Evaluating the Time of Emergence of Heat Waves using Different Definitions

by

Christine M. Padalino

Submitted to the Department of Earth, Atmospheric, and Planetary Sciences
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Abstract

Heat extremes, such as heat waves, are characterized by human health effects, increased mortality, and ecosystem-wide impacts. Previous studies of heat waves do not define when and where heat wave frequency will be distinguishable from the background frequency of heat waves in the coming century, and previous studies of heat extremes do not analyze how varying the definition of heat waves contribute to emergence. Using daily resolution of 10 CMIP6 era General Circulation Models forced by the SSP2-4.5 warming scenario, we evaluate the frequency of two definitions presented by the Intergovernmental Panel on Climate Change (IPCC) of heat waves in a reference period and in the future climate to determine the "time of emergence", or the time when the frequency of heat waves becomes perceptibly different from the background frequency. For heat waves that exceed 5°C above the historical climatology, time of emergence is earliest in high latitude regions and is most correlated with the signal. For heat waves that exceed the 90^{th} percentile of the historical climatology, time of emergence is earliest in low latitude regions and is most correlated with the signal to noise ratio. Identifying the time of emergence for the frequency of heat waves can contribute to potential mitigation policies and techniques that are region and time specific.

Thesis Supervisor: Susan Solomon
Title: Lee and Geraldine Martin Professor of Environmental Studies

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Chapter 1

Introduction

1.1 Introduction

Extreme climate and weather events are the most perceptible outcomes of anthropogenic climate change. Extreme heat events, or heat waves, are the greatest cause of weather-related deaths annually (eg. [Luber and McGeehin, 2008]; [World Health Organization, 2009]; [Mora et al., 2017]; [Mitchell et al., 2016]).The Intergovernmental Panel on Climate Change (IPCC) in 2007 reported that increasing global mean temperatures are likely to increase future heat stress related mortality [IPCC, 2007]. Numerous studies have attributed the influence of historical global warming on a variety of climate extremes (eg. [Dosio et al., 2018]; [Zampieri et al., 2016]; [Russo et al., 2014]; [Russo et al., 2015]; [Russo et al., 2016]; [Perkins-Kirkpatrick and Gibson, 2017]; [Meehl and Tebaldi, 2004]; [Lehner et al., 2018]; [Coumou and Robinson, 2013]; [Kharin et al., 2013]). Many investigate heat waves on both global and regional scales, at long- and short-time scales (eg. [Dosio et al., 2018]; [Fischer and Schär, 2009]; [Zampieri et al., 2016]; [Russo et al., 2014]; [Russo et al., 2015]; [Russo et al., 2016]; [Perkins-Kirkpatrick and Gibson, 2017]; [Meehl and Tebaldi, 2004]; [Lehner et al., 2018]; [Coumou and Robinson, 2013]; [King and Karoly, 2017]; [King et al., 2017]; [Im et al., 2017]; [Lopez et al., 2018]; [Harrington et al., 2016]).

Diagnosing where and when changes in heat waves will be distinguishable from the background level is important for future mitigation strategies. However, different heat wave analyses use different indices to define what a heat wave constitutes. Frich et al. 2002 proposed multiple measures of extreme temperatures, which have been since used by IPCC reports to define heat waves [Frich et al., 2002]. In 2007, the IPCC defined a heat wave as "at least five consecutive days with maximum temperature at least 5°C higher than the climatology of the same calendar day". In 2019, the definition used was "a period of abnormally hot weather often defined with reference to a relative temperature threshold" that "would normally be as rare as or rarer than the 10^{th} or 90^{th} percentile of a probability density function estimated from observations" [IPCC, 2019].

In this analysis, we compare the time of emergence of the frequency of summer heat waves under a moderate warming scenario using these two definitions on a global scale. The time of emergence evaluates the "when" of the changes in heat extremes, and the global analysis determines the "where". We find that patterns of time of emergence is very dependent on the definition of a heat wave. Early emergence is seen in high latitudes under the definition that requires exceedance of 5°C above the historical climatology, but early emergence is seen in low latitudes under the definition that requires only exceeding the 90^{th} percentile of the historical climatology. Mitigation strategies that target early emergence locations can decrease the effects of heat extremes, not only on the human population but also the local ecosystem, but further work on which definition makes a heat wave more consequential would be needed to better inform potential policies.

1.2 Background and Motivation

The most common metric of climate change is global mean warming. Temperature thresholds for global mean warming are set as international targets by the IPCC to inform policy; however, the mean magnitude of warming in many regions will exceed these temperature targets, particularly over land, due to global variability in the distribution of the warming associated with anthropogenic climate change [Seneviratne et al., 2016]. Even more consequential to the impacts of climate change are the changes in maximum temperatures and temperature extremes. Heat stress and heat extremes have been shown to reduce labor productivity (eg. Dunne et al. 2013), affect human health and increase mortality (eg. [Luber and McGeehin, 2008]; [World Health Organization, 2009]; [Mora et al., 2017]; [Mitchell et al., 2016]), and impact cornerstone ecosystems globally (eg. [Xu et al., 2020]; [Breshears et al., 2021]; [Vinagre et al., 2018]; [Stillman, 2019]; [Seddon et al., 2016]). Determining when these impacts are going to noticeably affect regions can allow for more targeted mitigation strategies to lessen the severity of the impacts.

The time of emergence assessments of climate signals are key for predicting the future climate as well as predicting future impacts and mitigation strategies in different regions and interpreting past changes. Time of emergence is the time at which a signal of a climate variable emerges from the noise of background climate variability. Evaluating the spatial distribution of time of emergence of mean temperatures began with seminal papers done by Mahlstein et al. 2011 and Hawkins and Sutton 2012. These two studies took different approaches to estimating time of emergence of warm seasonal averaged temperatures but found similar patterns. Both observed and modelled data indicated the earliest time of emergence in low latitudes during the summer months, suggesting a correlation between time of emergence and the interannual variability of a region ([Mahlstein et al., 2011]; [Hawkins and Sutton, 2012]).

These time of emergence studies focus specifically on mean temperature changes, lending the question of using these same analytical methods, what would the pattern of temperature extreme changes look like and depend on? Many of the previous studies on heat waves and temperature extremes come close to answering this question, but do not specifically address the "when" of emergence. It is likely that heat waves have increased in frequency and/or duration on a global scale already [IPCC, 2013], but limited daily data records affect the certainty of an increase from before 1950 [Zampieri et al., 2016] and do not address when and where early or late emergence occurs. Using models to estimate the historical frequency of heat waves and comparing them to observations and projections, would help to answer if the signal of heat wave frequency has already emerged, and if it has not, when it will.

Relationships between the magnitude of warming (eg. [Dosio et al., 2018]) or the rate of warming [Fischer et al., 2021] and the frequency of heat waves has been evaluated. Under a 2°C scenario of warming, versus a 1.5°C scenario, the frequency of heat waves at the end of the century would double over most of the globe, and the fraction of people exposed to severe heat waves once every five years would increase from 13.8% to 36.9% with the additional 0.5°C of warming [Dosio et al., 2018]. Additionally, the probability of extreme, record-shattering heat waves increases depending on the warming rate and is pathway dependent regarding how the global mean temperature increase is reached [Fischer et al., 2021]. A study by Diffenbaugh et al. 2021 also found that these future heat waves would not be occurring in the absence of anthropogenically forced warming. None of these assessments, however, investigate when in the coming century the change in frequency of heat waves will be perceptible to the environment and human population in various regions [Diffenbaugh and Davenport, 2021].

Time of emergence analysis on extremes has also been done, but none focus on the heat wave metric. Extreme summer season temperatures and extreme daily temperatures have been evaluated for Europe under various degrees of warming [King and Karoly, 2017], in Australia under various degrees of warming [King et al., 2017], in South Asia [Im et al., 2017], in the mid-United States [Lopez et al., 2018], and globally [Harrington et al., 2016]. These studies all show increased frequencies of temperature extremes in the various regions, and Harrington et al. 2016 find earlier emergence of daily temperature extremes in low latitude countries at a RCP8.5 level of warming, similar to the time of emergence findings of summer mean temperatures in Mahlstein et al. 2011.

Single day temperature extremes, however, do not have the same impact as sustained extreme temperatures that are observed in heat waves. The mechanism for determining what constitutes a heat wave is difficult not only because there are many different metrics to define a heat wave but also because the definitions are influenced by human perception of severity [Robinson, 2001]. In this analysis we compare two different definitions that IPCC reports have used to increase the robustness of the estimates of the time of emergence of heat waves, and also to compare the impacts of different definitions. The first definition was used in the 2007 IPCC report, which defined a heat wave as “at least five consecutive days with maximum temperature at least 5°C higher than the climatology of the same calendar day”. The second definition is taken from the 2019 IPCC special report on global warming of 1.5°C, which used a definition of “a period of abnormally hot weather often defined with reference to a relative temperature threshold” that “would normally be as rare as or rarer than the 10^{th} or 90^{th} percentile of a probability density function estimated from observations."

Our results will attempt to characterize time of emergence of the frequency of heat waves as defined above. We compare not only the differences in patterns between time of emergence of the two definitions, but also the correlations of time of emergence with the time of emergence and signal, noise, and signal to noise ratio. This analysis will allow for consideration of correlations of population density and vegetation vulnerability with the distribution of heat wave emergence that could help identify particular regions especially vulnerable to heat waves and heat stress effects.

Chapter 2

Methods and Results

2.1 Methods

2.1.1 Climate Model Data

We analyze climate model data from CMIP6 [Eyring et al., 2016]. The data has been regridded to a regular latitude-longitude 5° × 5° grid as done in Hawkins and Sutton 2012. We use one simulation from each of the General Circulation Models (GCMs) used in our study. We identified 10 models that had historical runs with GHG forcing and temperature at the surface (TAS) projections until 2100 under SSP2-4.5 forcing. The models and simulation numbers used are listed in Table 2.1.

Model	Simulation Run
ACCESS-CM2	1
ACCESS-ESM1-5	1
BCC-CSM2-MR	1
CanESM5	8
CNRM-CM6-1	1
GFDL-ESM4	1
IPSL-CM6A-LR	1
MIROC6	1
MRI-ESM2-0	1
NorESM2-LM	1

Table 2.1: List of models and simulation runs used in the analysis.

2.1.2 Definitions

We compare two different definitions of a heatwaves in this analysis. The first is "defined as the longest period in the year of at least five consecutive days with maximum temperature at least 5°C higher than the climatology of the same calendar day" [IPCC, 2007]. The second definition we explore is "a period of abnormally hot weather often defined with reference to a relative temperature threshold" lasting for five or more days that "would normally be as rare as or rarer than the 10^{th} or 90^{th} percentile of a probability density function estimated from observations" [IPCC, 2019]. A heatwave that lasted ten to fifteen days would be counted as two five-day heatwaves, fifteen to twenty as three five-day heat waves, etc.

The climatology is estimated as the mean value over the period 1850-1975 for each day at each grid cell. Summer is then defined using the historical climatology, finding the three consecutive months with the hottest average temperature. In the signal to noise analysis, the signal is defined as the difference between mean summer temperatures in degrees Celsius from 2080-2100 and the mean summer temperatures in degrees Celsius during the background period 1900-1930. The noise is defined as the standard deviation of daily temperature anomalies relative to the 1850-1950 climatology. The signal to noise ratio is the division of the multi-model means of the signal and noise.

2.1.3 Statistical Tests

As in Mahlstein et al. 2011, the statistical test used to determine the time of emergence will be the two-sample Kolmogorov-Smirnov test for each grid point. The two-sample Kolmogorov-Smirnov test is used to determine if two data samples come from the same distribution. This test was selected because it does not assume a normal distribution within the data, which is not expected when evaluating extreme values.

For a thirty-year window starting with 1900-1929, we will determine the frequency of heat waves using both definitions above (5°C above the climatology and above the

90^{th} percentile of the climatology). We will then step up the yearly values by 10 years and find the frequency of heat waves for that time period. We will perform the two-sample Kolmogorov-Smirnov test to determine if the two samples of frequencies are statistically different. We will step up the thirty-year window by 10 years until the extreme value is considered to be emerged, or when the Kolmogorov-Smirnov test rejects with a 95% significance. The time of emergence is identified as the final year in the earliest thirty-year window where the frequency of these heat waves is statistically different from historical (1900-1930) frequency for each model, and the multi-model time of emergence is the year where 80% of the models detect emergence.

Correlations for the signal, noise, and signal to noise analysis are calculated with the Spearman Rank Correlation Coefficient. This test evaluates a statistical dependence between rankings of two variables, determining how accurately a relationship between two variables can be explained using a monotonic function. The correlation coefficient is described as ρ and has an associated p value that determines the significance of the correlation.

2.2 Results

2.2.1 Individual Model Evaluation of Time of Emergence for Two Heat Wave Definitions

The results of the time of emergence analysis spatially visualized for each General Circulation Model (GCM) used are shown in Figure 2-1 and Figure 2-2. Figure 2-1 shows the time of emergence of heat wave frequencies for summer heat waves that exceed 5°C above the historical climatology for five or more consecutive days. Ten different GCMs are used in the analysis. The earliest possible year of emergence is 1950 and the latest possible year of emergence is 2100. Summer is defined as the three consecutive months with the highest mean temperature. The patterns across models show emergence over land with little or even no emergence by 2100 in the tropics nor in the Southern Ocean. Additionally, earlier emergence is observed in higher latitudes. There are inter-model differences observed at grid points, but these large-scale patterns are observed in all ten models.

Figure 2-2 shows the time of emergence of the frequency of summer heat waves that exceed the 90th percentile of the historical climatology temperature distribution for five or more consecutive days. Results using this definition are dramatically different from Figure 1. The same ten GCMs were used for this analysis as the 5°C above the historical climatology definition. All models now show earlier time of emergence in low latitudes, with later time of emergence north of the tropics in the Northern Hemisphere. Additionally, most models indicate very late or no emergence in the Southern Ocean. As with the previous definition, differences are observed at various grid points between models, but common broad patterns exist.

2.2.2 Time of Emergence at Individual Grid Cells

Figure 2-3 resolves the time series of daily summer temperatures, the mean summer temperature, time of emergence thresholds, and times of emergence at eight representative grid points. Five of the grid points (50°N 15°E (Europe), 20°N 80°E (Indian Peninsula), 20°S 25°E (Southern Africa), 5°S 50°W (Amazon Rain forest), and 35°N 80°W (North America)) show emergence for both the 5°C above historical climatology definition and the above the 90th percentile of the historical climatology definition. Two grid points, Europe and Southern Africa, show a ten-year difference in time of emergence between the two definitions, with the 5°C above historical climatology definition emerging first in Europe and the above the 90th percentile of the historical climatology definition emerging first in Southern Africa. North America shows an intermediate separation between the two definitions, while the Amazon Rain forest and Indian Peninsula show greater than 50 years difference in time of emergence between the definitions.

The other three grid points either show only emergence of the above the 90th percentile of historical climatology definition or no emergence. In the North Pacific (15°N 155°W) and in Australia (30°S 115°E), only the 90th percentile of the historical climatology definition emerges, with the North Pacific emerging earlier (2000) than

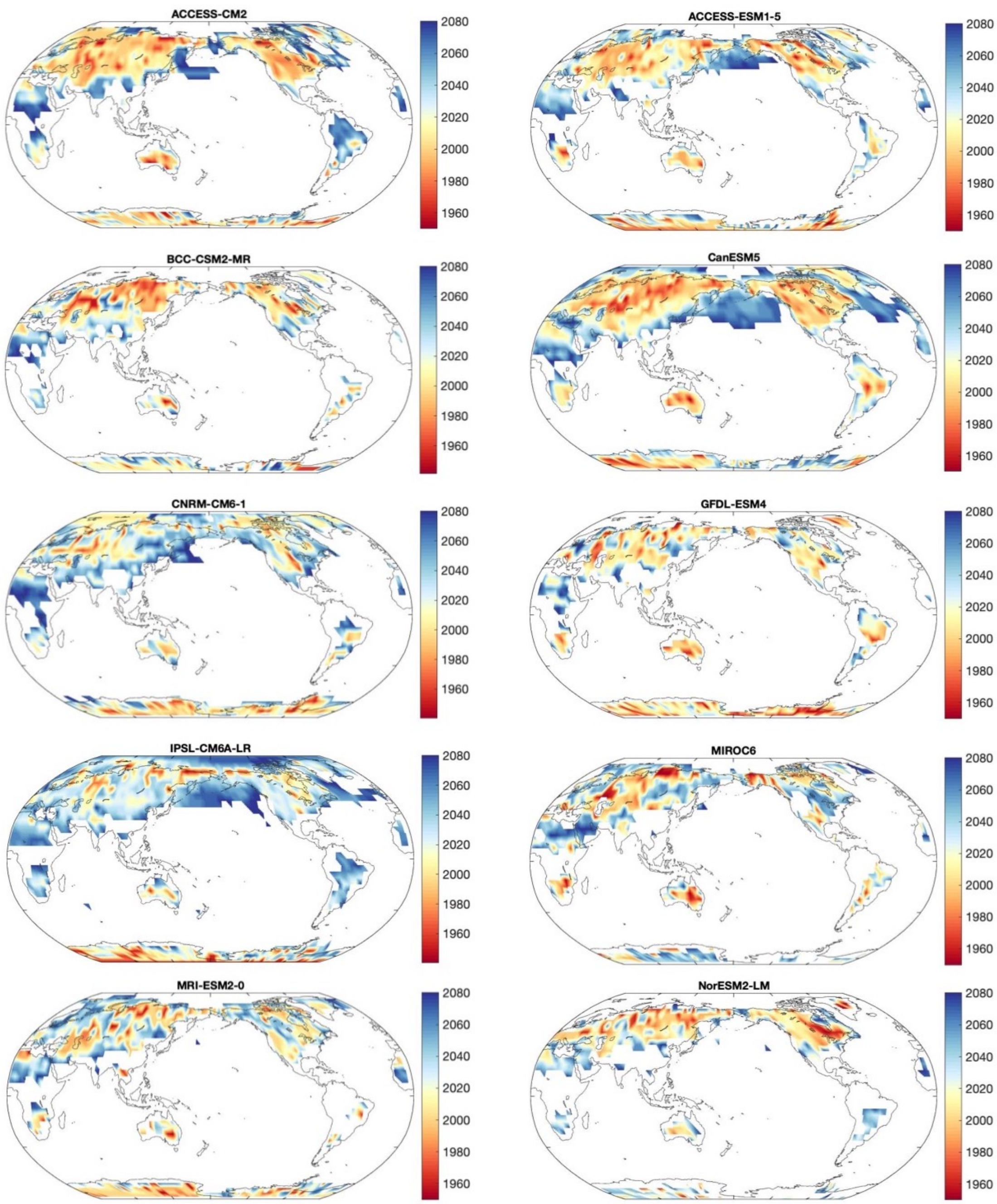

Figure 2-1: The Time of Emergence of summer heat waves that are 5°C above the historical climatology and sustained for at least five days for 10 General Circulation Models (GCMs). The color bar indicates the final year in the earliest thirty-year window where the frequency of these heat waves is statistically different from historical (1900-1930) frequency using the two sample Kolmogorov-Smirnov statistical test. Each map is labeled with the GCM used. GCMs are all forced by the SSP2-4.5 emission scenario. White indicates that the frequency has not been identified to be statistically different by the end of the simulation period (2100).

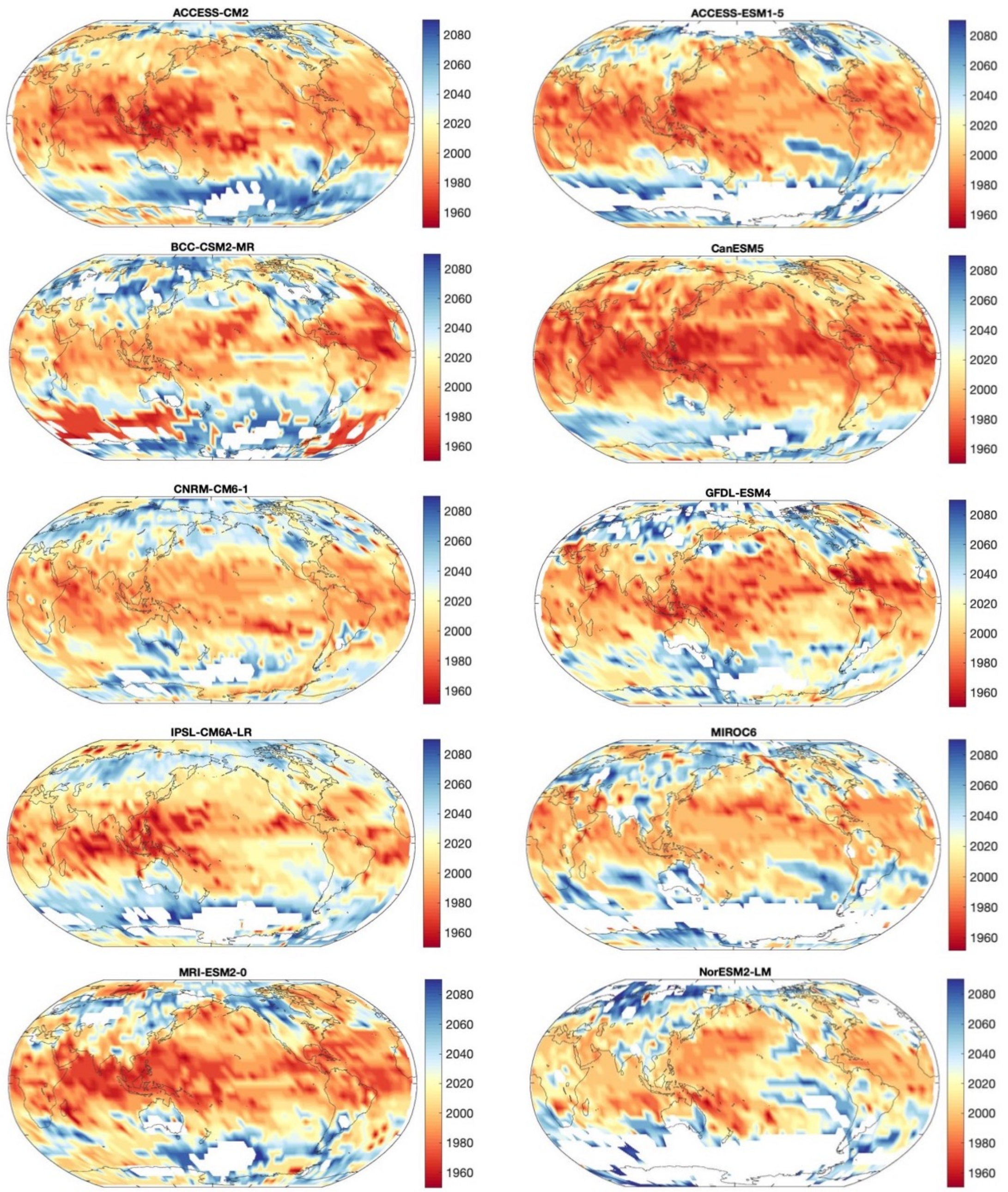

Figure 2-2: The Time of Emergence of summer heat waves that are above the 90^{th} percentile of the historical climatology and sustained for at least five days for 10 General Circulation Models (GCMs). The color bar indicates the final year in the earliest thirty-year window where the frequency of these heat waves is statistically different from historical (1900-1930) frequency using the two sample Kolmogorov-Smirnov statistical test. Each map is labeled with the GCM used. GCMs are all forced by the SSP2-4.5 emission scenario. White indicates that the frequency has not been identified to be statistically different by the end of the simulation period (2100).

Australia (2030). In the Southern Ocean (60°S 105°W), neither definition shows a time of emergence. Larger images of the time series plots shown in Figure 2-3 are provided in the appendix A. Figures 2-1, 2-2, and 2-3 reveal that the definition of a heat wave is critical to interpreting emergence dates.

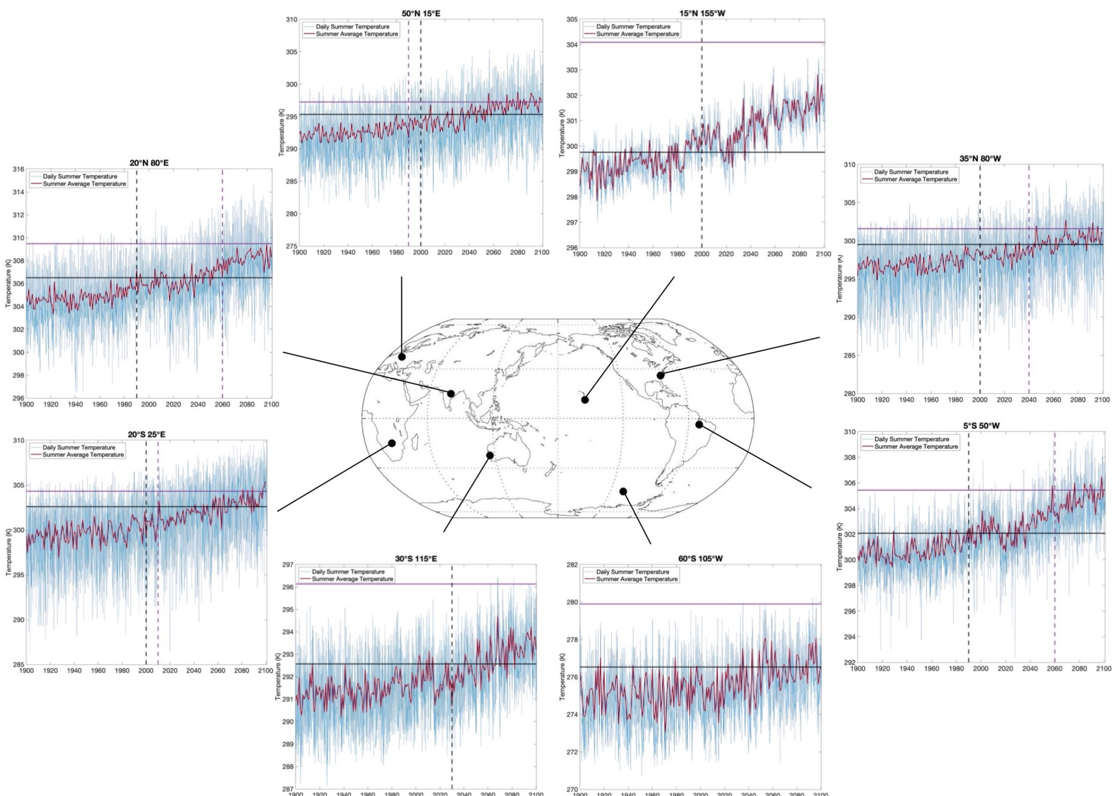

Figure 2-3: Example time series plots of daily and mean summer temperatures over 1900-2100 for ACCESS-CM2 along with temperature thresholds for the two heat wave definitions and times of emergence for the grid point. The solid blue line shows the daily summer temperature record over the period. The solid red line indicates the mean summer average temperature for each year. The purple horizontal lines are the average summer temperature thresholds of 5°C above the historical climatology. The black horizontal lines are the average summer temperature thresholds of the 90^{th} percentile of the historical climatology. The purple dashed vertical lines are the time of emergence for the 5°C above the historical climatology definition of a heat wave and black dashed vertical lines are the time of emergence for the 90^{th} percentile above the historical climatology definition of a heat wave. When the time of emergence for a definition is unlabeled, the frequency of heat waves is considered to not have emerged from background frequency by 2100. Larger images of each time series are provided in the appendix.

2.2.3 Multi Model Time of Emergence

Figure 2-4 and Figure 2-5 show the multi-model time of emergence of summer heat waves using the two different definitions of heat waves. The time of emergence maps from each model shown in Figure 2-1 and Figure 2-2 were evaluated at each grid point to determine what year 80% or more of the models show a time of emergence for the frequency of heat waves. As with the individual model analysis, the earliest time of emergence possible was 1950 and the latest 2100. Figure 2-4 is the multi-model map of time of emergence for the frequency of heat waves that are 5°C above the historical climatology. It shows early time of emergence for high latitude land regions, later emergence for lower latitude land regions, and no emergence over water.

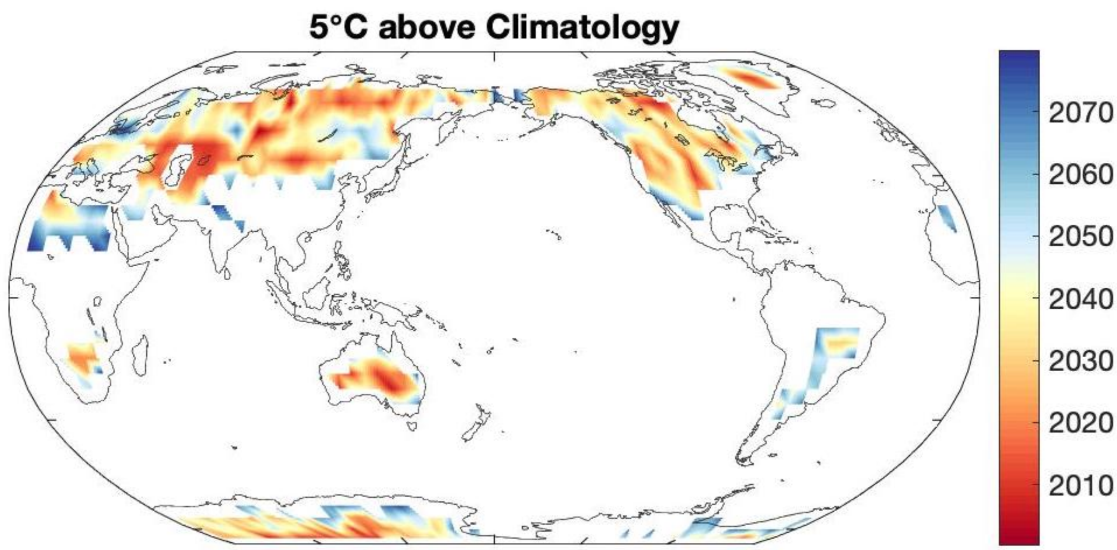

Figure 2-4: Multi-model Time of Emergence of summer heat waves that are 5°C above historical climatology and sustained for five or more days. Summer is defined as the three hottest consecutive monthly averages in the climatological year. The color bar indicates the final year in the earliest thirty-year window where the frequency of these heat waves is statistically different from historical (1900-1930) frequency using the two sample Kolmogorov-Smirnov statistical test for at least 80% of the General Circulation Models (GCMs) shown in Figure 2-1. White indicates that the frequency is not been identified to be statistically different in 80% or more of the models by the end of the simulation period (2100). All GCMs are forced by SSP2-4.5 emissions scenario.

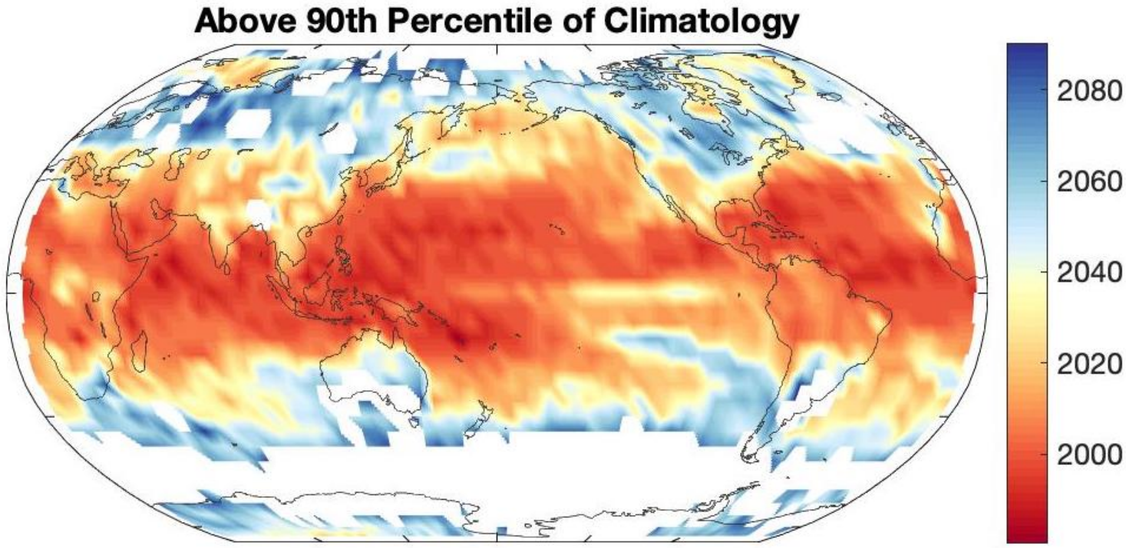

Figure 2-5: Multi-model Time of Emergence of summer heat waves that are above the 90^{th} percentile of the historical climatology and sustained for five or more days. Summer is defined as the three hottest consecutive monthly averages in the climatological year. The color bar indicates the final year in the earliest thirty-year window where the frequency of these heat waves is statistically different from historical (1900-1930) frequency using the two sample Kolmogorov-Smirnov statistical test for at least 80% of the General Circulation Models (GCMs) shown in Figure 2-2. White indicates that the frequency is not been identified to be statistically different in 80% or more of the models by the end of the simulation period (2100). All GCMs are forced by SSP2-4.5 emissions scenario.

Figure 2-5 is the multi-model map of time of emergence for summer heat waves that are above the 90^{th} percentile of the historical climatology. This definition shows earliest emergence in low latitudes, later emergence in the high latitudes of the Northern Hemisphere, and no emergence over the Southern Ocean.

Chapter 3

Discussion and Conclusion

3.1 Discussion

3.1.1 Differences between individual model evaluations of time of emergence

The time of emergence analysis from each model shown in Figure 2-1 and Figure 2-2 resolves inter-model differences in which grid cells show emergence when. Specifically looking at Figure 2-1, one of the most obvious inter-model differences is whether any emergence is observed in the North Pacific, North Atlantic, and Arctic Circle. Five of the models (ACCESS-CM2, ACCESS-ESM1-5, CanESM, CNRM-CM6-1, and IPSL-CM6A-LR) show more similar patterns with each other than the remaining five models, with earlier emergence over land and some emergence over the oceans.

Recent work evaluating CMIP6 models has found that this new generation of GCMs shows a higher range in equilibrium climate sensitivity (ECS) than in CMIP5 [Meehl et al., 2020]. To determine ECS, CO2 levels are instantaneously doubled, and the model is run to an equilibrium state. The change in temperature that occurs is defined as the ECS and is considered to be a representation of the climate sensitivity of the system [Charney et al., 1979]. The reason for the increase in climate sensitivity of CMIP6 models is not yet fully resolved, but researchers and modeling groups have found it is possibly due to aerosol effects and cloud feedbacks [Meehl et al., 2020].

Model	ECS
ACCESS-CM2	4.7
ACCESS-ESM1-5	3.9
BCC-CSM2-MR	3.0
CNRM-CM6-1	4.8
CanESM5	5.6
GFDL-ESM4	2.6
IPSL-CM6A-LR	4.6
MIROC6	2.6
MRI-ESM2-0	3.2
NorESM2-LM	2.5

Table 3.1: Equilibrium Climate Sensitivity (ECS), a hypothetical value of global warming at equilibrium for a doubling of CO2, values for each General Circulation Model assessed in this analysis. Table adapted from Meehl et al. 2020.

Evaluating the differences between time of emergence estimates through the framing of model climate sensitivity yields a distinct relationship. The five models that show any emergence over oceans are all characterized by higher ECS values (Table 3.1). The models with lower ECS values (BCC-CSM2-MR, GFDL-ESM4, MIROC6, MRI-ESM2-0, and NorESM2-LM) all show a lesser southern extent of emergence in the Northern Hemisphere, no emergence over oceans, and most show later time of emergence when compared to the high ECS models.

Some relationships also are observed between Figure 2-2 inter-model differences and ECS values. The model that shows the earliest global time of emergence is CanESM5, the most sensitive climate model represented in this analysis. On the other hand, MIROC6, NorESM2-LM, and GFDL-ESM4 show some of the latest time of emergence in high latitudes in the Northern Hemisphere, and show little emergence over the Southern Ocean. Relating the time of emergence patterns of individual models to model climate sensitivity demonstrates that this analysis is robust for a wide range of estimated projected climate feedback systems with relatively few models analyzed. However, the multi-model result of the analysis shown in Figure 2-4 and Figure 2-5 does emphasize the results of the low climate sensitivity models because the threshold of emergence was set at 80% of the models needing to show emergence to be considered statistically significant across all models.

3.1.2 Differences between heat wave definitions

One of the central findings of this work is the differences between two different IPCC heat wave definitions. The "5°C definition" evaluates a heat wave as a period of five or more consecutive days that are hotter than 5°C above the historical climatology. The "90th percentile definition" considers a heat wave to be five consecutive days that are hotter than the 90th percentile of the historical climatology. As shown in Figure 2-4 and Figure 2-5, these two definitions produce time of emergence distributions that are very different. In the 5°C definition (Figure 2-4), no emergence is observed over the oceans, and there is a trend of earlier time of emergence with increasing latitude on land. Almost the reverse is observed with the 90$^{\text{th}}$ percentile definition (Figure 2-5). While there is still no emergence over the Southern Ocean, there is a trend of later time of emergence with increasing latitude not only on land but also in the ocean basins.

Examining time series at different representative grid points along with the relative thresholds of emergence and times of emergence begins to explain the differences in the patterns observed between the two definitions. A time series from the Southern Ocean at a grid point where neither definition emerges (Figure 2-3, Figure A-5) shows a wide range of variability in both the daily data and the mean summer average as well as decadal variability. The 90$^{\text{th}}$ percentile definition mean threshold is consistently exceeded, with only a slight increase in mean and daily temperatures toward the end of the century. The 5°C definition mean threshold is never crossed until 2090 and is only reached once or twice by the daily data. The two definitions show different reasons why the Southern Ocean does not show an increase in the frequency of heat waves by 2100; either the frequency is remaining stable over the time period as in the 90$^{\text{th}}$ percentile definition, or there are no heat waves that exceed the 5°C definition.

The same issue with the 5°C definition is observed in the other oceanic grid point observed and the coastal grid point observed. In both of these locations, the 5°C definition threshold is never or seldom crossed, even by the end of the century. However, unlike the Southern Ocean, the Pacific Ocean (Figure 2-3, Figure A-2) and coastal

Australia (Figure 2-3, Figure A-6) both have emergence under the 90^{th} percentile definition. Both of these locations in fact show the mean summer temperature increasing beyond the average 90^{th} percentile of the summer historical climatology by 2100.

The difference in emergence between definitions at these two grid points is caused largely by the damping effect the ocean has on extreme temperature values and the variability of the region. Comparing the range in daily temperature values between the grid point in the Pacific and a grid point in Europe shows that Europe has up to a 15°C difference in minimum and maximum summer temperatures in the historical period, while the Pacific has only about a 3°C difference. The ocean modulates the temperature such that exceeding 5°C above the historical climatology is extremely unlikely, even with increased mean temperatures of 3°C. On the other hand, exceeding the 90^{th} percentile of the historical climatology can occur in continental regions because the threshold is not as affected by the damping of the ocean.

Grid cells that show emergence for both definitions also show some variability between when the different definitions emerge, both independently and in relationship to each other. Two grid points (Europe and Southern Africa) show only a 10-year difference in time of emergence between the two definitions, but in Europe (Figure 2-3, Figure A-1) the time of emergence of the 5°C definition is sooner than that of the 90^{th} percentile definition while in Southern Africa (Figure 2-3, Figure A-7) the opposite is observed. In both however, the threshold for emergence under the 5°C definition is higher than the 90^{th} percentile, but by a small margin. The timing of the emergences in Europe is likely due to the increase in high temperature daily values just before 1990. This analysis does not account for a signal emerging and staying emerged, so the stagnation of increasing temperature after the time of emergence does not affect the result.

Finally, there are three example grid point time series representing two highly populated areas and a key ecological location. Each of these grid points shows emergence under both definitions with a 40-to-70-year separation between emergence under the 90^{th} percentile definition and emergence for the 5°C definition. The greater the difference in mean threshold temperature values for emergence, the greater the difference between times of emergence are. North America (Figure 2-3, Figure A-3), the Indian Peninsula (Figure 2-3, Figure A-8), and the Amazon Rain forest (Figure 2-3, Figure A-4) all have varying levels of variability in daily summer temperatures, with North America having the most variability. This increase in variability could explain why the 5°C definition emerges sooner at this grid point relative to the Amazon Rain forest and Indian Peninsula.

3.1.3 Signal, Noise, and Signal to Noise analysis

Quantifying the relationship between not only the variability, but also the increasing signal, and signal to noise ratio provides additional insight into the patterns of time of emergence of climate change for each definition. We define signal as the difference between mean summer temperatures in degrees Celsius from 2080-2100 and the mean summer temperatures in degrees Celsius during the background period 1900-1930. The noise we define as the standard deviation of the daily temperature anomalies relative to the 1850-1950 climatology. The multi-model means of the signal, noise, and signal to noise ratio are shown in Figure 3-1. We then calculated the correlations between the time of emergence map for each definition with the signal, noise, and signal to noise ratio (Table 3.2).

The 5°C definition shows the greatest negative correlation to the signal, meaning the more warming, the earlier the time of emergence. The 90^{th} percentile definition shows the greatest negative correlation with the signal to noise ratio, meaning that places where the warming is dominating over the internal variability of the location are going to see earlier time of emergence. Visually comparing the maps also shows this relationship. The signal is highest in high latitudes, corresponding to early time of emergence under the 5°C definition. The signal to noise ratio is lowest in high latitudes, correlating to late time of emergence under the 90^{th} percentile definition. It is also very high in low latitudes, especially areas affected by El Niño, and the same pattern is observed in the 90^{th} percentile definition time of emergence map.

As expected with both definitions, noise is correlated to the time of emergence, but

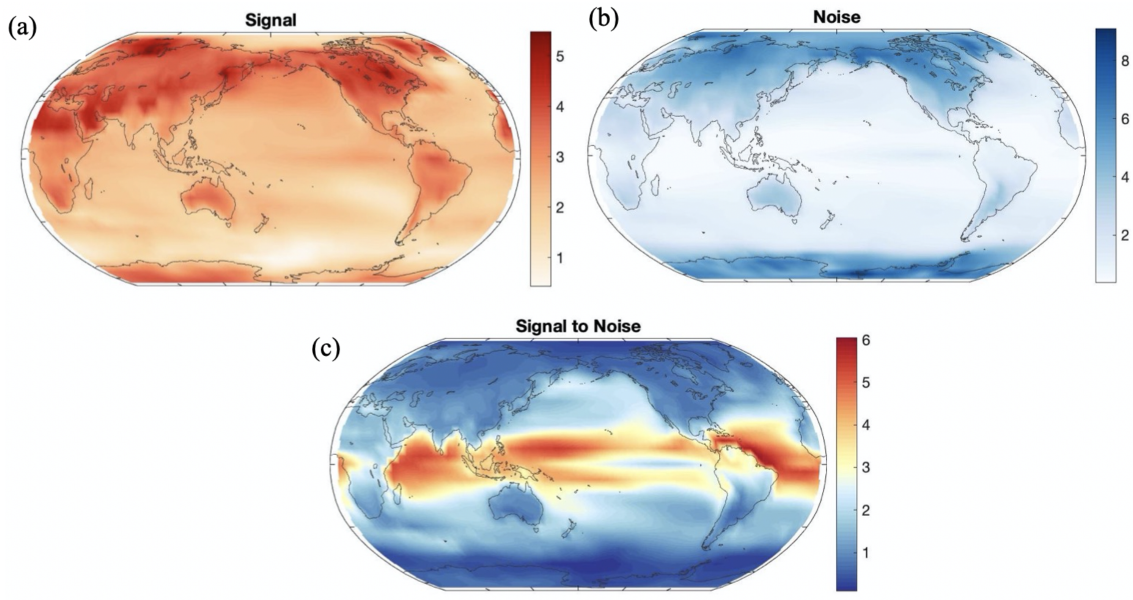

Figure 3-1: The signal of warming, the noise of daily variability, and the signal to noise ratio. (a) The signal is defined as the difference between mean summer temperatures in degrees Celsius from 2080-2100 and the mean summer temperatures in degrees Celsius during the background period 1900-1930. Figure 6a is a multi-model mean of this difference. (b) The noise is defined as the standard deviation of daily temperature anomalies relative to the 1850-1950 climatology. Figure 6b is a multi-model mean of the standard deviations from each model. (c) The signal to noise ratio is the division of the multi-model mean signal (a) and the multi-model mean noise (b).

in different ways. For the 5°C definition, the noise is correlated negatively, meaning more noise will lead to an earlier time of emergence. For the 90^{th} percentile definition, the noise is correlated positively, meaning that more noise will actually lead to a later time of emergence. These correlations are reflected in the differences in the patterns

Definition	Signal Correlation	Noise Correlation	Signal to Noise Correlation
5°C Above Historical Climatology (Figure 2-4)	-0.6575	-0.5467	0.3298
Above 90th Percentile of Historical Climatology (Figure 2-5)	-0.2350	0.6449	-0.8279

Table 3.2: Correlation coefficients for both heat wave definitions and signal, noise, and signal to noise ratio. Each correlation coefficient reported has a p-value of less than 0.05 and are considered statistically significant.

between the two definitions. Noise is highest in the high latitudes, and the 5°C definition emerges first in those latitudes while the 90^{th} percentile definition emerges later in those latitudes. While the noise plays a role in both definitions, the impact varies based on what is meant by a heat wave.

3.1.4 Significance of Emergence Patterns

These emergence patterns for both the 5°C definition and the 90^{th} percentile definition will have varying impacts on the human population and the ecosystems in each region. The patterns in the time of emergence of heat waves that are 5°C above the historical climatology (Figure 2-4) are the opposite of the trends observed by time of emergence of mean summer temperatures. This definition also has the strongest correlation with the signal, rather than the signal to noise ratio as found in Mahlstein et al. 2011. In addition, the earliest emergence in northern latitudes suggests a greater impact on historically high emitting countries, in contrast with the findings in Mahlstein et al. 2011.

The patterns in Figure 2-5 and correlation for the 90^{th} percentile definition with the signal to noise ratio however are very similar to those found in Mahlstein et al 2011. Figure 2-3 also supports this similarity between the mean summer warming and the emergence of heat waves that exceed the 90^{th} percentile of the historical climatology, as in many grid points, the mean summer temperatures end up exceeding the 90^{th} percentile threshold by the end of the century, suggesting an emergence of the mean summer temperature as well. The early emergence in the low latitudes supports the Mahlstein et al. 2011 finding that low latitude and historically low emitting countries will be most affected by increasing temperatures, and therefore temperature extremes.

The signal to noise ratio is such an important parameter in climate impacts because changes in climate in a region that has larger variability may have less severe impacts on those ecosystems and populations that are adapted to large changes on short time scales [Williams et al., 2007]. Low to mid latitude regions where temperatures are less variable and high diversity ecosystems such as rain forests dominate will be most affected by more frequent heat waves that exceed the 90^{th} percentile of the historical climatology in the coming century. While the 90th percentile definition shows later emergence in the higher latitudes, these latitudes are more affected by sustained temperature perturbations that are 5°C above the historical climatology. Such large temperature increases that persist for multiple days could also have an effect on important ecosystems at high latitudes.

In addition to ecosystem impacts, impacts on the human population living in any region are going to be affected by some type of heat wave, likely before 2050, but definitely before the end of the century. Comparing to estimated population density under the SSP2-4.5 scenario in Figure 3-2, high population centers in India, coastal China, Europe, West Africa, and coastal United States are quickly going to be affected by an increased frequency in heat waves. Locations without adequate mitigation strategies will be faced with increased heat-related deaths due to more persistent heat waves.

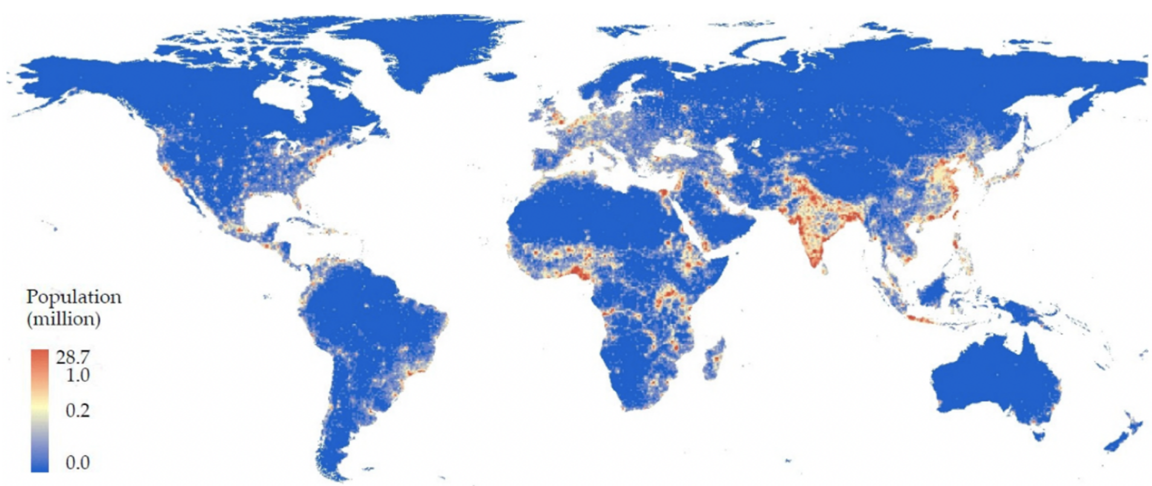

Figure 3-2: Population density at 0.5-degree grid cells in 2080 as estimated by SSP2-4.5 scenario (Murakami and Yamagata 2019).

3.1.5 Future Directions

This analysis has demonstrated that the definition of a heat wave significantly affects analysis of potential future impacts. Expanding the analysis of time of emergence to other heat wave definitions found in literature could strengthen the results shown here and further inform mitigation strategies. In addition, this analysis does not take into the difference in heat stress between urban and rural areas [Fischer et al., 2012] or vulnerability, adaptation options, and acclimatization of the population which could all decrease the effects of heat waves [Wu et al., 2014]. Further relating the impacts and damage of heat waves with vulnerability would help to separate effects on ecosystems and human health risks.

3.2 Conclusion

This analysis showed that summer heat wave frequency has already emerged from the frequency of heat waves in 1900-1930 or will soon emerge. However, the characteristics of the heat wave affect where emergence will first be observed. Heat waves that have temperatures that are greater than 5°C above the historical climatology emerge soonest in high latitudes and are most correlated to the signal of warming. Using a definition that requires exceeding the 90^{th} percentile of the historical climatology, heat waves have already become more frequent throughout much of the tropics and will become more frequent throughout most continental areas by the end of the century. The signal to noise ratio appears as the most significant driver of heat waves that are determined by the 90^{th} percentile definition. The correlations shown in this analysis has implications for the potential adaptability of vulnerable low latitude ecosystems and populations to an increase in frequency of heat waves.

Appendix A

Additional Figures

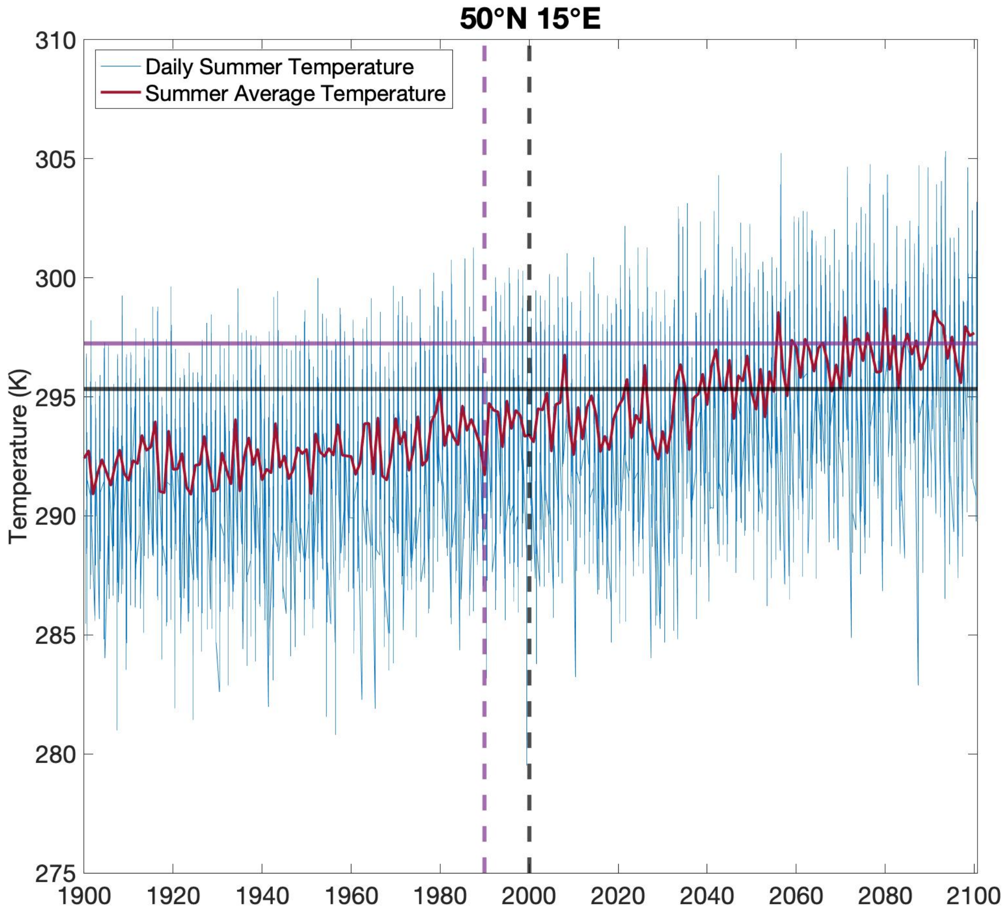

Figure A-1: Larger time series plot of daily and mean summer temperatures over 1900-2100 for ACCESS-CM2 along with temperature thresholds for the two heat wave definitions and times of emergence for Europe as shown in Figure 2-3. The solid blue line shows the daily summer temperature record over the period. The solid red line indicates the mean summer average temperature for each year. The purple horizontal lines are the average summer temperature thresholds of 5°C above the historical climatology. The black horizontal lines are the average summer temperature thresholds of the 90^{th} percentile of the historical climatology. The purple dashed vertical lines are the time of emergence for the 5°C above the historical climatology definition of a heat wave and black dashed vertical lines are the time of emergence for the 90^{th} percentile above the historical climatology definition of a heat wave. When the time of emergence for a definition is unlabeled, the frequency of heat waves is considered to not have emerged from background frequency by 2100.

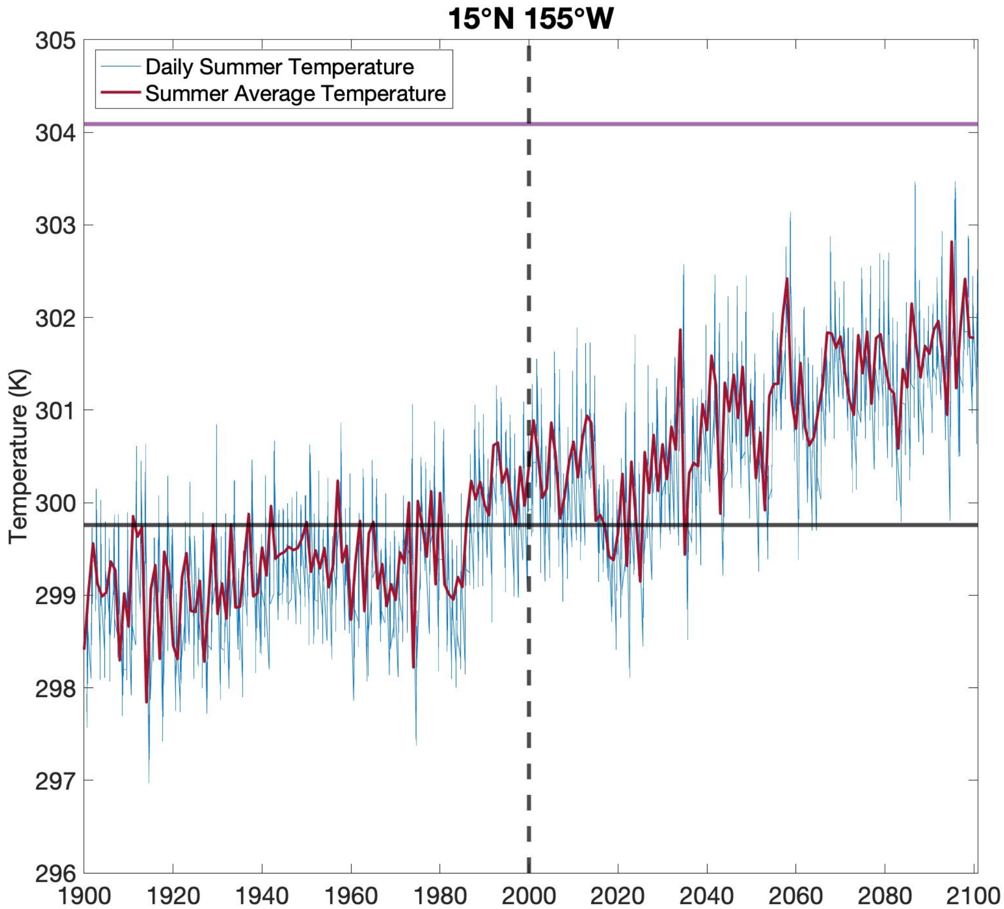

Figure A-2: Larger time series plot of daily and mean summer temperatures over 1900-2100 for ACCESS-CM2 along with temperature thresholds for the two heat wave definitions and times of emergence for the North Pacific as shown in Figure 2-3. The solid blue line shows the daily summer temperature record over the period. The solid red line indicates the mean summer average temperature for each year. The purple horizontal lines are the average summer temperature thresholds of 5°C above the historical climatology. The black horizontal lines are the average summer temperature thresholds of the 90^{th} percentile of the historical climatology. The purple dashed vertical lines are the time of emergence for the 5°C above the historical climatology definition of a heat wave and black dashed vertical lines are the time of emergence for the 90^{th} percentile above the historical climatology definition of a heat wave. When the time of emergence for a definition is unlabeled, the frequency of heat waves is considered to not have emerged from background frequency by 2100.

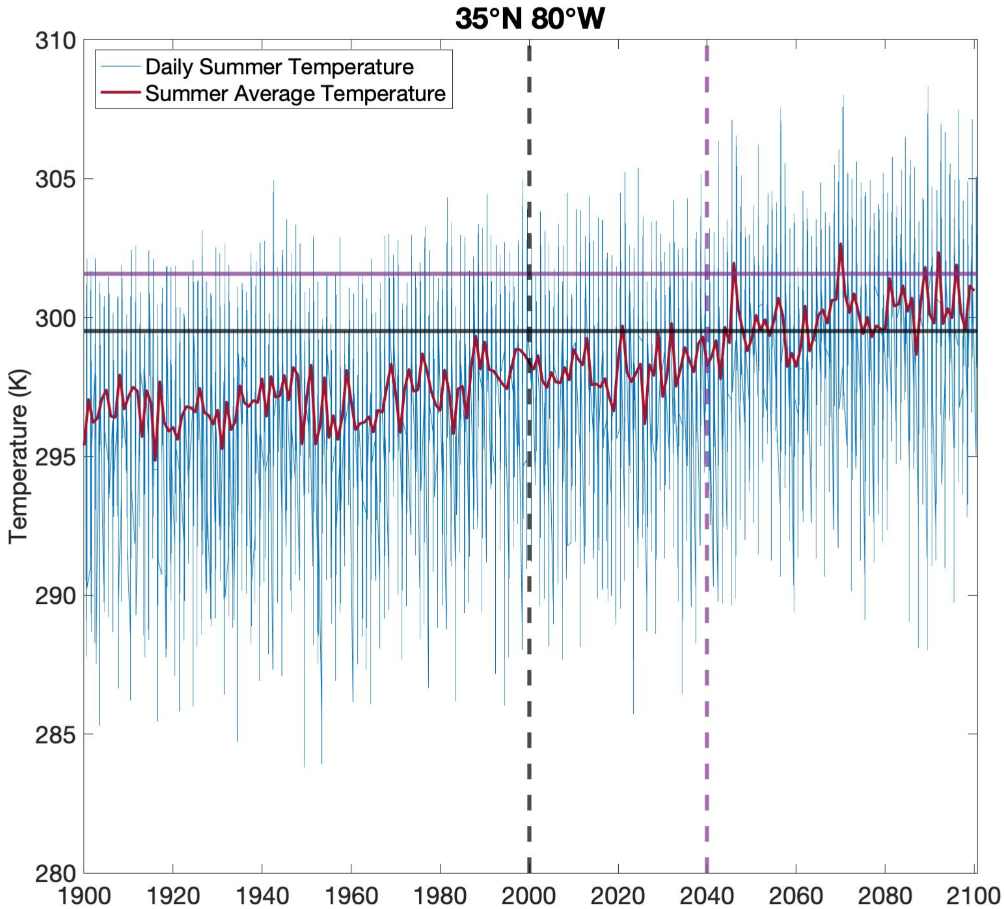

Figure A-3: Larger time series plot of daily and mean summer temperatures over 1900-2100 for ACCESS-CM2 along with temperature thresholds for the two heat wave definitions and times of emergence for North America as shown in Figure 2-3. The solid blue line shows the daily summer temperature record over the period. The solid red line indicates the mean summer average temperature for each year. The purple horizontal lines are the average summer temperature thresholds of 5°C above the historical climatology. The black horizontal lines are the average summer temperature thresholds of the 90^{th} percentile of the historical climatology. The purple dashed vertical lines are the time of emergence for the 5°C above the historical climatology definition of a heat wave and black dashed vertical lines are the time of emergence for the 90^{th} percentile above the historical climatology definition of a heat wave. When the time of emergence for a definition is unlabeled, the frequency of heat waves is considered to not have emerged from background frequency by 2100.

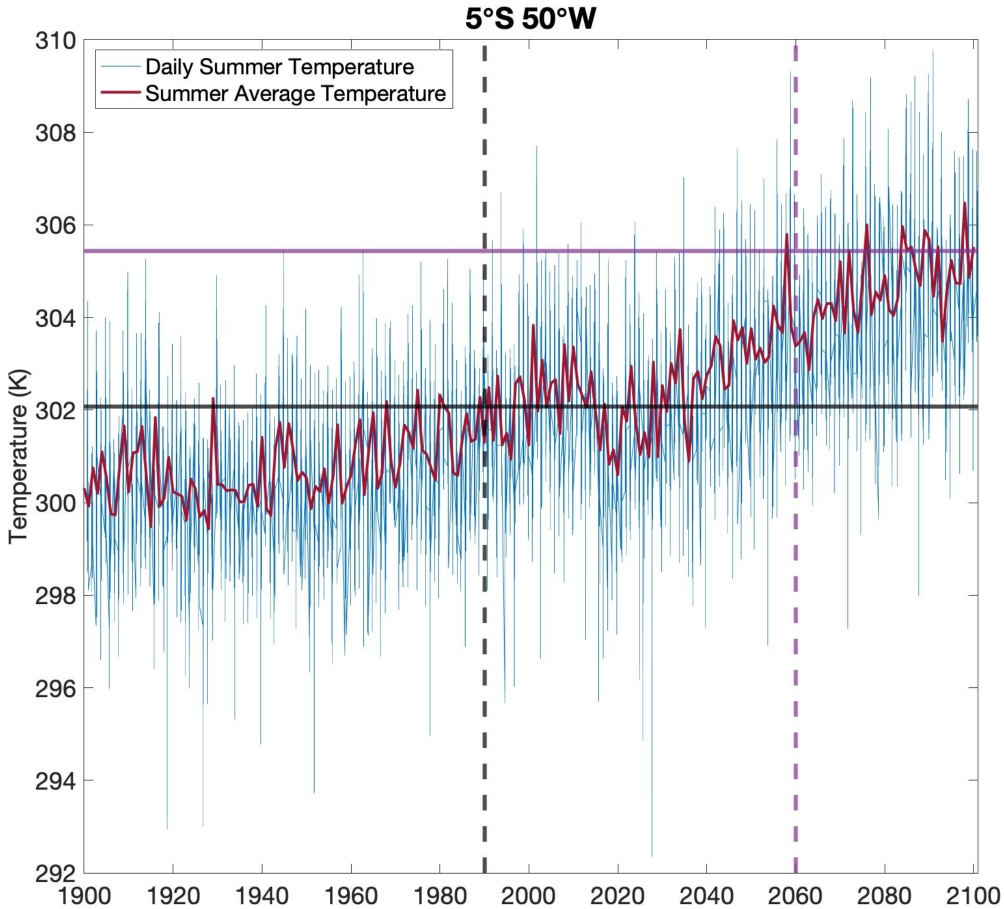

Figure A-4: Larger time series plot of daily and mean summer temperatures over 1900-2100 for ACCESS-CM2 along with temperature thresholds for the two heat wave definitions and times of emergence for the Amazon Rain forest as shown in Figure 2-3. The solid blue line shows the daily summer temperature record over the period. The solid red line indicates the mean summer average temperature for each year. The purple horizontal lines are the average summer temperature thresholds of 5°C above the historical climatology. The black horizontal lines are the average summer temperature thresholds of the 90th percentile of the historical climatology. The purple dashed vertical lines are the time of emergence for the 5°C above the historical climatology definition of a heat wave and black dashed vertical lines are the time of emergence for the 90th percentile above the historical climatology definition of a heat wave. When the time of emergence for a definition is unlabeled, the frequency of heat waves is considered to not have emerged from background frequency by 2100.

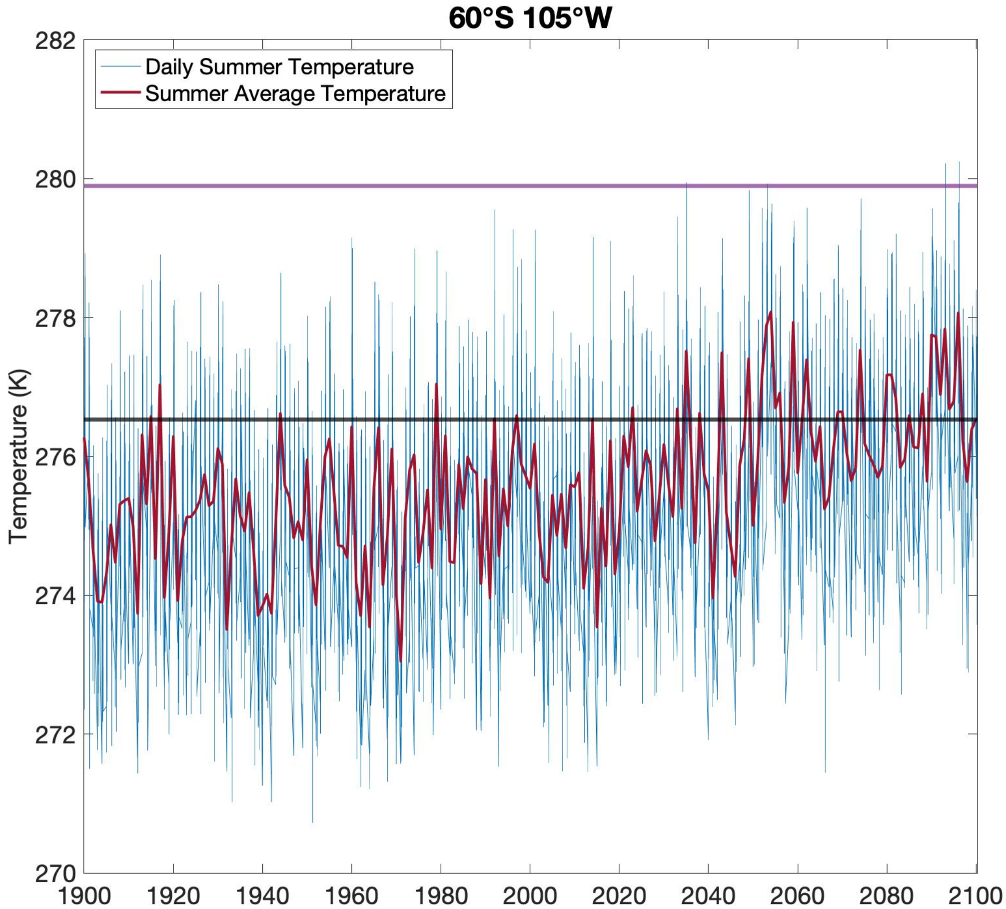

Figure A-5: Larger time series plot of daily and mean summer temperatures over 1900-2100 for ACCESS-CM2 along with temperature thresholds for the two heat wave definitions and times of emergence for the Southern Ocean as shown in Figure 2-3. The solid blue line shows the daily summer temperature record over the period. The solid red line indicates the mean summer average temperature for each year. The purple horizontal lines are the average summer temperature thresholds of 5°C above the historical climatology. The black horizontal lines are the average summer temperature thresholds of the 90th percentile of the historical climatology. The purple dashed vertical lines are the time of emergence for the 5°C above the historical climatology definition of a heat wave and black dashed vertical lines are the time of emergence for the 90th percentile above the historical climatology definition of a heat wave. When the time of emergence for a definition is unlabeled, the frequency of heat waves is considered to not have emerged from background frequency by 2100.

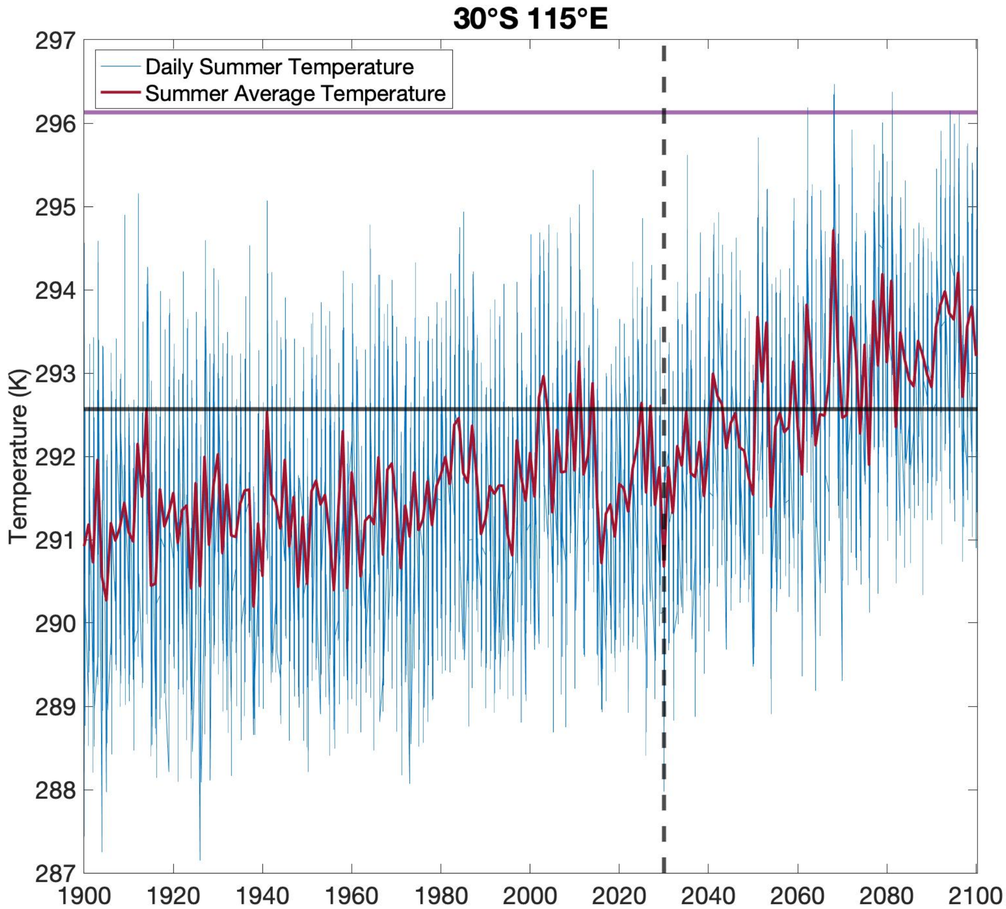

Figure A-6: Larger time series plot of daily and mean summer temperatures over 1900-2100 for ACCESS-CM2 along with temperature thresholds for the two heat wave definitions and times of emergence for Australia as shown in Figure 2-3. The solid blue line shows the daily summer temperature record over the period. The solid red line indicates the mean summer average temperature for each year. The purple horizontal lines are the average summer temperature thresholds of 5°C above the historical climatology. The black horizontal lines are the average summer temperature thresholds of the 90^{th} percentile of the historical climatology. The purple dashed vertical lines are the time of emergence for the 5°C above the historical climatology definition of a heat wave and black dashed vertical lines are the time of emergence for the 90^{th} percentile above the historical climatology definition of a heat wave. When the time of emergence for a definition is unlabeled, the frequency of heat waves is considered to not have emerged from background frequency by 2100.

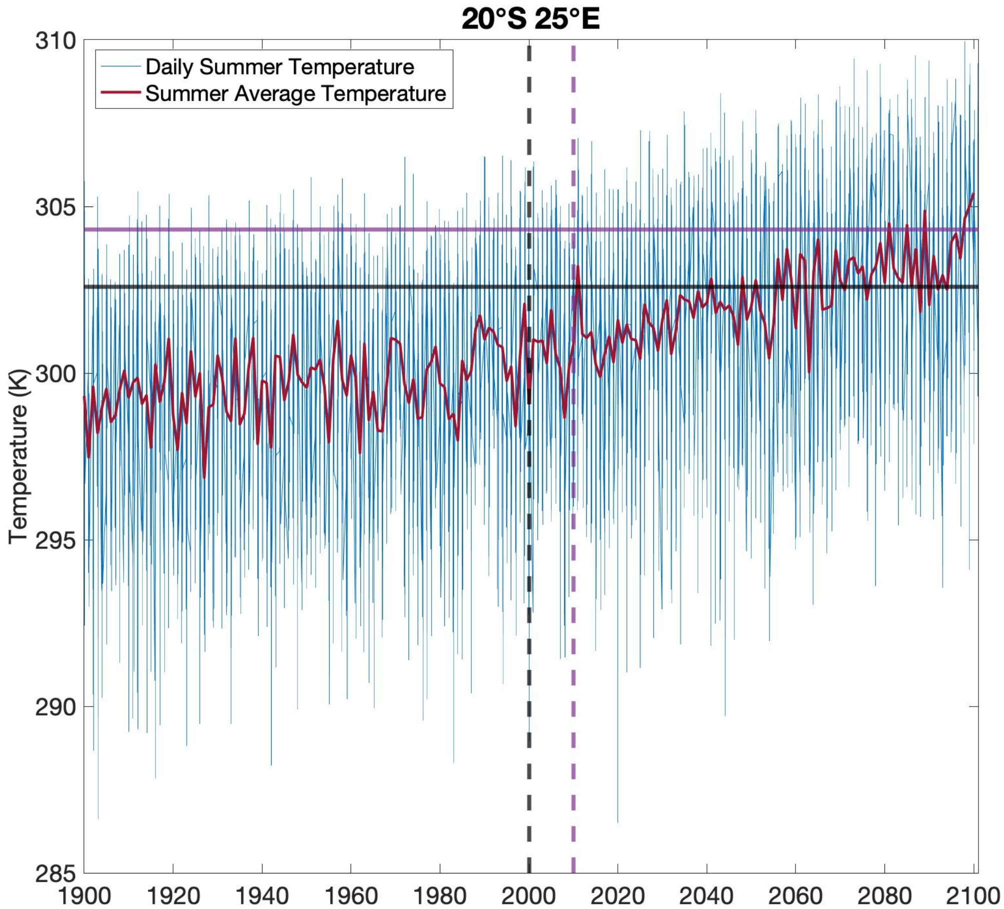

Figure A-7: Larger time series plot of daily and mean summer temperatures over 1900-2100 for ACCESS-CM2 along with temperature thresholds for the two heat wave definitions and times of emergence for Southern Africa as shown in Figure 2-3. The solid blue line shows the daily summer temperature record over the period. The solid red line indicates the mean summer average temperature for each year. The purple horizontal lines are the average summer temperature thresholds of 5°C above the historical climatology. The black horizontal lines are the average summer temperature thresholds of the 90^{th} percentile of the historical climatology. The purple dashed vertical lines are the time of emergence for the 5°C above the historical climatology definition of a heat wave and black dashed vertical lines are the time of emergence for the 90^{th} percentile above the historical climatology definition of a heat wave. When the time of emergence for a definition is unlabeled, the frequency of heat waves is considered to not have emerged from background frequency by 2100.

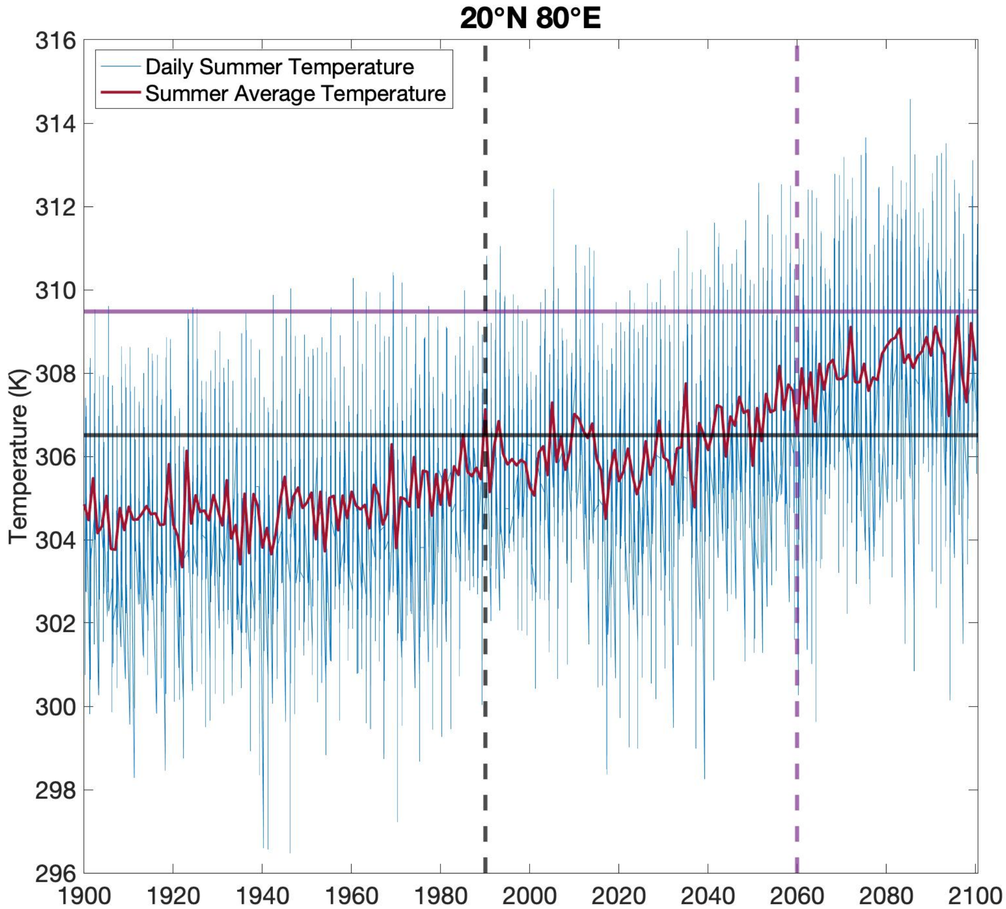

Figure A-8: Larger time series plot of daily and mean summer temperatures over 1900-2100 for ACCESS-CM2 along with temperature thresholds for the two heat wave definitions and times of emergence for the Indian Peninsula as shown in Figure 2-3. The solid blue line shows the daily summer temperature record over the period. The solid red line indicates the mean summer average temperature for each year. The purple horizontal lines are the average summer temperature thresholds of 5°C above the historical climatology. The black horizontal lines are the average summer temperature thresholds of the 90th percentile of the historical climatology. The purple dashed vertical lines are the time of emergence for the 5°C above the historical climatology definition of a heat wave and black dashed vertical lines are the time of emergence for the 90th percentile above the historical climatology definition of a heat wave. When the time of emergence for a definition is unlabeled, the frequency of heat waves is considered to not have emerged from background frequency by 2100.

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