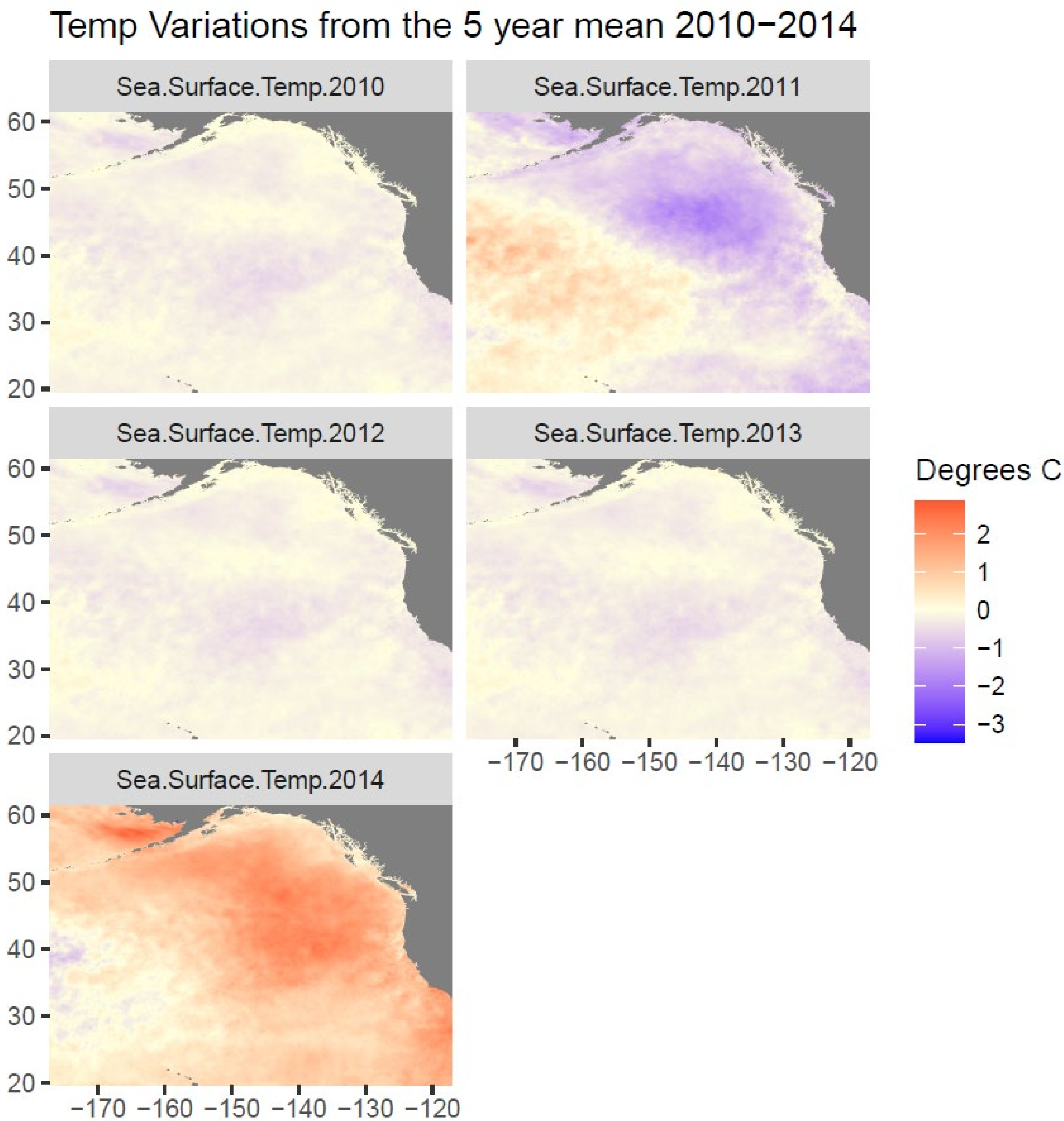
```
> global(SST_Stack_2005_2009, fun = "min", na.rm=T)
                              min
Sea.Surface.Temp.2005 0.1158386
Sea.Surface.Temp.2006 0.1124817
Sea.Surface.Temp.2007 0.1158386
Sea.Surface.Temp.2008 0.1108337
Sea.Surface.Temp.2009 0.1058386
```

Annual Maximum Sea Surface Temps 2000 – 2004:

```
> global(SST_Stack_2005_2009, fun = "max", na.rm=T)
                              max
Sea.Surface.Temp.2005 27.05917
Sea.Surface.Temp.2006 27.23834
Sea.Surface.Temp.2007 27.12832
Sea.Surface.Temp.2008 27.05667
Sea.Surface.Temp.2009 26.84082
```

Map Series 3)

<u>Spatial Variation of Sea Surface Temperature: 2010 – 2014</u>



Map Series 3 Data)

<u>Annual mean, minimum, maximum temperature (degrees C):</u>

Annual Mean Sea Surface Temps 2010 – 2014:

```
> global(SST_Stack_2010_2014, fun = "mean", na.rm=T)
                            mean
Sea.Surface.Temp.2010 15.04191
Sea.Surface.Temp.2011 14.92962
Sea.Surface.Temp.2012 15.05191
Sea.Surface.Temp.2013 15.04191
Sea.Surface.Temp.2014 16.13060
```

Annual Minimum Sea Surface Temps 2010 – 2014:

```
> global(SST_Stack_2010_2014, fun = "min", na.rm=T)
                             min
Sea.Surface.Temp.2010  0.1016577
Sea.Surface.Temp.2011  0.1108948
Sea.Surface.Temp.2012  0.1116577
Sea.Surface.Temp.2013  0.1016577
Sea.Surface.Temp.2014 -1.2300171
```

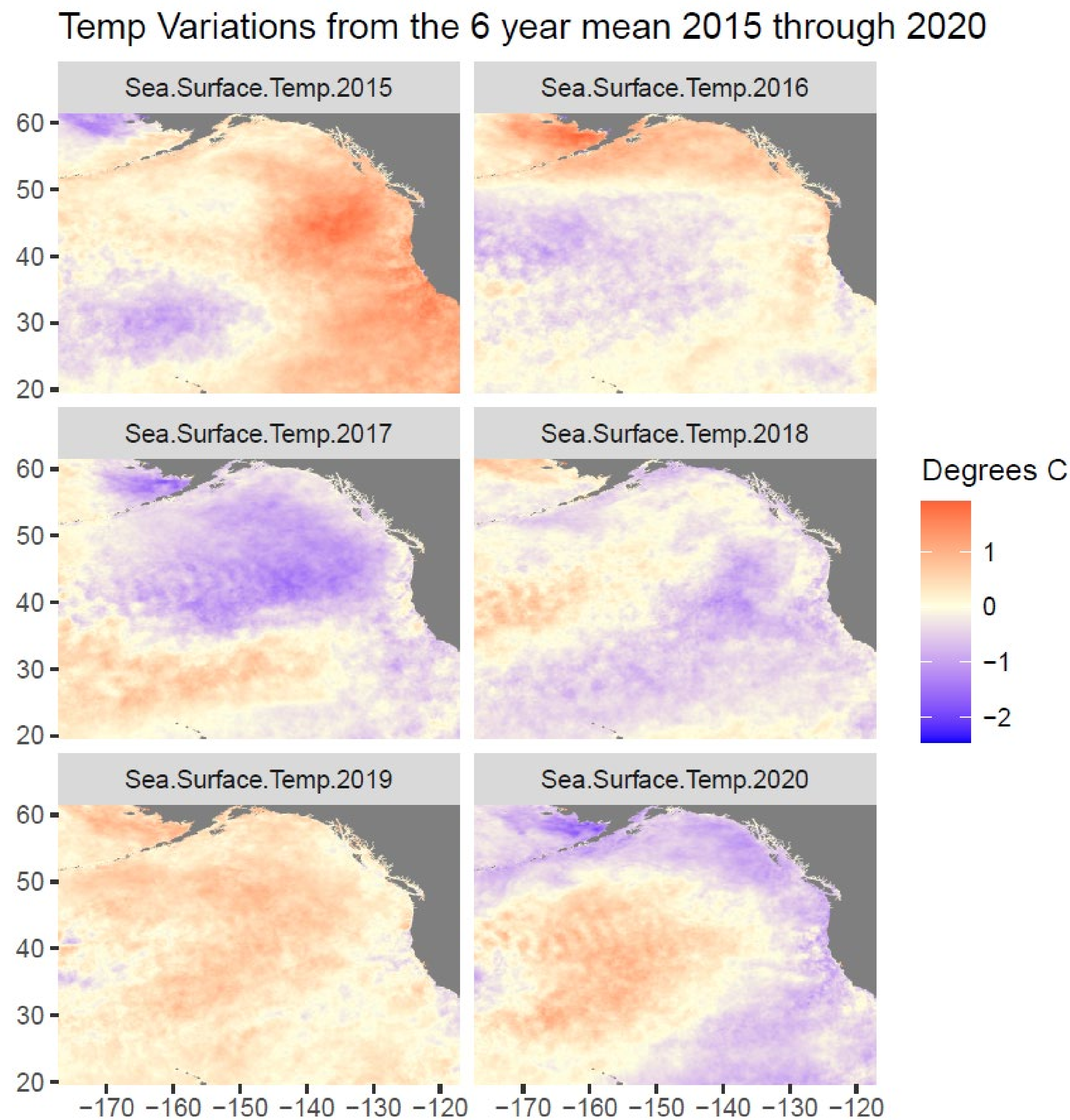
Annual Maximum Sea Surface Temps 2010 – 2014:

```
> global(SST_Stack_2010_2014, fun = "max", na.rm=T)
                             max
Sea.Surface.Temp.2010 26.67667
Sea.Surface.Temp.2011 27.07546
Sea.Surface.Temp.2012 26.68667
Sea.Surface.Temp.2013 26.67667
Sea.Surface.Temp.2014 27.15667
```

Map Series 4)

<u>Spatial Variation of Sea Surface Temperature: 2015 – 2020</u>

Summary of the overall 6 year mean 2005 – 2009 (Degrees Celsius):



Map Series 4 Data)

<u>Annual mean, minimum, maximum temperature (degrees C):</u>

Annual Mean Sea Surface Temps 2015– 2020:

```
> global(SST_Stack_2015_2020, fun = "mean", na.rm=T)
                             mean
Sea.Surface.Temp.2015 16.21758
Sea.Surface.Temp.2016 15.91048
Sea.Surface.Temp.2017 15.61203
Sea.Surface.Temp.2018 15.66556
Sea.Surface.Temp.2019 16.17041
Sea.Surface.Temp.2020 15.77212
```

Annual Minimum Sea Surface Temps 2015– 2020:

```
> global(SST_Stack_2015_2020, fun = "min", na.rm=T)
                              min
Sea.Surface.Temp.2015 0.1108337
Sea.Surface.Temp.2016 0.1149841
Sea.Surface.Temp.2017 0.1516663
Sea.Surface.Temp.2018 2.7358337
Sea.Surface.Temp.2019 2.7166687
Sea.Surface.Temp.2020 2.2045532
```

Annual Maximum Sea Surface Temps 2015– 2020:

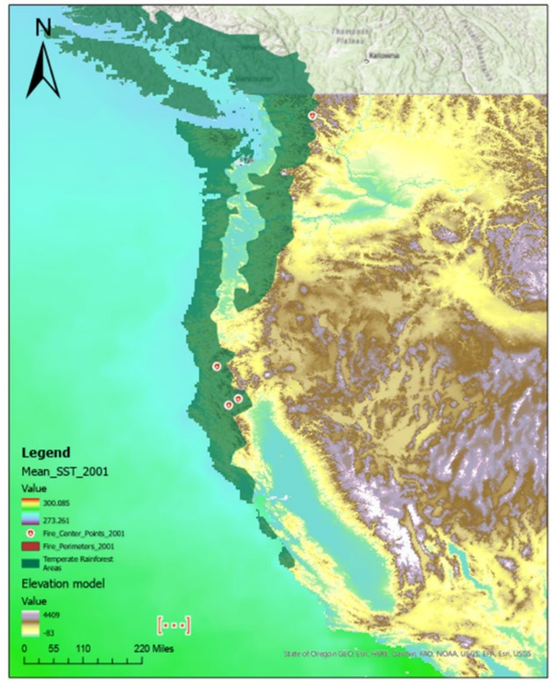
```
> global(SST_Stack_2015_2020, fun = "max", na.rm=T)
                              max
Sea.Surface.Temp.2015 27.08999
Sea.Surface.Temp.2016 26.97833
Sea.Surface.Temp.2017 27.29498
Sea.Surface.Temp.2018 26.80917
Sea.Surface.Temp.2019 27.27166
Sea.Surface.Temp.2020 27.14272
```

The Following map series depict the locations and dimensions of wildfires in rainforest areas of the continental us for each year from 2000 – 2020.

Map Series 5) **Wildfire center points and perimeters 2000 - 2003**

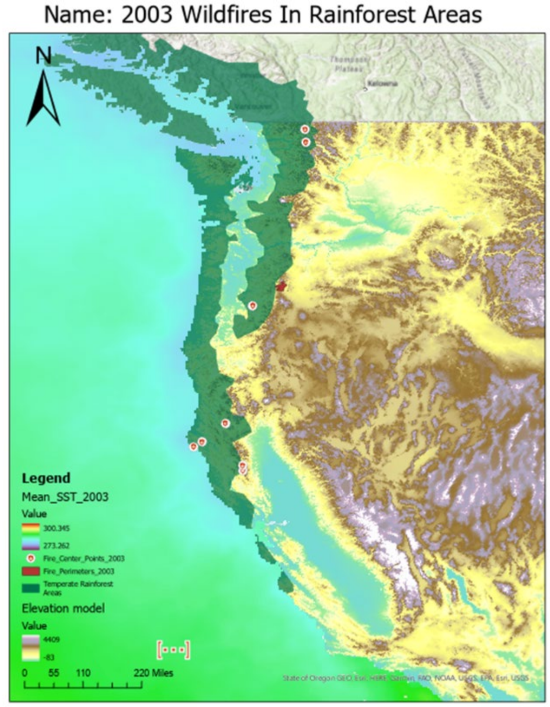
Name: 2000 Wildfires In Rainforest Areas

Name: 2001 Wildfires In Rainforest Areas



Name: 2002 Wildfires In Rainforest Areas

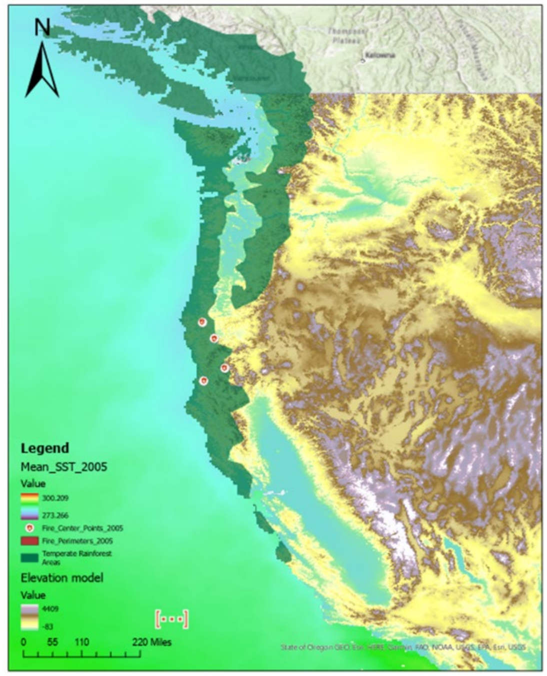
Name: 2003 Wildfires In Rainforest Areas



Map Series 6) **Wildfire center points and perimeters 2004 - 2007**

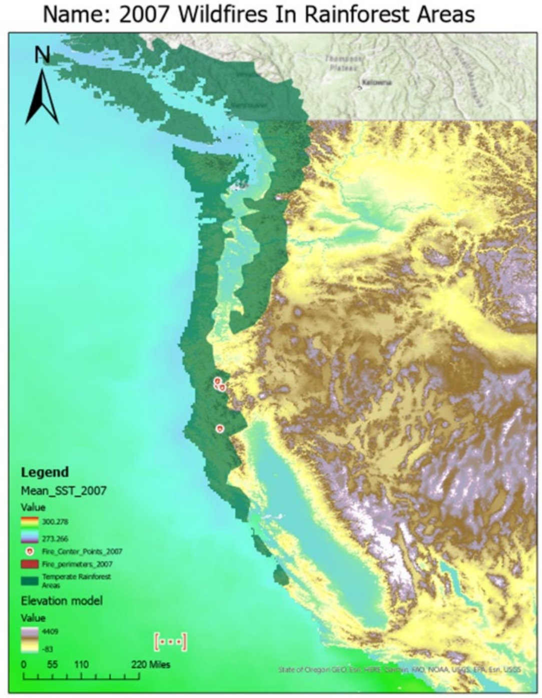
Name: 2004 Wildfires In Rainforest Areas

Name: 2005 Wildfires In Rainforest Areas



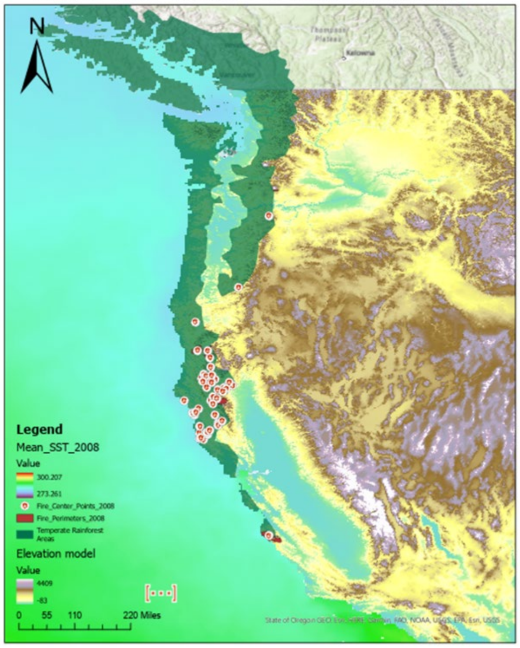
Name: 2006 Wildfires In Rainforest Areas

Name: 2007 Wildfires In Rainforest Areas

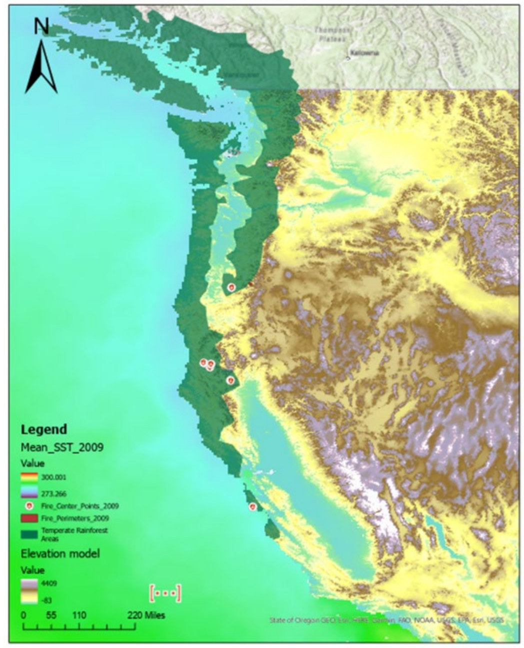


Map Series 7) **Wildfire center points and perimeters 2008 - 2011**

Name: 2008 Wildfires In Rainforest Areas

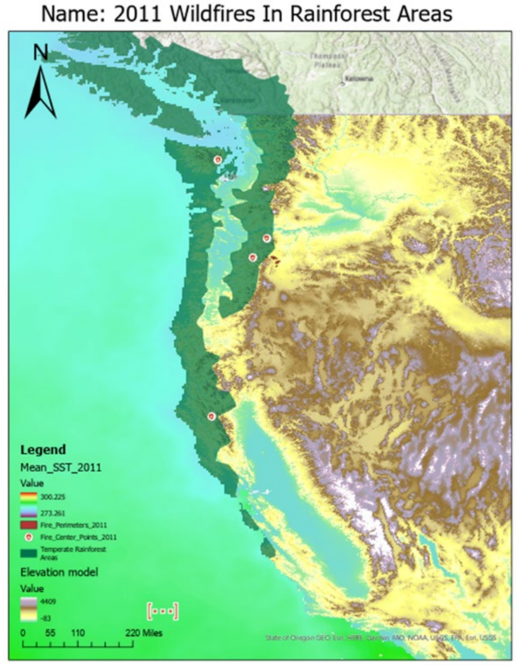


Name: 2009 Wildfires In Rainforest Areas

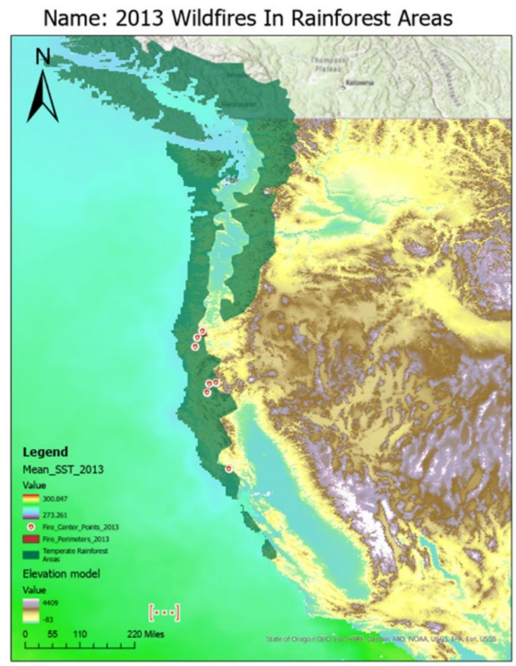


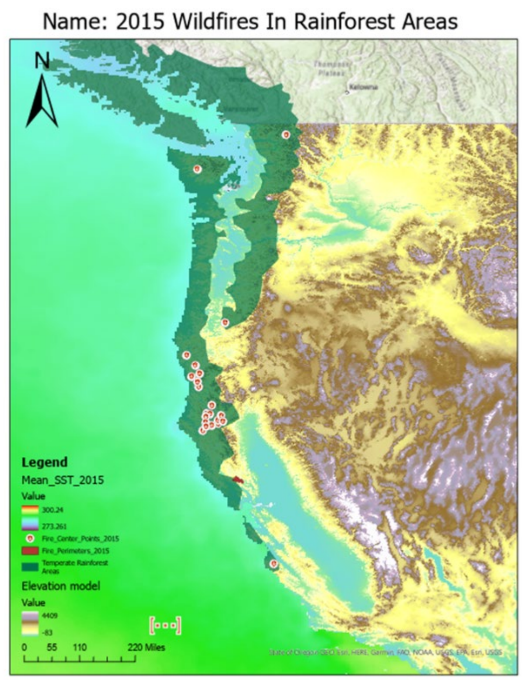
Name: 2010 Wildfires In Rainforest Areas

Name: 2011 Wildfires In Rainforest Areas



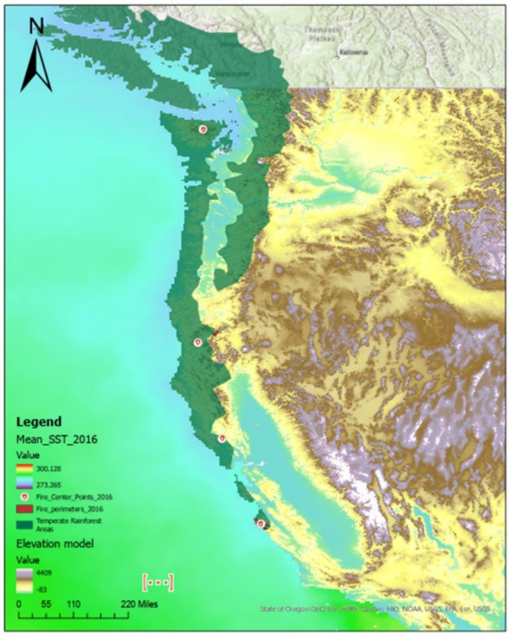
Map Series 8) **Wildfire center points and perimeters 2012 – 2015.**



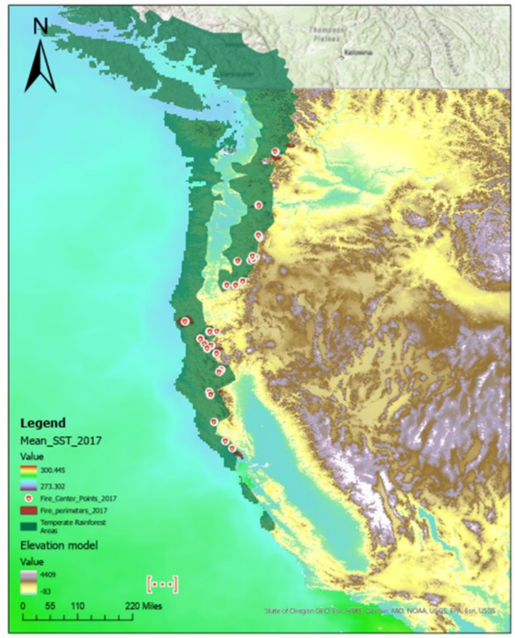


Map Series 9) **Wildfire center points and perimeters 2016 – 2019.**

Name: 2016 Wildfires In Rainforest Areas

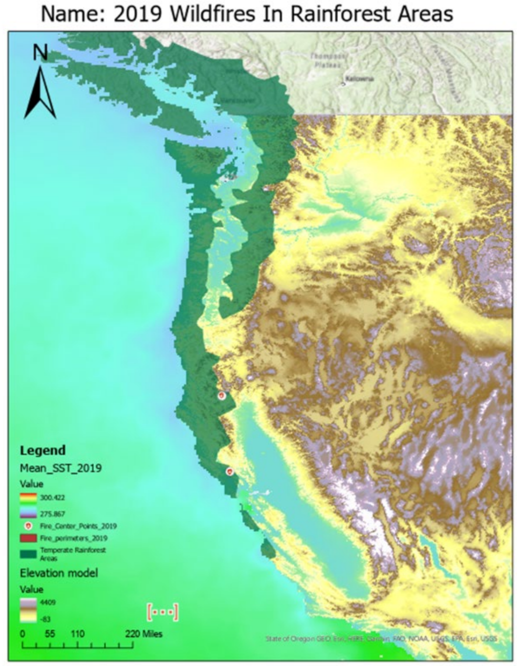


Name: 2017 Wildfires In Rainforest Areas



Name: 2018 Wildfires In Rainforest Areas

Name: 2019 Wildfires In Rainforest Areas



Map Series 10) **Wildfire center points and perimeters 2020.**

Name: 2020 Wildfires In Rainforest Areas

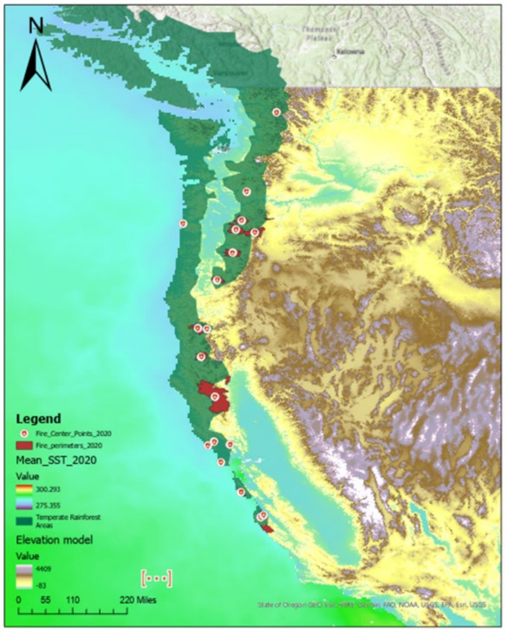


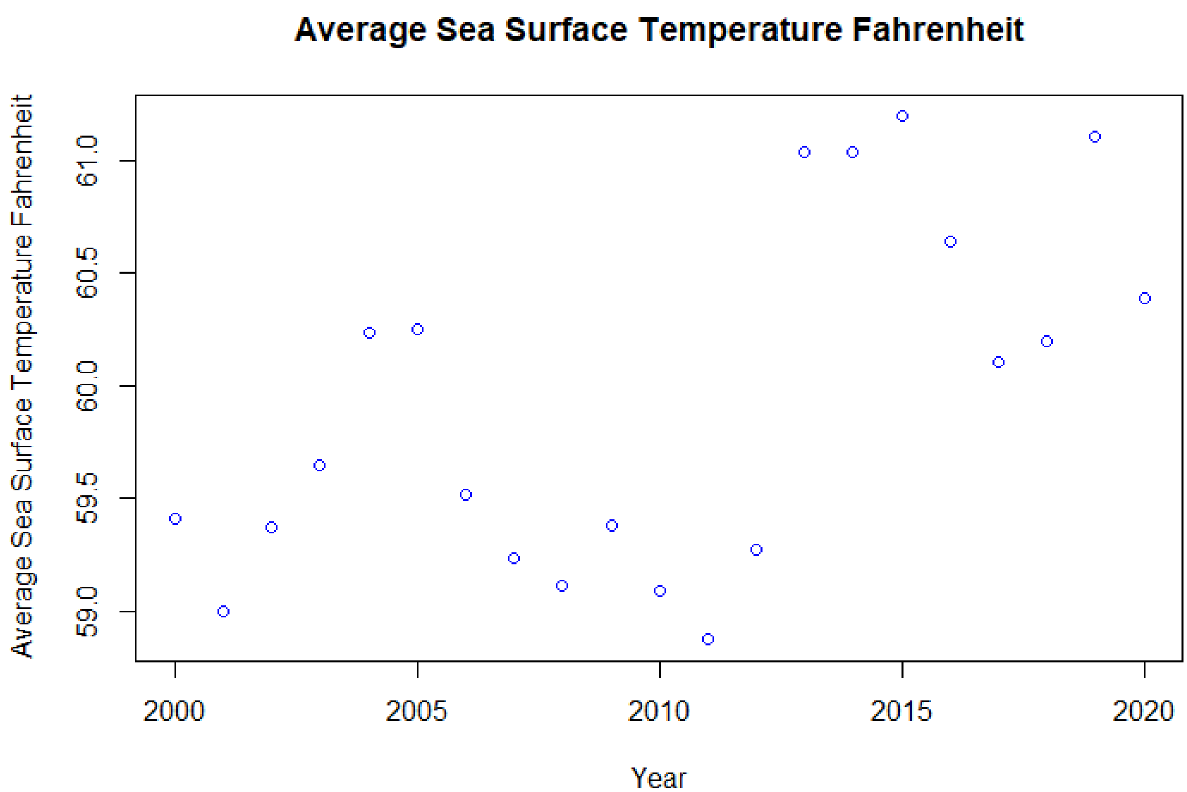
Figure 1)

Sea Surface Temperature:

Average North Pacific Sea Surface temperature 2000 – 2020:

Hypothesis: Average Annual North Pacific Sea Surface temperature has increased in a statistically significant manner during the period from the year 2000 to 2020.

Null hypothesis: Average Annual North Pacific Sea Surface temperature has not increased in a statistically significant manner during this period.



Analysis of the Linear Model for Mean Sea Surface Temperature 2000 – 2020:

```
> summary(SST_C_LM)

Call:
lm(formula = Project_values$Year ~ Project_values$`AVG _SS_TEMP_C`)

Residuals:
    Min      1Q  Median      3Q     Max 
-7.5952 -4.6120  0.2479  3.9329  7.6823 

Coefficients:
                                Estimate Std. Error t value Pr(>|t|)    
(Intercept)                     1875.434     41.452  45.243  < 2e-16 ***
Project_values$`AVG _SS_TEMP_C`    8.679      2.672   3.247  0.00424 ** 
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 5.105 on 19 degrees of freedom
Multiple R-squared:  0.3569,	Adjusted R-squared:  0.3231 
F-statistic: 10.55 on 1 and 19 DF,  p-value: 0.004238
```

The linear model for sea surface temperature has a p-value of 0.00423. This value is statistically significant at the 0.05 level, and the null hypothesis can be rejected.

Mann- Kendall Analysis of change over time for average sea surface temperature:

```
> MannKendall(Project_values$`AVG _SS_TEMP_C`)
tau = 0.32, 2-sided pvalue =0.046162
```

Upon performing a Mann-Kendall trend test for change over time I observed that the p-value is 0.046162. This value is also significant at the 0.05 level, further indicating that the average sea surface temperature has increased in a statistically significant manner during this period.

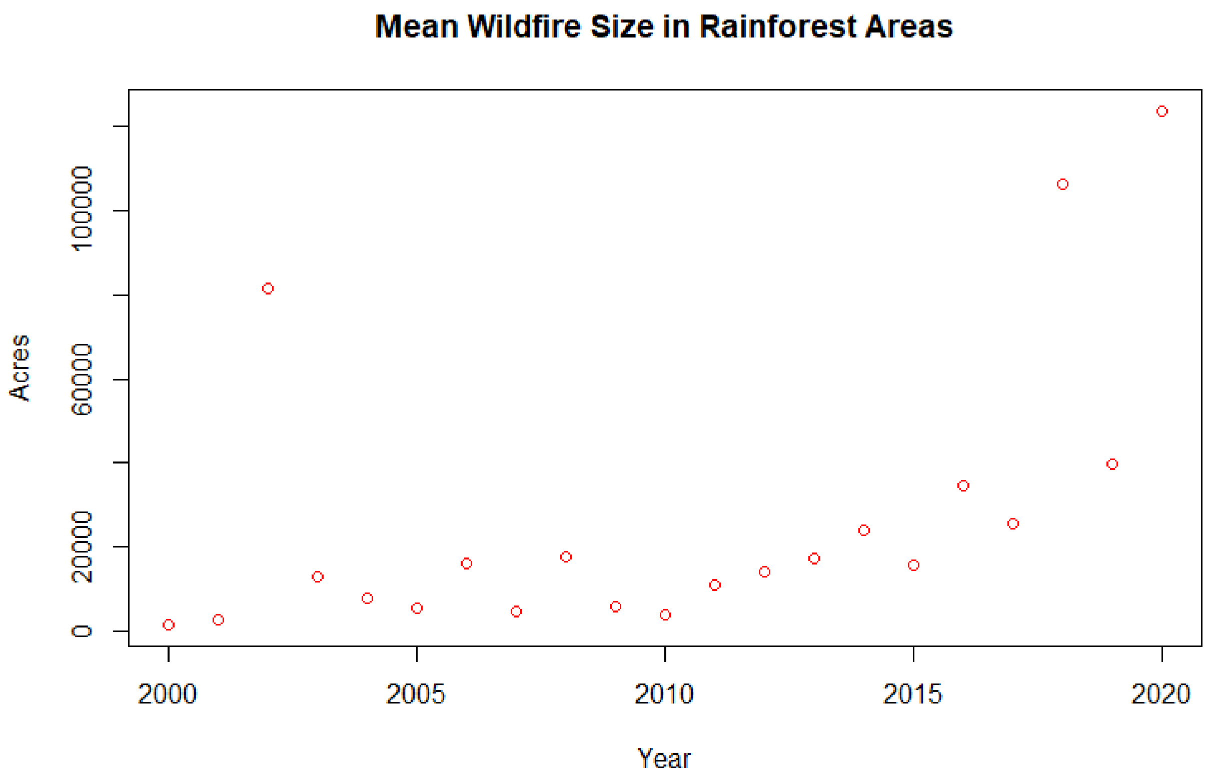
Figure 2)

Wildfire:

<u>Mean Wildfire size in Rainforest Areas 2000 – 2020:</u>

Hypothesis: Mean wildfire size in rainforest areas has increased in a statistically significant manner during the period from the year 2000 to 2020.

Null hypothesis: Mean wildfire size in rainforest areas has not increased in a statistically significant manner during this period.



Analysis of the linear model for Mean Wildfire size:

```
> summary(Mean_Fire_Size_LM)

Call:
lm(formula = Project_values$Year ~ Project_values$Mean_Fire_Size)

Residuals:
     Min       1Q   Median       3Q      Max 
-12.9038  -3.0169   0.9342   3.9129   7.8834 

Coefficients:
                               Estimate Std. Error  t value Pr(>|t|)    
(Intercept)                   2.008e+03  1.553e+00 1292.508   <2e-16 ***
Project_values$Mean_Fire_Size 9.054e-05  3.604e-05    2.512   0.0212 *  
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 5.516 on 19 degrees of freedom
Multiple R-squared:  0.2493,	Adjusted R-squared:  0.2098 
F-statistic: 6.311 on 1 and 19 DF,  p-value: 0.02119
```

The linear model for sea surface temperature has a p-value of 0.02119. This value is statistically significant at the 0.05 level, and the null hypothesis can be rejected.

Mann- Kendall Analysis of change over time for Mean Fire Size

```
> MannKendall(Project_values$Mean_Fire_Size)
tau = 0.562, 2-sided pvalue =0.0004108
```

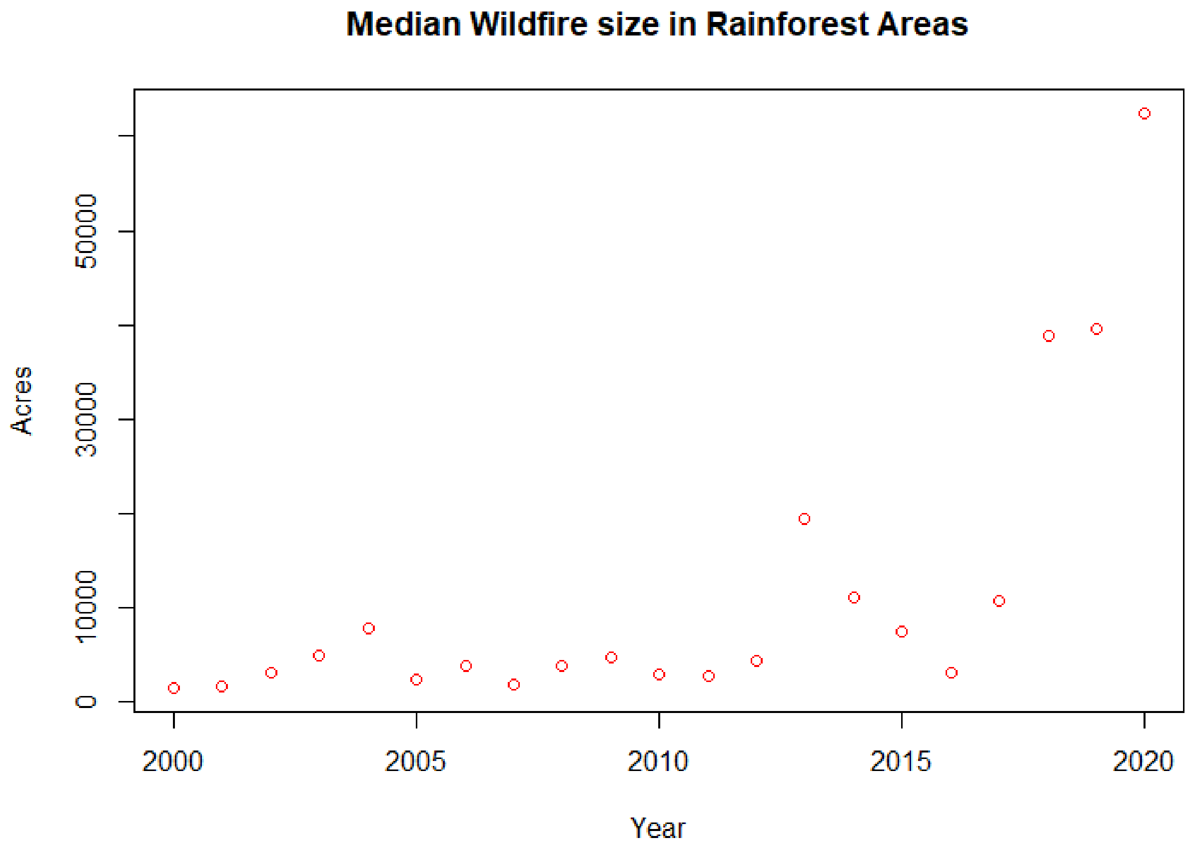
Upon performing a Mann-Kendall trend test for change over time I observed that the p-value is 0.004108 This value is also significant at the 0.05 level, further indicating that the mean size of wildfires occurring in rainforest and cool temperate forest areas has increased in a statistically significant manner during this period.

Figure 3)

<u>Median Wildfire size in Rainforest Areas 2000 – 2020:</u>

Hypothesis: Median wildfire size in temperate rainforest areas has increased in a statistically significant manner during the period from the year 2000 to 2020.

Null hypothesis: Median wildfire size in temperate rainforest areas has not increased in a statistically significant manner during this period.



Analysis of the linear model for Median Wildfire size:

```
> summary(Median_Fire_Size_LM)

Call:
lm(formula = Project_values$Year ~ Project_values$Median_Fire_Size)

Residuals:
    Min      1Q  Median      3Q     Max 
-7.3917 -3.4728  0.7651  3.2454  8.1794 

Coefficients:
                                Estimate Std. Error  t value Pr(>|t|)    
(Intercept)                    2.007e+03  1.258e+00 1595.008  < 2e-16 ***
Project_values$Median_Fire_Size 2.637e-04  6.502e-05    4.056 0.000674 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 4.661 on 19 degrees of freedom
Multiple R-squared:  0.464,	Adjusted R-squared:  0.4358 
F-statistic: 16.45 on 1 and 19 DF,  p-value: 0.0006744
```

The linear model for sea surface temperature has a p-value of 0.0006744. This value is statistically significant at the 0.05 level, and the null hypothesis can be rejected.

Mann- Kendall Analysis of change over time for Median Fire Size:

```
> MannKendall(Project_values$Median_Fire_Size)
tau = 0.571, 2-sided pvalue =0.0003264
```

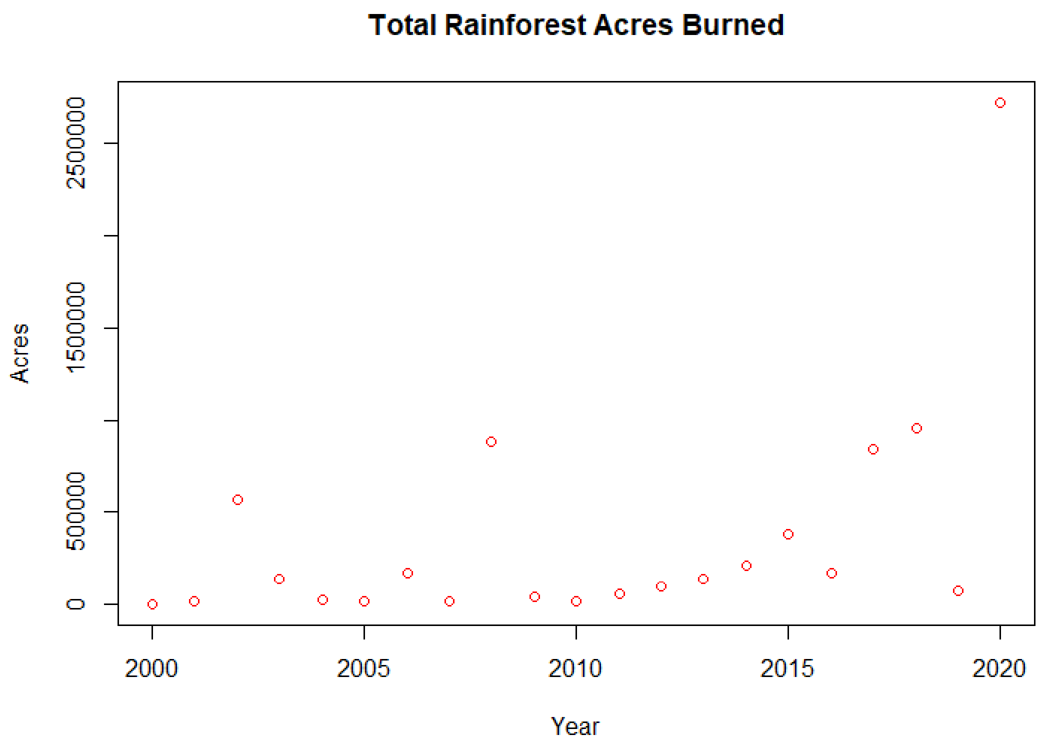
After performing a Mann-Kendall trend test for change over time we see that the p-value is 0.0003264 This value is also significant at the 0.05 level, further indicating that the median size of wildfires occurring in rainforest and cool temperate forest areas has increased in a statistically significant manner during this period.

Figure 4)

<u>Total Acreage of Temperate Rainforest Habitat Burned Annually, 2000 – 2020:</u>

Hypothesis: Total Acreage of cool temperate rainforest areas burned each year has increased in a statistically significant manner during the period from the year 2000 to 2020.

Null hypothesis: Total Acreage of cool temperate rainforest areas burned each year has not increased in a statistically significant manner during this period.



Analysis of the linear model for total Rainforest area burned:

```
> summary(Acreage_Burned_LM)

Call:
lm(formula = Project_values$Year ~ Project_values$Acreage_Burned)

Residuals:
    Min      1Q  Median      3Q     Max 
-9.0097 -4.4023  0.5473  4.6726 10.3634 

Coefficients:
                               Estimate Std. Error  t value Pr(>|t|)    
(Intercept)                   2.008e+03  1.415e+00 1419.641   <2e-16 ***
Project_values$Acreage_Burned 4.836e-06  2.005e-06    2.413   0.0261 *  
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 5.57 on 19 degrees of freedom
Multiple R-squared:  0.2345,    Adjusted R-squared:  0.1942 
F-statistic: 5.821 on 1 and 19 DF,  p-value: 0.02611
```

The linear model for total acreage burned has a p-value of 0.02611. This value is statistically significant at the 0.05 level, and the null hypothesis can be rejected.

Mann-Kendall Analysis of change over time for total rainforest area burned:

```
> MannKendall(Project_values$Acreage_Burned)
tau = 0.438, 2-sided pvalue =0.0059974
```

After performing a Mann-Kendall trend test for change over time we see that the p-value is 0.0059974 This value is also significant at the 0.05 level, further indicating that the median size of wildfires occurring in rainforest and cool temperate forest areas has increased in a statistically significant manner during this period.

Figure 5)

<u>Pearson Correlation Coefficient Test Results:</u>

In this section I have used the Pearson correlation coefficient test to determine the level of statistical correlation between the independent variables I have listed above. I have also compared the data to other weather variables such as annual average temperature and annual average precipitation, obtained from NOAA data compiled by weather stations in the Pacific Northwest.

Sea Surface Temperature and Wildfire Size

North Pacific Sea Surface temperature and Median Fire Size:

```
> ## SST VS Median Fire Size
> cor(Project_values$`AVG _SS_TEMP_F`, Project_values$Median_Fire_Size, method = c("pearson"))
[1] 0.4809193
```

The strongest positive correlation I found in my study was between average annual North Pacific sea surface temperature and the median size of wildfires which occurred in temperate forest areas. The r value is 0.4809193, which corresponds to a **48.09%** correlation between these variables.

North Pacific Sea Surface temperature and Mean Fire Size:

```
> ## SST VS Mean Fire Size
> cor(Project_values$`AVG _SS_TEMP_F`, Project_values$Mean_Fire_Size, method = c("pearson"))
[1] 0.2617028
```

The next highest positive correlation I found in this study was between average annual North Pacific Sea Surface Temperature and the mean size of wildfires which occurred in temperate forest areas. The r value is 0.2617028, which corresponds to a **26.17%** correlation between these variables. This result is generally similar to the r value for median wildfire size but there is a high degree of variability in the size of individual fires from year to year. In some years the largest fire is relatively close to the median size, and in others it is multiple times the acreage of the median.

North Pacific Sea Surface temperature and Total Rainforest Habitat Burned:

```
> # SST VS Total Acreage Burned
> cor(Project_values$`AVG _SS_TEMP_F`, Project_values$Acreage_Burned, method = c("pearson"))
[1] 0.1638057
```

There is a weak positive correlation between average annual North Pacific Sea Surface Temperature and the total acreage of wildfires which occurred in temperate forest areas. The r value is 0.1638057, which corresponds to a **16.38%** correlation between these variables. As with the mean result, this statistic is greatly influenced by the variability in the size of individual fires from year to year. This may also be due to the fact that this study is focused specifically on the temperate rainforest areas of the pacific Northwest, which although less fire prone than other areas of the American west, can be affected by wildfire events which spill over from drier more arid regions.

Figure 6)

Regional Weather conditions and Fire Size

In this section of the results, I examined the relationship between fire size and other weather variables present in the Pacific Northwest over the 20-year period from 2000 to 2020. I examined the relationship between wildfire size, annual average temperature and annual average precipitation.The data is derived from NOAA historical observations from Olympia Washington, Portland Oregon, Medford Oregon, and Eureka California. I have presented the variables which were demonstrated to

Median Fire Size and Regional Annual Average Precipitation:

```
> #Median Fire Size Vs Precip
> cor(Project_values$Median_Fire_Size, Project_values$Regional_Annual_AVG_Precip, method = c("pearson"))
[1] -0.3255965
```

The strongest negative correlation I found in my study was between the median size of wildfires which occurred in temperate forest areas and average annual precipitation across the Pacific Northwest coastal region. The r value is -0.3255965, which corresponds to a **-32.55%** correlation between these variables.

Mean and Median Fire Size and Regional Annual Average Temperature:

```
> # Median Fire Size Vs Annual AVG Temperature
> cor(Project_values$Median_Fire_Size, Project_values$Regional_Annual_AVG_Temp, method = c("pearson"))
[1] 0.2560154
> # Mean Fire Size Vs Annual AVG Temperature
> cor(Project_values$Mean_Fire_Size, Project_values$Regional_Annual_AVG_Temp, method = c("pearson"))
[1] 0.2537997
```

Both Mean and Median fire size had an 25% correlation with annual average temperature in the Pacific Northwest. The r value of the median fire size was -0.2560154, which corresponds to a **25.60%** correlation between these variables. The r value of the mean fire size was 0.2537997 which corresponds to a **25.37%** correlation between these variables.

Table 1) The following are the raw data values derived from my analysis of the Copernicus satellite data for sea surface temperature as well as the Monitoring Trends in Burn Severity program data for wildfire incidents occurring within the temperate rainforest.

Year	AVG _SS_TEMP_F	AVG _SS_TEMP_C	Num_Rainforest_Wildfire_Incidents	Acreage_Burned	Mean_Fire_Size	Median_Fire_Size	Min_Fire_Size	Max_Fire_Size
2000	59.410336	15.22798	1	1505	1505	1505	1505	1505
2001	58.99904	14.99947	7	20,077	2,868.10	1,760	1,032	8,723
2002	59.372	15.20666	7	569,829	81,404.10	3,091	1,066	495,308
2003	59.64543	15.35857	11	143,684	13,062.20	4,903	1,106	91,281
2004	60.23304	15.68502	4	30,720	7,680	7,941	1,155	13,683
2005	60.25156	15.69531	4	21,346	5,336.50	2,394	1,311	15,247
2006	59.513338	15.28521	11	175,424	15,947.60	3,794	1,037	100,962
2007	59.23549	15.13083	4	19,497	4,874.30	1,966	1,364	14,201
2008	59.1109	15.06161	50	882,898	17,658.00	3,971	1,071	164,537
2009	59.38307	15.21281	7	41,137	5,876.70	4,702	1,091	14,605
2010	59.09345	15.05191	4	15,482	3,870.50	2,948	1,611	7,975
2011	58.87332	14.92962	5	55,962	11,192.40	2,881	1,114	44,498
2012	59.27369	15.15205	7	98,241	14,034.40	4,509	1,098	43,689
2013	61.03508	16.1306	8	137,262	17,157.80	19,508.50	2,108	28,911
2014	61.03508	16.1306	9	215,038	23,893.10	11,181	4,063	118,491
2015	61.19164	16.21758	24	379,614	15,817.30	7,489.50	1,085	78,531
2016	60.63886	15.91048	5	173,829	34,765.80	3,131	1,699	132,380
2017	60.10166	15.61203	33	842,281	25,523.70	10,764	1,056	194,877
2018	60.19801	15.66556	9	956,090	106,232.20	38,800	1,775	427,048
2019	61.10673	16.17041	2	79,148	39,574	39,574	1,368	77,780
2020	60.38982	15.77212	22	2,723,122	123,778.30	62,480.50	2,161	1,068,802

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