Global Annual Precipitation Cycles and Variability

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ABSTRACT

Changes in the timing of precipitation within a year can impact ecosystems, agriculture, infrastructure, and many other aspects of life. A shift in the wet season can lead to droughts or flooding, causing financial losses as well as risking human lives. This study uses high resolution daily precipitation data to objectively identify the timing and duration of the wet season across the globe in historical and future periods. Datasets include the Global Precipitation Climate Project (GPCP), the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) project, and 10 historical and 8 future model simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5). In general, shorter wet seasons have been occurring worldwide according to the historical simulations and the observational data. Exceptions can be found in eastern Asia and in many southern hemisphere ocean areas, where longer wet seasons have been observed. The future model simulations, using representative concentration pathway 8.5, project different changes in timing and duration of wet season for locations worldwide. Across the majority of the globe, the wet season is projected to become shorter in the 21st century. Supporting prior regional work, shorter wet seasons are expected in the coming years in the Amazon, southern Africa, and much of the contiguous United States. The Arctic could see a reduction or extension of the wet season by as much as 15 days per decade due to a later onset and earlier cessation. These results have important consequences for planning and managing water resources in the future.

1. Introduction

Climate change entails far more than a rise in the global average annual temperature. Precipitation patterns and cycles are changing as well as the average temperatures. The three major aspects of precipitation cycles are the the magnitude of precipitation received, frequency of precipitating days, and the timing of the precipitation. This study will focus primarily on the timing aspect of the annual cycles worldwide, defining the wet season by its onset and cessation dates. Our goal is to determine the timing and duration of a every locations wet season and to identify trends that have occurred in the past or will occur throughout the century.

If the timing of the precipitation cycle changes over time, the effects on any given ecosystem can be devastating. Shorter wet seasons can leave the rainforest dry and susceptible to more frequent and more catastrophic fires (Fu et al. 2013). A wetter spring for the southwest United States could in turn reduce the fire risk during the early summer when temperatures begin to rise (Pal et al. 2013). However, if the summer monsoons are delayed, the fire season could be just as long, only shifted later in the year.

Previous work has identified changing seasonality of precipitation globally over the past several decades. For example, using monthly data, Chou et al. (2013) determined the range of precipitation between the wet season and dry season. In general, regions are receiving more precipitation during the wet season and even less precipitation during the dry season, indicating that locations are seeing a general increase in seasonality. Similar conclusions were reached by Pascale et al. (2015) using monthly data.

Other work has focused on the seasonality and the timing of the wet season in specific regions, with studies pertaining to Southern Amazonia (Fu et al. 2013; Liebmann and Marengo 2001), the tropics (Feng and Porporato 2013), Africa (Dunning et al. 2016), or the contiguous United States (Pryor and Schoof 2008; Pal et al. 2013). In the Amazon, there have been shorter wet seasons overall (Fu et al. 2013). Liebmann and Marengo (2001) also confirmed a link between the length of wet season in the Ama-

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zon and the sea surface temperatures of the nearby oceans. In other parts of the tropics, Feng and Porporato (2013) discovered not only longer but also later arriving wet seasons with the exception being West Africa. Bridging this gap, the study by Dunning et al. (2016) identified the climatology of the onset and cessation of the wet season for Africa. A later onset date in Western Africa was seen in reanalysis data, but not in the observational datasets. Back in the Western Hemisphere, Pryor and Schoof (2008) discovered that the both the west coast and the east coast of the contiguous United States are experiencing an earlier start to the wet season, i.e. a wetter spring, matching the behavior of coastal Africa found by the observational data in the study by Dunning et al. (2016). Farther inland, Pal et al. (2013) found a trend toward shorter wet seasons in the Mississippi River Valley and into the Great Lakes region. The Southwest also showed evidence of later onsets to the summer monsoon according to this study.

There are many ways to determine the onset and cessation of the wet and dry season. One method is to use the cumulative daily mean rainfall anomaly (Dunning et al. 2016). This method provides a precise onset date, but global daily data is not available for longer than approximately 35 years. Other studies have used anomalies of 5-day running averages of rainfall amount (Liebmann and Marengo 2001) to define the onset and cessation of the wet season. Still others have implemented a three-month running average, determining the wet season to be the three-month period with the most rainfall (Chou et al. 2013). While global monthly data is available for a much longer period than daily data, using the wettest 3 months does not allow us to see changes in the timing unless the onset or cessation dates are changing by more than a month.

The goal of this study, is to reconcile the regional work described above by applying one universal daily identification technique to the entire globe. By investigating observations and global climate model output of the 20th and 21st centuries we create a climatology of wet season characteristics as well as projections of future trends.

2. Methods and Data

a. Data Sets

The Global Precipitation Climate Project (GPCP) (Huffman et al. 2001) and the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks- Climate Data Record (PERSIANN-CDR) (Sorooshian et al. 2000; Ashouri et al. 2015) observational data sets are used for this study. Both provide daily data, with GPCP spanning October 1996 through October 2015 at 1° resolution globally, and PERSIANN from 60°N to 60°S at quarter-degree resolution between 1983 and 2017. Both data sets employ Geostationary Operational Environmental Satellites, and GPCP also uses Polar Operational Environmental Satellites to measure daily precipitation using microwave and infrared sensing. GPCP and PERSIANN-CDR are not independent as they use data from some of the same satellites. However, the GPCP data also uses in situ rain gauge measurements. For the purposes of this project, only complete years of data were used and leap days were removed.

Daily precipitation data from models as part of the Coupled Model Intercomparison Project, phase 5 (CMIP5) (Taylor et al. 2012) are also used (Table 1). Two different experiments are used in this study: historical (1900-2005) and representative concentration pathway (RCP) 8.5 (2006-2100). Historical simulations use natural and anthropogenic forcing, based on observed changes in atmospheric chemistry over the past century. In the RCP 8.5 models, the radiative forcing increases throughout the twenty-first century before reaching a level of 8.5 W m^{-2} at the end of the century. The 10 historical and 8 RCP 8.5 models used in this study are listed in Table 1. The model data is re-gridded bilinearly to 1° resolution (matching the GPCP grid) so as to compare more accurately with the observational data sets.

TABLE 1: CMIP5 models used, historical and future projections with specified horizontal resolution.

ModelAbbreviation	*Historical*	*Future*	*HorizontalResolution*
ACCESS1-0		X	1.25° x 1.88°
ACCESS1-3		X	1.25° x 1.88°
CMCC-CESM	X		3.34° x 3.75°
CMCC-CMS	X		3.71° x 3.75°
CNRM-CM5		X	1.4° x 1.4°
GFDL-CM3	X	X	2° x 2.5°
GFDL-ESM2G	X	X	2.0° x 2.5°
GFDL-ESM2M	X		2.0° x 2.5°
HadCM3	X		2.5° x 3.75°
HadGEM2-CC	X	X	1.25° x 1.88°
HadGEM2-ES	X		1.25° x 1.87°
IPSL-CM5A-LR		X	2° x 3.75°
MPI-ESM-P	X		1.9° x 1.88°
NORESM1-M	X	X	1.9° x 2.5°

b. Methods and Definitions

The definitions of wet season onset and cessation date used in this study are based on the index created by Liebmann and Marengo (2001) and expanded by Dunning et al. (2016). The algorithm to identify onset and cessation dates is implemented in the observations and model datasets as follows, for each year and each grid point, as illustrated in Figure 1.

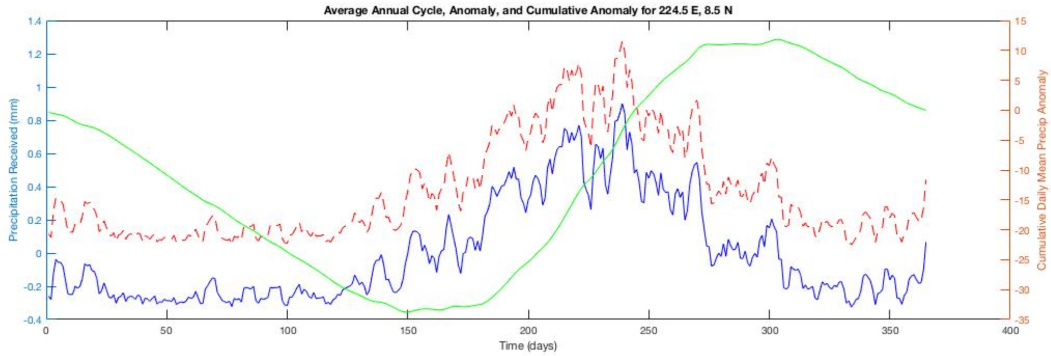

FIG. 1: Example of the algorithm to determine wet seasons characteristics. Annual cycle of precipitation (red) for a given location (224.5°E, 8.5°N), daily mean rainfall anomaly (blue), and the cumulative daily mean rainfall anomaly (green).

1. Precipitation anomaly is calculated by subtracting the yearly mean precipitation (e.g. Figure 1 blue line) from the annual cycle (e.g. Figure 1 red line).

2. The cumulative daily mean rainfall anomaly is calculated, using a 5-day running mean (e.g. Figure 1 green line).

3. The minimum and maximum of the cumulative anomaly are then calculated to determine the timing of the wet season.

The onset of the wet season is defined as the day on which the minimum cumulative anomaly occurs- the day of the year which indicates the start of an increase in the value of the cumulative daily mean rainfall anomaly. The cessation of the wet season is defined as the day on which the maximum cumulative anomaly occurs- the day of the year which indicates the start of a decrease in the cumulative daily mean rainfall anomaly. The duration of the wet season is then calculated by taking the difference between the onset and cessation dates (Dunning et al. 2016). The algorithm was applied to the average annual cycle to determine the climatology, and to individual years. For regions that exhibit more than one wet season, only the most prominent wet season was taken into consideration.

Linear trends are defined by fitting a least squares line to the variable of interest (e.g. onset date). To determine statistical significance, a t-test was used, and a 95 % confidence interval was calculated. Any trends above or below the threshold are considered significant. For the CMIP5 models, we tested for model agreement on the sign of the trend; if more than 6 of the 8 RCP 8.5 models used or more than 8 of the 10 historical simulations used agreed, the trend was considered significant.

3. Results

a. Historical

1) WET SEASON ONSET

The average onset of the wet season varies by geographic location, as shown in Figure 2. Common features are evident in the patterns of the onset of the wet season. For example, the northward progression of the ITCZ is seen in Africa and in the Atlantic Ocean. The onset dates from the PERSIANN data (Figure 2b and 2c) are generally earlier than the onset dates in the GPCP data (Figure 2a). For example, the PERSIANN data shows the wet season beginning in December for the Amazon, southern Africa, the eastern Mediterranean, and most of Australia. In contrast, GPCP records the onset dates in these regions to be in January. The wet season in eastern Asia begins in late May or early June according to the PERSIANN data, but GPCP indicates the onset closer to July.

The historical CMIP5 models (Figure 2d) agree more closely with the PERSIANN observations, showing earlier onset dates than GPCP. The PERSIANN data however does not include the poles, while the GPCP data and the CMIP5 models do. GPCP shows the onset of the wet season occurring in December in the Arctic, while the models show a very different solution, placing the onset of the wet season closer to April or May. Throughout Antarctica, the differences are still large, but not as pronounced as those in the Arctic. While the GPCP data shows the wet season beginning in November, the CMIP5 models indicate the start of the wet season sometime in August. The discrepancies between the models and the observations may be attributed to the lack of precipitation in the polar regions, where some locations receive less than 150 mm of precipitation each year, or to a poorly defined wet season.

Figure 3 shows trends in onset dates. In general, the Northern Hemisphere has not seen a consistent, long-term

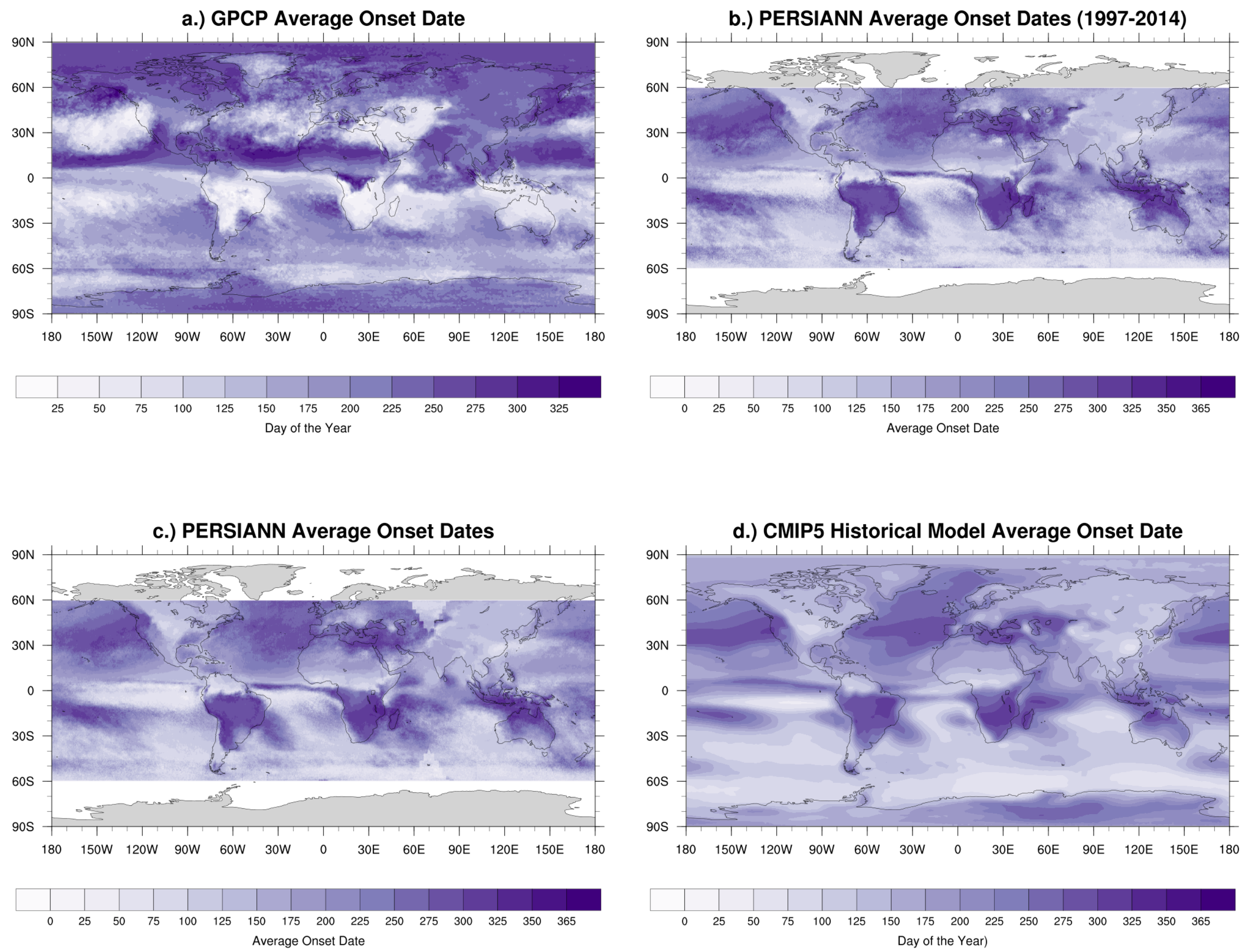

FIG. 2: Onset dates from the a.) GPCP observations from 1997-2014 b.) PERSIANN-CDR data from 1997-2014 c.) PERSIANN-CDR data from 1983-2017 and d.) CMIP5 historical model average from 1900-2005.

trend in the onset of the wet season, but more consistent and significant trends of the onset exist in the Southern Hemisphere. One area of interest in the northern hemisphere is the northern Balkan Peninsula, which has shown a trend toward a later onset of about 20 days per decade according to the PERSIANN data (Figure 3c). However, GPCP does not agree with this trend, showing slightly earlier onset dates each year. When only the 18 years covered by the GPCP data were isolated from the PERSIANN dataset (Figure 3b), the findings for this region matched the GPCP trends, indicating that the trend toward a later onset date in the Balkan region has occurred prior to the late 1990s. The historical CMIP5 model runs agree with the trend toward a later onset in the Balkan region over the 106 years in these experiments, further supporting the idea of a more recent change in the trend of onset date.

The PERSIANN data indicates a trend of a 20- or 30-day earlier onset each decade along the eastern contiguous United States. The GPCP data does not agree, indicating a neutral trend through this region or even a slight trend toward a later onset. Examining the GPCP time frame of the PERSIANN data, this trend toward an earlier onset is even more pronounced, showing the onset arriving 70 or 80 days earlier each decade. The CMIP5 models show no prominent trend, perhaps only a slight inclination toward a later onset. Given the lack of agreement among datasets, more investigation is required to identify and understand a trend.

A notable region of statistically significant trends is just equatorward of Antarctica over the open southern Atlantic. This region exhibits a trend of the wet season arriving 6 or 7 days earlier each year. Although the CMIP5 historical models do not agree and the PERSIANN data does not ex-

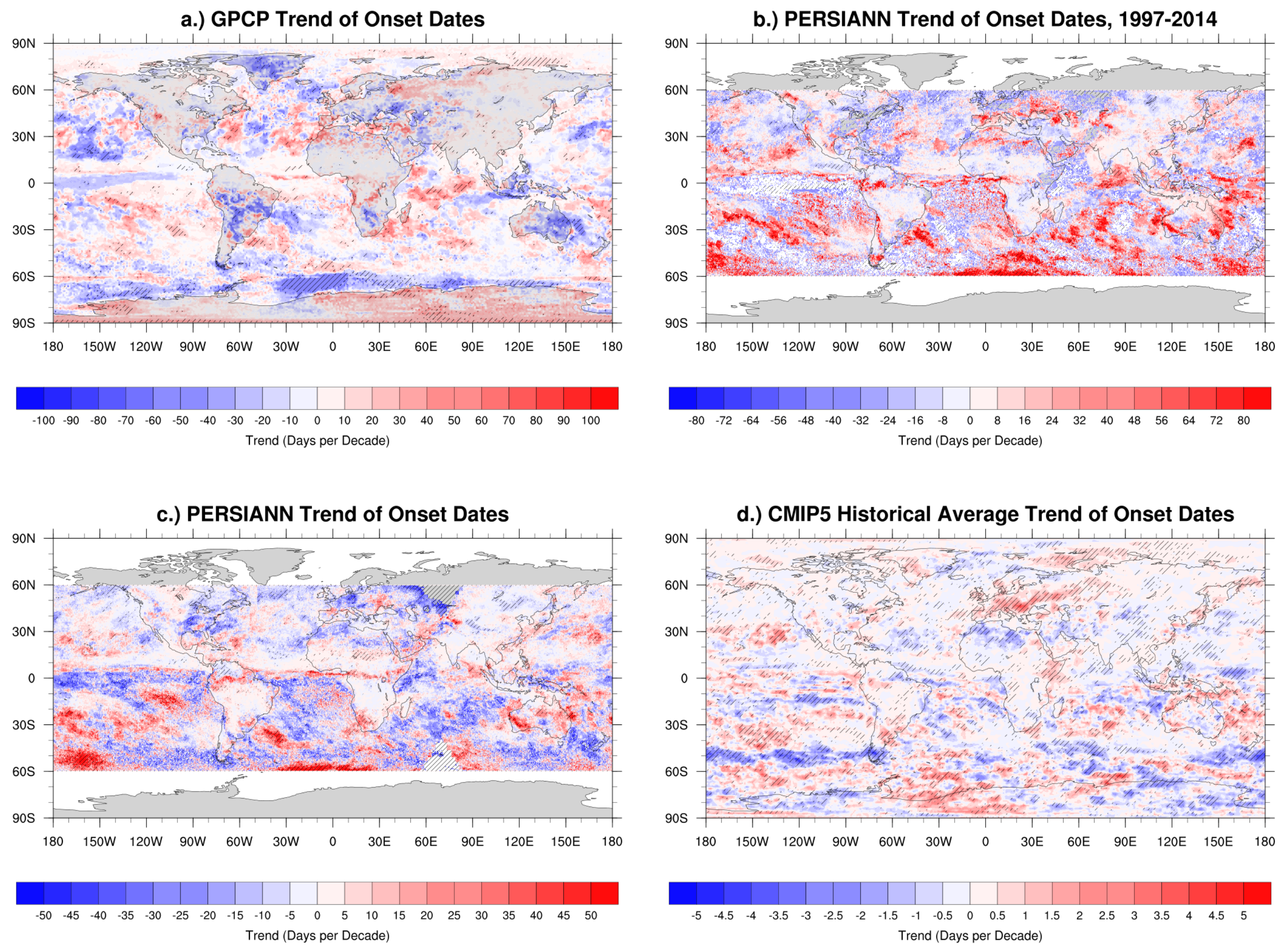

FIG. 3: Trend of onset dates from the a.) GPCP observations from 1997-2014 b.) PERSIANN-CDR data from 1997-2014 c.) PERSIANN-CDR data from 1983-2017 and d.) CMIP5 historical model average from 1900-2005. Blue shading indicates an earlier onset date each decade, and red shading indicates a later onset each decade. Hatching on a, b, and c, indicate significance of the trend to a 95% level. Hatching on d. indicates 9 or 10 of the 10 models used agree on the sign of the trend.

tend far enough south, the significance of the trend of this broad area is suggestive of its reality. Finally, South America is an area of sharp disagreement among the datasets examined. Although the PERSIANN data indicates no definitive trend across the continent, the GPCP data shows the onset arriving around 60 days earlier each decade for most of the central part of the continent. The CMIP5 models show no significant trends as well as a lack of a true pattern throughout this region.

2) WET SEASON CESSATION

The average cessation of the wet season also shows the expected patterns across the datasets used (Figure 4). For example, rather than a northward progression, a southward progression of the ITCZ is seen. The cessation of the wet season occurs later for locations closer to the equator, which matches the movement of the ITCZ at the end of the boreal summer. As seen in Figure 4, this pattern emerges not only in Africa and in the Atlantic but around the entire globe near the equator. Again, the PERSIANN data (Figure 4b and 4c) shows the cessation of the wet season occurring earlier than the GPCP data (Figure 4a) does in many regions, including southern Africa, most of South America, and northern Australia. The CMIP5 models (Figure 4d) do not match either observational dataset particularly well, but lie closer to the observations from the PERSIANN data. The models indicate the cessation dates in December for southern Africa, the Amazon, and

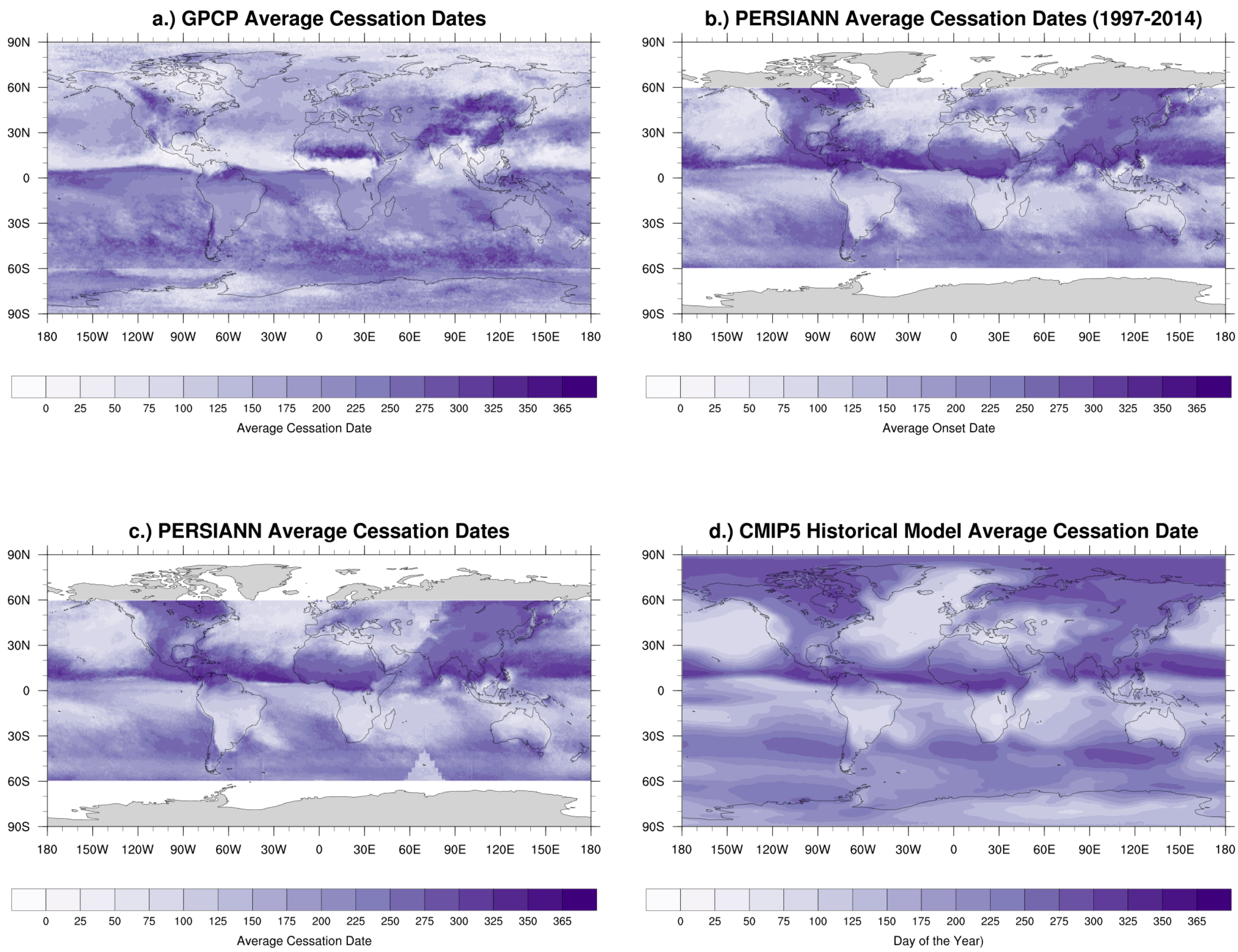

FIG. 4: Average cessation date from the a.) GPCP observations from 1997-2014 b.) PERSIANN-CDR data from 1997-2014 c.) PERSIANN-CDR data from 1983-2017 and d.) CMIP5 historical model average from 1900-2005. Day 1 is January 1st, day 365 is December 31st.

northern Australia, about 30 days earlier than the PERSIANN data.

Some trends in the cessation date can be seen in all of the datasets used in this study (Figure 5). Both the GPCP and PERSIANN data show an earlier cessation in some parts of eastern Europe, although the placement of the trends differs slightly. The GPCP data shows a trend of 30 to 40 days earlier per decade in western Russia, while the PERSIANN data observes a trend of the same magnitude farther west into the Balkan Peninsula. The two observational datasets disagree on the sign of the trend in the region of the Atlantic off the coast of the Carolinas and Florida. The GPCP data is showing a trend toward an earlier cessation date, with the wet season ending 40 to 50 days earlier each decade. Conversely, the PERSIANN data shows the wet season ending 20 days later each decade. This trend toward a later cessation date is even stronger according to the PERSIANN data from 1997-2014. The CMIP5 model average indicates little trend in this region but does show the cessation occurring 2 to 3 days earlier each decade in an ocean area slightly north of the region of interest. The lack of agreement indicates that further investigation is needed to verify the pattern observed.

There is a great amount of discrepancy in the trends of the cessation date around the equator. The GPCP data (Figure 5a) shows an earlier cessation date in the Atlantic and in Africa but a later cessation date in general toward the Pacific. The PERSIANN data (Figure 5b and 5c) shows little to no trend in these areas both in the complete 35-year period as well as in the years corresponding to the GPCP data. The exception in the PERSIANN data is in

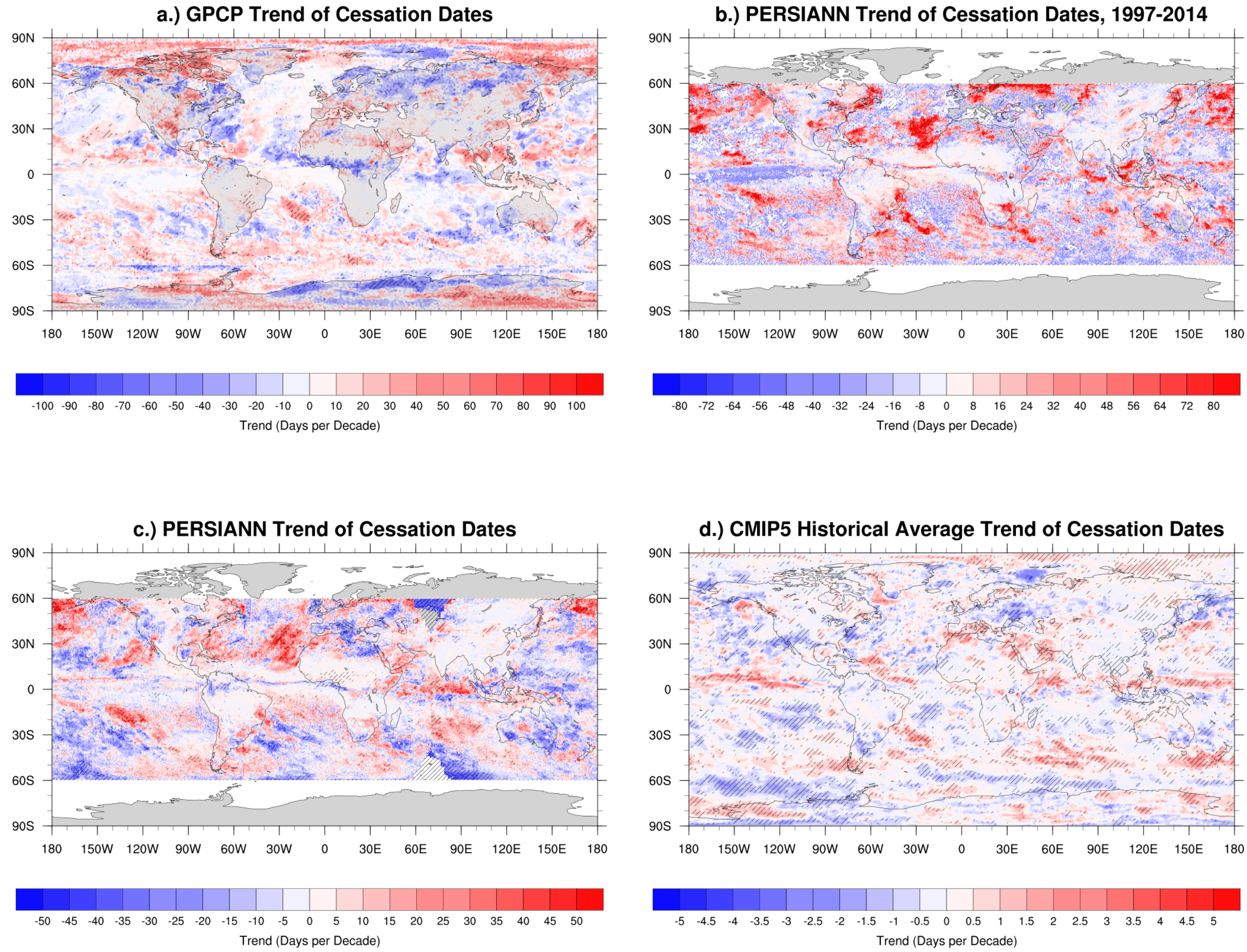

FIG. 5: Trend of cessation dates from the a.) GPCP observations from 1997-2014 b.) PERSIANN-CDR data from 1997-2014 c.) PERSIANN-CDR data from 1983-2017 and d.) CMIP5 historical model average from 1900-2005. Blue shading indicates an earlier cessation date each decade, and red shading indicates a later cessation each decade. Hatching on a, b, and c, indicate significance of the trend to a 95% level. Hatching on d. indicates 9 or 10 of the 10 models used agree on the sign of the trend.

the central Indian Ocean, where the wet season appears to be ending 60 or more days later each decade. The CMIP5 models (Figure 5d) contradict both observational datasets, showing the wet season ending 1 to 2 days later each year for most of the equatorial region. Between the lack of consistency and the absence of statistical significance in these trends, the findings must be further investigated.

While the GPCP data shows a trend toward a later cessation date across much of the Arctic, the historical model runs show little to no trend existing in the Arctic. On the other end of the world, Antarctica is shown in the GPCP data to be experiencing primarily later cessation dates each year with some offshore regions experiencing the wet season ending 60 to 70 days earlier reach decade. The historical models are not as aggressive with the trends shown. This points to the possibility of the trends developing recently as a result of climate change. To make this link with certainty, further research must be done.

3) WET SEASON DURATION

According to the observational data, most of the world has been trending toward shorter wet seasons in the past several years, as seen in Figure 6. The GPCP data (Figure 6a) shows the wet season getting shorter by as much as 100 days per decade in the Arctic. Similar findings appear in western Antarctica due to the delay in the onset of the wet season and the earlier cessation dates each

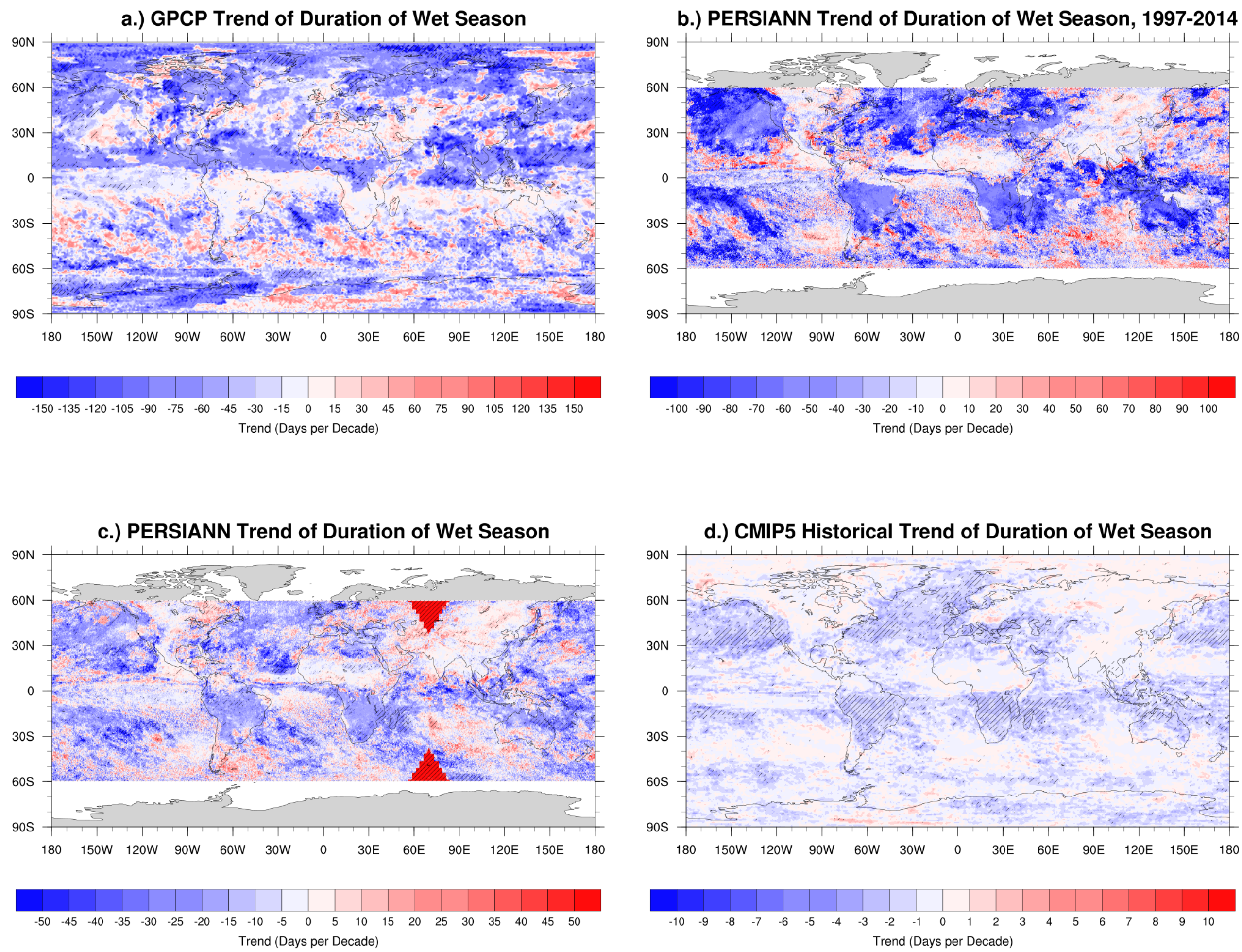

FIG. 6: Trend of duration of wet season from the a.) GPCP observations from 1997-2014 b.) PERSIANN-CDR data from 1997-2014 c.) PERSIANN-CDR data from 1983-2017 and d.) CMIP5 historical model average from 1900-2005. Blue shading indicates an shorter wet season each decade, and red shading indicates a longer wet season each decade. Hatching on a, b, and c, indicate significance of the trend to a 95% level. Hatching on d. indicates 9 or 10 of the 10 models used agree on the sign of the trend.

decade. Another area of interest is central Africa, showing a shorter wet season by as much as 100 days each decade as well. This result is due to the trend toward a later arrival of the wet season and a trend toward an early cessation in this region. Furthermore, inland India is experiencing dramatic reductions in the wet season duration according to the GPCP data. The western tropical Pacific also exhibits trends toward a shorter wet season by 70 or more days per decade. However, the only region of these showing statistically significant trends is the Arctic in regions north of Russia and near Greenland.

The PERSIANN data, shown in Figure 6b and 6c, agrees that the wet season in central and southern Africa is getting shorter each decade, by 20 days per decade in the full time frame and by 40 to 50 days per decade between the years of 1997 and 2014. This indicates a recent amplification of the trend of the duration of the wet season. The PERSIANN data shows no trend over the Indian subcontinent in the full 35-year period, and even in the years covered by the GPCP data, there is only a trend of around 3 to 5 days shorter per decade. The full dataset also shows little trend in the tropical North Pacific. A region that the PERSIANN data consistently identifies as receiving shorter wet seasons each year is the Amazon Rainforest. The GPCP data shows little to no trend in this area, but the PERSIANN dataset shows the wet season getting 20 to 25 days shorter each decade over the 35 years and 50 to 60 days per decade over the shorter time frame.

The historical CMIP5 models, as shown in Figure 6d, agree with many of the trends identified by the observational data. According to the model average, wet seasons have been getting shorter in the Amazon and in southern Africa by about 3 to 4 days per decade. Again, these trends in the duration of the wet season arise from the Amazon experiencing later onsets each year and earlier cessations as well. The Indian subcontinent remains an area of uncertainty, with trends in most of the region showing the wet season shortening by 1 day per decade. There is still no agreement on the sign of the trend of duration in the Arctic. Most of the Arctic has been experiencing changes in the wet season by at most only 1 day per decade according to the historical simulations. The exception to this finding is the region extending into the Arctic from the North Atlantic, showing the wet season getting 3 to 4 days shorter each decade.

b. Future

1) WET SEASON ONSETS

The RCP 8.5 projections from the CMIP5 models indicate some dramatic pattern changes in the onset of wet seasons around the world (Figure 7). In general, the northern hemisphere is trending toward later onsets, while the southern hemisphere is trending toward earlier onsets over time. At least 7 of the 8 models agree that the Arctic is an area of large change. The entire Arctic is anticipated to experience the onset of the wet season arriving 5 to 7 days later each decade despite the historical models and the observations showing no clear pattern in the changes in this region during the 20th century (Figure 7).

Europe is projected to see the wet season arriving 5 to 6 days later each decade, a trend seen consistently throughout the past observations in this region. The Caribbean will likely see later wet seasons, approximately 4 or 5 days later each decade. This trend has not yet been observed and was not seen by the historical CMIP5 simulations. Similar findings exist along the Appalachian Mountain chain in the contiguous United States, but this projection is in opposition to the findings from the past century. Southern and western Africa are expected to see little change in the onset of the wet season, but the ocean region south of Madagascar could see significantly later onset dates as time passes. This trend was not identified by the full PERSIANN dataset but was found both in the PERSIANN data from 1997-2014 and in the GPCP dataset. This implies that this trend has been recently developing and could be enhanced by climate change.

A belt just south of the equator exhibiting later onset dates also stretches almost entirely around the globe. The only regions predicted to experience an earlier onset of precipitation include the South Pacific and northwestern Africa. While the PERSIANN dataset indicated similar trends in the onset of the wet season in the past, the GPCP data indicated the exact opposite trend occurring in this region. Finally, in the South Pacific, the wet season could arrive 8 to 10 days earlier per decade in the central South Pacific and 4 to 5 days earlier each decade off the Antarctic coast.

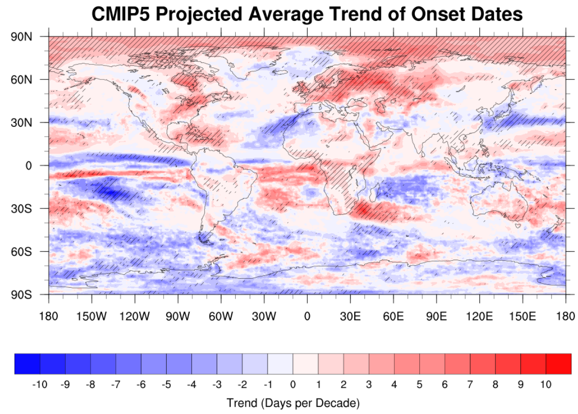

FIG. 7: The projected average trend of onset dates according to the future runs of the 8 selected CMIP5 models. Red shading indicates a later onset each year, and blue shading indicates an earlier onset each year. Hatching indicates trends agreed upon by at least 6 of the 8 models used.

2) CESSATIONS

The CMIP5 models predict some notable trends in the cessation dates of the wet season in the coming decades (Figure 8). Most notable is the region in the Arctic north of Russia, expected to exhibit trends toward an earlier cessation by 9 or 10 days each decade. The trend toward an earlier cessation date is found by the GPCP data as well, indicating the possibility of the emergence of this trend over more recent years as a result of climate change. The same can be said about much of eastern Europe. The Hudson Bay also shows this dramatic trend emerging, but no trends have been observed in the past or anticipated by the historical CMIP5 simulations. More investigation is necessary to determine the validity of this projection.

Much of the contiguous United States is expected to see the wet season ending 4 or 5 days earlier each decade, as is much of the Caribbean. This trend has not been observed by the GPCP data nor by the historical CMIP5 models but has to some extent been seen by the PERSIANN data. A belt around the 30°S parallel also exhibits a similar pattern, with a more dramatic trend occurring off the southeastern coast of the continent of Africa. Only the full PERSIANN data has found this trend to exist off the southeastern coast of Africa. Both the GPCP data and the historical

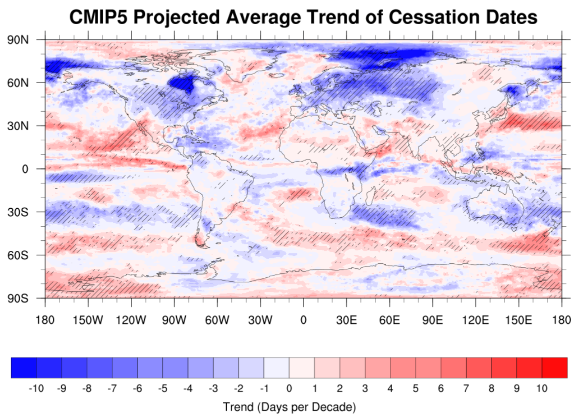

FIG. 8: The projected average trend of cessation dates according to the future runs of the 8 selected CMIP models. Red shading indicates a later cessation date each year, and blue shading indicates an earlier cessation date each year. Hatching indicates trends agreed upon by at least 6 of the 8 models used.

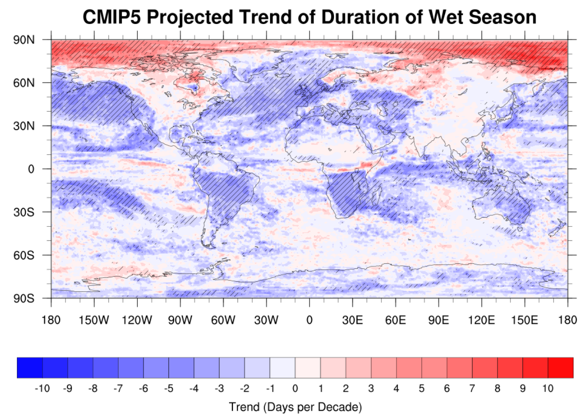

FIG. 9: The projected average trend of duration of wet season according to the future runs of the 8 selected CMIP5 models. Red shading indicates a longer wet season each year, and blue shading indicates a shorter wet season each year. Hatching indicates trends agreed upon by at least 6 of the 8 models used.

CMIP5 simulations have seen little to no trend in this region.

Some regions are expected to experience a later cessation date each year. Much of Antarctica falls under this trend, with the wet season appearing to end 2 to 4 days later every decade. In certain areas, like the eastern half of Antarctica, the GPCP data shows the emergence of this trend, implying the possibility of another trend emerging due to climate change. A similar trend occurs around the 50°S parallel with the trend steepening to 4 or 5 days later each decade around 150°E. This trend has been seen over all of the historical data used in this study. In the northern hemisphere, the only pattern in which a later cessation date seems to occur is a belt around the 30°N parallel. The strongest trend in this area is found in the western North Pacific. Noted is the anomalous behavior of the Caribbean, which falls in this region but shows a trend toward an earlier cessation date as time goes on. This trend has not been seen by the observations or the historical simulations.

3) DURATIONS

According to the future CMIP5 models, most of the world will be seeing shorter wet seasons in the 21st century (Figure 9). For example, the Amazon rainforest, according to most of the models, will experience a shorter wet season by 2 or 3 days each decade. A similar pattern is seen in southern Africa. So far, observations from the GPCP data set have shown little to no trend in the duration of the wet season in the Amazon between the years 1997 and 2014.

A noteworthy contradiction to this projected shortening is the Arctic, a region with a trend of a 6- to 7- day longer wet season each decade. However, this is highly misleading. In many locations, at least 6 of the 8 models agree that the wet season in the Arctic will decrease in duration over time, matching the behavior expected given the trend toward later onsets and earlier cessations. The remaining models indicate a trend toward longer wet seasons that is around five times the magnitude of the trends toward shorter wet seasons. The average of the 8 models therefore is a positive trend toward a longer wet season due to the skew of the mean toward the outliers. Some select regions within the Arctic do indeed indicate a trend toward a longer wet season, but there are regions with shorter projected wet seasons interspersed. Figure 10 shows the spread of the trends observed throughout the higher latitudes of the northern hemisphere. Overall, there is great variability in the trend of the duration of the wet season within the Arctic. Further investigation is necessary to determine the cause of this variability and the changes that will occur in this area.

4. Conclusions

We have applied the algorithm from Dunning et al. (2016) and Liebmann and Marengo (2001) to objectively identify the specific date of onset and cessation of wet seasons across the entire globe in two observational datasets and CMIP5 models for the first time. At the poles, earlier onsets and cessations have been observed near Antarctica and later cessation dates have been observed in most of the Arctic. However, later onsets are projected to appear in

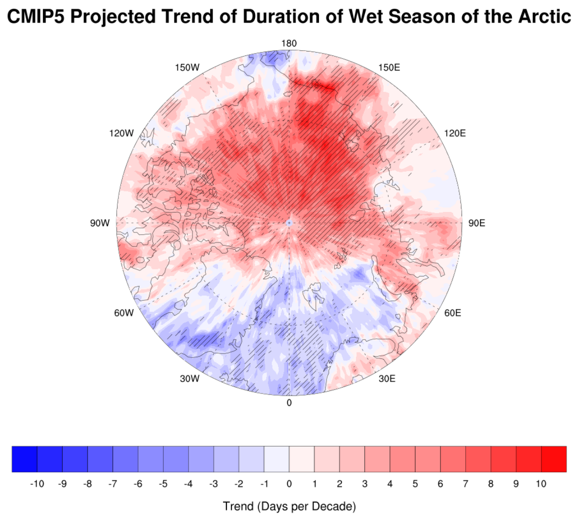

FIG. 10: The projected average trend of duration of wet season according to the future runs of the 8 CMIP5 models for 70°N to the north pole and from 140°W to 160°W. Red shading indicates a longer wet season each year, and hatching indicates trends agreed upon by at least 6 of the 8 models used.

the Arctic in the future. Later onsets and earlier cessations are projected to occur for the contiguous United States, the Caribbean, northern and eastern Europe, and Southern Africa. Shorter wet seasons are occurring in the Amazon and in south-central Africa according to observations, historical simulations, and the future CMIP5 models.

There are similarities and discrepancies among the climatology and trends of onset, cessation, and duration of wet seasons in two observational datasets, the 10 historical simulations, and the 8 future CMIP5 projections. Some of these findings confirmed those of prior works adding confidence to these results, including the following:

- Shorter wet season projected in the Amazon (Fu et al. 2013).

- Observed shortening wet season in the Mississippi River Valley and into the Great Lakes region (Pal et al. 2013). The historical simulations agree, but the future model runs show a lengthening due to an earlier onset date.

- Longer wet season projected along the equator (Feng and Porporato 2013), although the region of increase is not found to be as widespread in this study.

- The historical CMIP5 models are in agreement with the work of Pal et al. (2013). According to these simulations, the southwest United States is experiencing a later onset to the summer monsoon. While the GPCP data shows very little trend in this area, the sign of this trend agrees with the conclusion of a delayed summer monsoon. The PERSIANN data, however, shows the opposite trend for the full 35-year period. But upon examining the years 1997-2014, a sharp trend toward later onsets emerges. This indicates a recent change in the pattern of the southwest United States and the possibility of the effects of climate change.

- All three historical datasets agree that the east and west coasts of the United States are experiencing earlier onset dates, but this work shows smaller trends than those discovered by Pryor and Schoof (2008).

Some discrepancies found between this study and prior studies include:

- The GPCP duration trends oppose the patterns found in West Africa by Feng and Porporato (2013). The GPCP data shows a longer wet season in the West Africa, while Feng and Porporato (2013) found it to be the only region to strongly oppose the general trend of the tropics toward longer wet seasons each year.

- The GPCP data shows longer wet seasons in the Amazon, opposing the findings of Fu et al. (2013)

- The GPCP data shows later onsets in the extreme northwest coastal regions of western Africa, but Dunning et al. (2016) did not find identical trends.

Reasons for the differences from prior studies include the usage of different datasets and different origins of data (e.g. satellite and in situ blend versus entirely in situ), different time periods being studied, and the usage of monthly data as opposed to daily data.

The trends in the GPCP dataset are generally larger than those of the other datasets used, as expected during a short (18 years) period of time due to internal variability. The range of trend values is cut in half for the PERSIANN data set, which uses almost double the amount of time as the GPCP data. The trends identified through use of the CMIP5 model averages carry values around 2% of the values found through GPCP due to the fact that this study used 106 years of data from the historical model runs. Some different trends are observed in the most recent years as opposed to those observed over the entirety of the 20th century. It is evident through comparison of the GPCP data with the historical model runs and the PERSIANN data both within and beyond the GPCP time frame that many changes have been occurring across the globe in the past two decades.

In the future, more observational datasets and CMIP5 models must be analyzed to reduce the uncertainty in historical and future trends, as well as to connect precipitation changes to changes in the general circulation and moisture availability. Other RCP scenarios would provide information about other possible trends rather than only the most extreme scenario. Finally, regions with bimodal cycles must be identified and reconciled so that the wet seasons can be analyzed individually (e.g. Yang et al. 2015).

The consequences of changes to the timing of the wet season on agriculture, socioeconomic structure, and infrastructure in the most vulnerable areas will likely begin to emerge in the coming years and decades. Perhaps the most notable region studied is the Arctic. Models project that the wet season in the Arctic will continue to extend by about 5 days every decade, which could cause dramatic changes in the ecosystem as a whole in the coming years.

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