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Changes in the seasonality of precipitation over the contiguous USA

S. C. Pryor[1] and J. T. Schoof[2]

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[1] Consequences of possible changes in annual total precipitation are dictated, in part, by the timing of precipitation events and changes therein. Herein, we investigated historical changes in precipitation seasonality over the US using observed station precipitation records to compute a standard seasonality index (SI) and the day of year on which certain percentiles of the annual total precipitation were achieved (percentile day of year). The mean SI from the majority of stations exhibited no difference in 1971–2000 relative to 30-year periods earlier in the century. However, analysis of the day of year on which certain percentiles of annual total precipitation were achieved indicated spatially coherent patterns of change. In some regions, the mean day of the year on which the 50th percentile of annual precipitation was achieved differed by 20–30 days between 1971–2000 and both 1911–1940 and 1941–1970. Output from the 10-Atmosphere-Ocean General Circulation Models (AOGCM) simulations of 1971–2000, 2046–2065, and 2081–2100 was used to determine whether AOGCMs are capable of representing the seasonal distribution of precipitation and to examine possible future changes. Many of the AOGCMs qualitatively captured spatial patterns of seasonality during 1971–2000, but there was considerable divergence between AOGCMs in terms of future changes. In both the west and southeast, 7 of 10 AOGCMs indicated later attainment of the 50th percentile accumulation in 2047–2065, implying a possible reversal of the twentieth-century tendency toward relative increases in precipitation receipt during winter and early spring over the southeast. However, this is also a region characterized by considerable interannual variability in the percentile day of year during the historical period.

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1. Introduction

[2] A number of prior studies have sought to identify historical changes in annual total precipitation and a variety of metrics of precipitation frequency and intensity [*Brommer et al.*, 2007; *Groisman et al.*, 1999, 2001, 2004; *Kunkel et al.*, 1999; *Pryor et al.*, 2008; *Schultz et al.*, 2007; *Sun et al.*, 2006], and to provide robust projections of those metrics into the future [*Buonomo et al.*, 2007; *Kattsov et al.*, 2007; *Liang et al.*, 2006; *Sun et al.*, 2007].

[3] Even in the absence of changes in annual total precipitation, changes in the seasonal receipt of precipitation greatly affect partitioning of the water into runoff, evapotranspiration and infiltration and thus flood forecasting, stream discharge and ecosystem responses [*Epstein et al.*, 2002; *Groisman et al.*, 2001; *Rosenberg et al.*, 2003; *Small et al.*, 2006; *Xiao and Moody*, 2004]. However, relatively few studies have examined time series of historical observations or simulations from coupled Atmosphere-Ocean General Circulation Models (AOGCMs) in the context of possible changes in the seasonality and/or seasonal distribution of precipitation, and those that have analyzed seasonality have done so using monthly data, or data aggregated to climatological seasons [*Gershunov and Cayan*, 2003; *Groisman et al.*, 2004; *Laurent and Cai*, 2007; *Small et al.*, 2006; *Wang and Zwiers*, 1999]. One study of historical data from across the United States of America (USA) resolved that on a nationwide basis data from the twentieth century (C20th) suggest increased total accumulated precipitation of 7% to 15% (per 100 years) in spring, summer, and autumn, with no change in winter [*Groisman et al.*, 2001].

[4] Virtually all AOGCMs imply a global increase in precipitation under global warming scenarios [*Sun et al.*, 2007]. However, there are considerable seasonal and regional variations both in the skill achieved by AOGCM [*Sun et al.*, 2006] and the projected changes in precipitation accumulation [*Christensen et al.*, 2007]. Over North America there are areas characterized by ensemble average increases (e.g., western North America in winter) and decreases in monthly total precipitation in individual climatological seasons (e.g., central North America in summer) [*Giorgi and Bi*, 2005].

[1]Department of Geography, Atmospheric Science Program, Indiana University, Bloomington, Indiana, USA.

[2]Department of Geography and Environmental Resources, Southern Illinois University, Carbondale, Illinois, USA.

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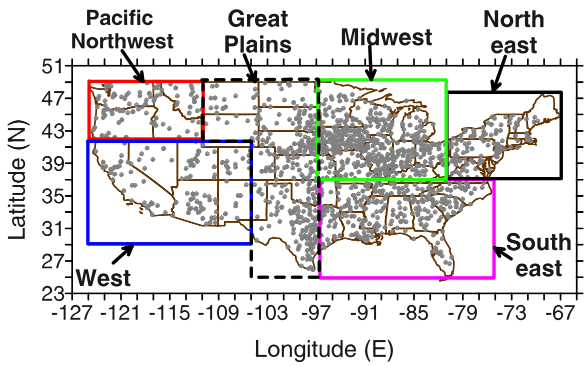

Figure 1. Map of the surface observing stations from which daily precipitation data are presented. Also shown are the regional definitions used which are derived from those used in the US regional climate change assessment [*National Assessment Synthesis Team*, 2000].

[5] A range of geophysical and ecological variables have exhibited changes such that mean definitions of, for example, growing season [*Reed*, 2006] or the onset date for spring [*Cayan et al.*, 2001], have evolved. Hence analysis of data at monthly time scales or in climatological seasons may not be optimal mechanisms for examining possible evolution of descriptors of the climate system. We assert that analysis of long-term and high-quality precipitation data time series and AOGCM output with daily resolution should allow a more complete characterization of historical and possible future temporal evolution of precipitation climatology.

2. Objectives

[6] Herein we use daily precipitation observations collected over the C20th at 1638 stations across the contiguous USA to address the question:

[7] 1. To what degree are changes in precipitation regimes being manifest as variations in the seasonality, and/or seasonal distribution of precipitation?

[8] We also use daily output from 10 AOGCM to address two further related questions:

[9] 2. To what degree are AOGCM simulations capable of representing the seasonal distribution of precipitation across the contiguous USA?

[10] 3. What do AOGCM simulations of possible future climates indicate at about changes in the seasonal distribution of precipitation?

[11] Identification and quantification of changes in the seasonal receipt of precipitation may have great utility to understanding changes in streamflow, particularly in regions not dominated by snow accumulation and melt, and to informing mitigation and adaptation strategies focused on ecosystem and flood responses to global climate change. We apply a percentile-based analysis to address questions regarding changes in the timing of precipitation and changes in the seasonality of precipitation across the contiguous USA in both historical and possible future climates. We are thus employing similar approaches to those used in the study of streamflow [*Maurer et al.*, 2007; *Regonda et al.*, 2005; *Stewart et al.*, 2005], and analysis of trends in the timing and amount of North American monsoon rainfall in Arizona and New Mexico during July, August and September [*Grantz et al.*, 2007]. We analyze the historical observations at each individual station and each grid cell in the AOGCM simulations and map the resulting patterns to examine spatial coherence. We also synthesize results using the six regions defined in the earlier USA regional climate change assessment [*National Assessment Synthesis Team*, 2000]; the Northwest, West, Great Plains, Midwest, Southeast and Northeast (Figure 1).

3. Methodology

3.1. Analysis of Observational Precipitation Time Series

[12] Daily precipitation for the historical period (1911–2000) are drawn from; the data set developed by *Kunkel et al.* [1998, 2005] and the National Weather Service Cooperative Observing Program (COOP) archive (http://www.nws.noaa.gov/om/coop/) (Figure 1). These are not independent data sources. The majority of the data in the Kunkel et al. database derive in part from the NWS COOP database, and have been extended to the pre-digital era and subject to homogenization efforts to correct for observer error, station discontinuity, and digitization errors. We also extracted data directly from the COOP data set to increase coverage of the western USA. The COOP data set is a valuable climate resource that provides manually observed information on precipitation receipt across the nation [*National Research Council*, 1998]. However, it is important to note that these data are subject to inhomogeneities (largely associated with changes in sampling protocols) and inaccuracies (due to incorrect or mis-reported readings). Nevertheless, these data sets are extensively used in climatological studies [e.g., *Easterling et al.*, 2007]. A recent inter-comparison of collocated automated (NCECONet) and manual (COOP) climate observations in North Carolina found daily rainfall values correlated well when corrected for time of day recording differences, and "Temperature and rainfall have high correlation (nearly 1.00 for maximum and minimum temperatures, 0.97 for rainfall) when monthly averages are used" [*Holder et al.*, 2006].

[13] Our analysis of precipitation seasonality is based on two metrics:

[14] 1. A seasonality index (SI) [*Walsh and Lawler*, 1981]:

$$SI = \frac{1}{R}\sum_{n=1}^{12}\left|X_n - \frac{R}{12}\right|$$

Where

[15] R is the annual total precipitation

[16] X_n = monthly total precipitation in month, n.

[17] SI were calculated for each station and each year and averaged by station to generate a mean SI for each analysis period.

[18] 2. The day of year at which the 10th, 25th, 50th, 75th and 90th percentiles of the annual total precipitation are achieved (referred to here as percentile day of year).

[19] The former represents a standard method of measuring precipitation seasonality, while the latter derives from

prior research referenced above. Both metrics are relatively insensitive to changes in biases in reporting accuracy of low and high precipitation accumulations [*Groisman and Knight*, 2008; *Pryor et al.*, 2008] over the data record.

[20] Precipitation time series exhibit greater spatial and temporal variability than temperature, which confounds analysis of long-term trends [e.g., *Stewart et al.*, 2005]. Hence two approaches are taken to quantifying historical changes in seasonality:

[21] 1. A trend analysis is conducted using the nonparametric Kendall's tau-based slope estimator [*Alexander et al.*, 2006] using station time series of the percentile day of year for 1911–2000 from each individual stations. This trend technique does not assume a distribution for the residuals and is relatively robust to outliers [*Sen*, 1968]. The linear trend is deemed statistically significant if it differs from 0 at the 90% confidence level, and the magnitude of the trend is given by the median of the series of slopes ($\frac{Y_j - Y_i}{t_j - t_i}$, where Y_x is the value of the metric at a given point t in time, and $1 \leq i < j \leq n$, where n is the total number of data points). For a station to be included in the analysis, it must have more than 70 years (between 1911 and 2000) in which more than 360 days exhibit valid (i.e., non-missing) data. Individual years where there are fewer than 360 valid observations at a given station are excluded from the analysis.

[22] 2. Data records of both the SI and percentile day of year are analyzed in three 30-year periods; 1911–1940, 1941–1970, and 1971–2000. Although, it is acknowledged that "... 30-yr normals are no longer generally useful for the design, planning, and decision-making purposes they were intended" because of non-stationarities in the climate system [*Livezey et al.*, 2007], thirty-year periods were chosen because it has been standard practice to define a climate "normal" as the arithmetic mean of a weather variable computed over three consecutive decades [*World Meteorological Organization*, 1984]. Also use of 30-year periods allows the observational record to be divided into three portions of equal length. As with the trend analysis, individual years where there are fewer than 360 valid observations at a given station are excluded from consideration. For a station to be included in the analysis, it must have more than 20 years in a given time window in which more than 360 days exhibit valid (i.e., non-missing) data. This means for comparison of the 1911–1940 and 1971–2000 time periods the analysis is conducted for 1290 stations, while for analysis of 1941–1970 versus 1971–2000, 1619 stations are used. The significance of differences in mean SI and percentile day of year in the three time periods was quantified using confidence intervals derived using bootstrapping [*Lunneborg*, 2000] of the annual values during 1971–2000. Thus an assessment of the differences between the time periods is conducted relative to interannual variability in 1971–2000. Time series of the annual values of each metric are multiply resampled (with replacement) to provide 1000 realizations of the mean value during 1971–2000. If the mean SI or percentile day of year from the 1911–1940 or 1941–1970 periods lie within the middle 900 values in an ordered sequence of the distribution of 1000 realizations from the 1971–2000 period, the SI or percentile day of year values in the two time windows are deemed to be not significantly different at the 90% confidence level. The magnitude of the differences in SI or percentile day of year is quantified as the mean value from 1971–2000 minus the mean value in the other two periods. Thus a positive number indicates higher SI or that the specified percentile of the total annual accumulation was attained later in 1971–2000 than during the earlier periods of the C20th.

3.2. Analysis of AOGCM-Derived Precipitation Time Series

[23] Ten coupled Atmosphere-Ocean General Circulation Models (AOGCMs) from the data set compiled for the 4th Assessment Report of the Intergovernmental Panel on Climate Change [*IPCC*, 2007] that have output available with daily resolution are used here; BCCR-BCM2.0, CCCMa-CGCM3.1, CNRM-CM3, CSIRO-MK3.0, GFDL-CM2.0, GISS-Model E R, IPSL-CM4, MIUB-ECHO-G, MPI-ECHAM5 and MRI-CGCM2.3.2 (see *Meehl et al.* [2007] and http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.php). These span a range of AOGCMs available in terms of spatial resolution (coarsest $\sim 4 \times 5°$, finest $\sim 1.9 \times 1.9°$) and model formulations (spectral versus Cartesian). Eight of these AOGCMs were also used in the analysis of precipitation intensity and frequency projections for the C21st conducted by *Sun et al.* [2007]. AOGCM output for 1961–2000 are taken from climate simulations of the C20th, while AOGCM output for 2046–2065 and 2081–2100 are from simulations conducted using the A2 emission scenario. This scenario equates to a moderate to high greenhouse gas cumulative emission resulting in global carbon dioxide emissions from industry and energy in 2100 that are almost four times the 1990 value [*Nakicenovic and Swart*, 2000].

[24] The AOGCM output is used first to analyze how well the AOGCM simulate the observed percentile day of year during 1971–2000. Then the AOGCM output is considered in terms of whether the simulations for years 2046–2065 and 2081–2100 lie within or beyond the uncertainty bounds bootstrapped from simulation of 1971–2000 computed as described in section 3.1.

4. Results and Discussion

4.1. Seasonality Index

[25] The spatial patterns of mean SI computed for 1971–2000 (Figure 2a) exhibit similar geographic variability to that reported using a different index and data from 1951–1960 by *Markham* [1970], the harmonic analysis of data from 1931–1960 by *Hsu and Wallace* [1976] and a regional analysis of a $2 \times 2°$ gridded data set encompassing 1901–1998 [*Li et al.*, 2005]. Lowest seasonality (mean SI < 0.6) is observed in the eastern USA – particularly in the northeast, indicating relatively even distribution of precipitation receipt through the year. Highest seasonality occurs in the southwest (in southern California) as a result of the relative dominance of winter precipitation.

[26] Comparing the mean SI from 1911–1940 and 1971–2000 using bootstrapped confidence intervals from 1971–2000 (Figure 2b), approximately 30% of stations exhibit significantly lower seasonality in the later time period, while 10% showed higher seasonality and the remainder

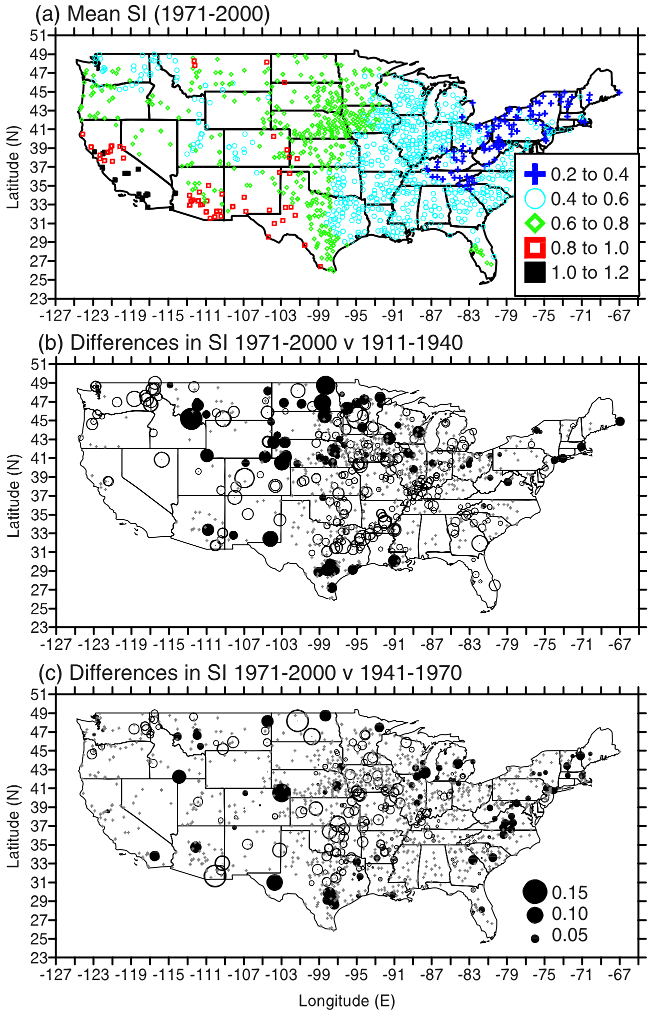

Figure 2. (a) Mean SI computed using data from 1971–2000. Frames b and c show differences in mean SI in (b) 1971–2000 versus 1911–1940 and (c) 1971–2000 versus 1941–1970. If the later time period exhibits significantly higher values than those of the earlier time period, the station is shown by a solid circle, while if the later time period exhibits significantly lower values than those of the earlier time period, the station is shown by an open circle. In each case, the diameter of the circle scales linearly with the difference in mean SI (see legend in frame c). If the mean SI from the 1911–1940 or 1941–1970 periods lies within the middle 900 values in an ordered sequence of the distribution of 1000 bootstrap realizations from the 1971–2000 period, the mean SI values are deemed to be not significantly different at the 90% confidence level and the station is shown by a plus symbol.

exhibit no difference. Comparable numbers for mean SI from 1941–1970 and 1971–2000 (Figure 2c), indicate approximately 20% of stations exhibit significantly lower seasonality in the later time period, while 10% showed higher seasonality and the remainder exhibit no difference. One can infer therefore, that there has not been an intensification of seasonality across the contiguous USA at the end of the C20th relative to present and historical inter-annual variability in SI. Indeed, the contrary appears to true if the relative numbers of stations that report higher and lower values of the mean SI in 1970–2000 is considered. A larger number of stations exhibit values of SI that were generally lower in 1971–2000 than during 1941–1970 (particularly in the central Great Plain states of Iowa, Arkansas, Oklahoma and Kansas) indicating a tendency toward decreased seasonality. Hence, in summary, this analysis of SI implies little or no change in the seasonality of precipitation receipt over the course of the C20th.

4.2. Percentile-Based Analyses Based on the Observations

[27] Analyses based on SI do not fully characterize possible shifts in the timing of precipitation receipt. Hence a second analysis was conducted to assess the day of year at which fixed percentiles of the annual total precipitation were achieved (Figure 3). The 10th percentile of total annual precipitation is reached earliest in the west-coast states, along the Gulf-coast states and the eastern seaboard. The region that exhibits the latest day of year for attaining 10% of the annual total precipitation accumulation is focused in the central Plains – particularly North and South Dakota and Iowa, and extending south into New Mexico. The 25th percentile of annual total precipitation is also obtained earliest in the west coast states (in accord with the winter and early spring maxima in precipitation identified by *Hsu and Wallace* [1976]), and that is also true for the 50th percentile precipitation which is obtained in most Californian sites prior to the end of March. The pattern for the latest accumulation of 25% of annual total precipitation is somewhat similar to that of the 10th percentile, with parts of the northern central Plains and upper Midwest not achieving 25% of the annual accumulation until over 150 days after the start of the year (i.e., in June) indicating the relatively dry winters and spring in the region. The regions that last reach 50% of annual total precipitation extends from Minnesota (in the western Midwest) east across the Great Lakes and are focused in and around New Mexico. In these regions, the CT (i.e., 50th percentile accumulation) of precipitation is not achieved until 200 days after the start of the year (i.e., in mid-July). In the upper Midwest, attainment of the 75th percentile occurs in September which emphasizes the importance of late-summer precipitation in this region (approximately 25% of the annual total precipitation falls between year day 210 and year day 250). In the Central Plains states of North and South Dakota and Nebraska the 25th percentile accumulation is attained at approximately year day 130, while the 75th percentile accumulation is reached on or about year day 225. Thus 50% of the annual total precipitation occurs between mid-May and early August. The earliest date for acquiring 75% of the annual total precipitation is observed in southern California, which implies a relatively wet winter and early spring and dry summer and fall in this area (leading to the high SI shown in Figure 2). Latest attainment of the 75th and 90th percentile accumulation is observed in the Pacific Northwest (Washington and Oregon) occurring in November and December, respectively, emphasizing the relatively dry summer and early fall in these states.

[28] Relatively few station time series exhibit significant trends in the percentile day of year based on the Kendall's

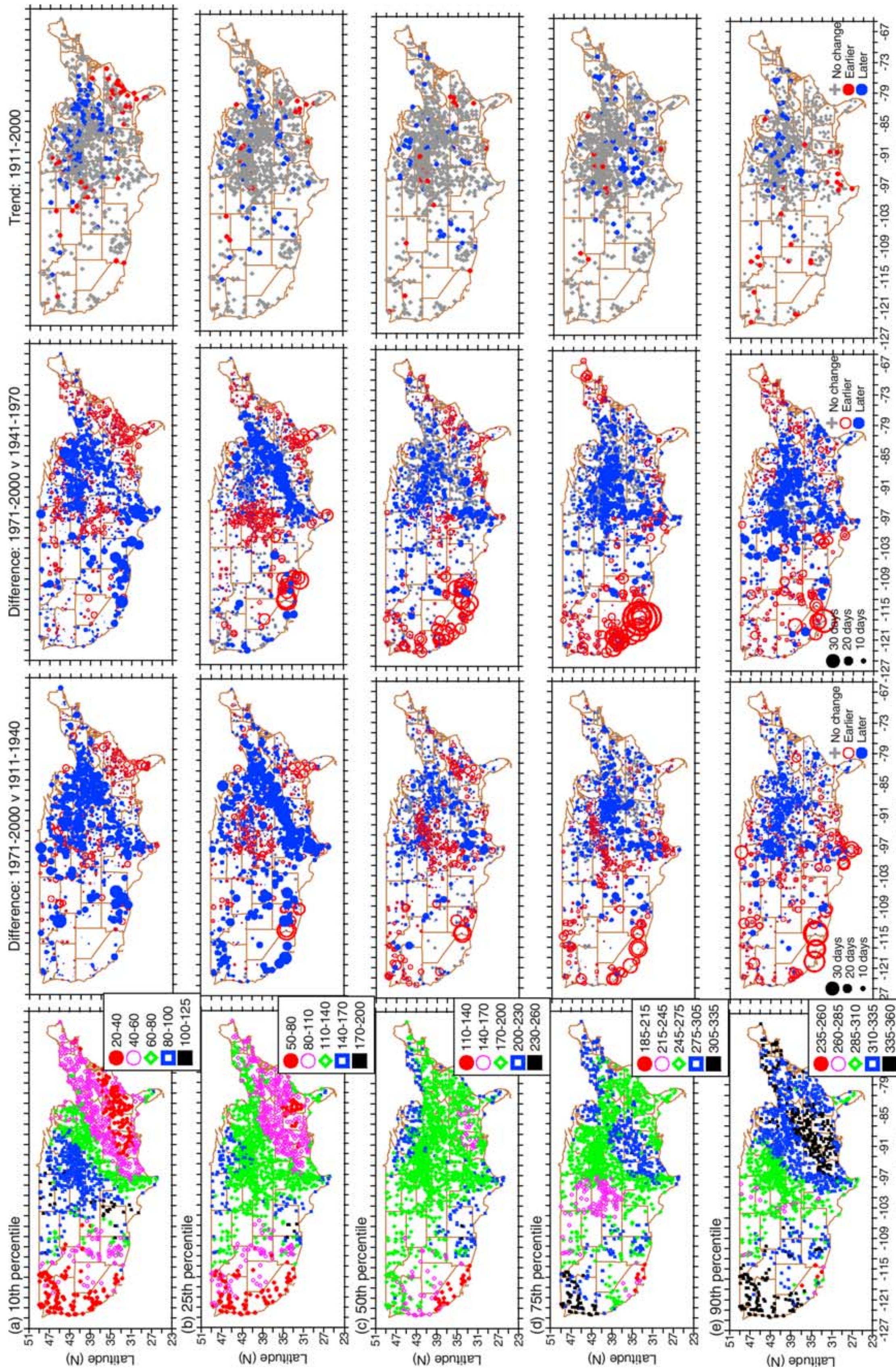
(a) 10th percentile
20-40
40-60
60-80
80-100
100-125
(b) 25th percentile
50-80
80-110
110-140
140-170
170-200
(c) 50th percentile
110-140
140-170
170-200
200-230
230-260
(d) 75th percentile
185-215
215-245
245-275
275-305
305-335
(e) 90th percentile
235-260
260-285
285-310
310-335
335-360
Difference: 1971-2000 v 1911-1940
Difference: 1971-2000 v 1941-1970
Trend: 1911-2000
30 days
20 days
10 days
No change
Earlier
Later
Latitude (N)
Longitude (E)

Figure 3

tau analysis (Figure 3). This may be partly due to the very high inter-annual variability. For example, the standard deviation of annual values for the 50th percentile day of year typically lies between 10 and 20% of the mean value computed using all 90-years of data. Stations that do exhibit significant long-term trends tend to be clustered in the western Midwest (particularly Missouri and Iowa) and indicate earlier achievement of the 10th and 25th percentile accumulations at the end of the C20th, which would imply relative increases in late spring/early summer precipitation in this region, with relative drying of the winter and spring. Conversely parts of the southeast exhibit some evidence for increase relative precipitation early in the year.

[29] Changes in the timing of percentile day of year implied by comparisons of data from the three time periods (1911–1940, 1941–1970, 1971–2000) are considerably more regionally coherent, implying a physical mechanism (rather than a statistical anomaly) (Figure 3). These results illustrate substantial shifts in the mean day of year on which certain percentiles of the annual total precipitation were achieved – with in some cases those dates differing by 30 days in the 1971–2000 period relative to either 1911–1940 or 1941–1970. The results indicate:

[30] 1. Significant changes in the precipitation climate of the west coast states. The dates on which the 25th percentile accumulation are attained exhibit little or no change with perhaps a slight tendency toward later attainment at the end of the C20th, while the 50th percentile accumulation is occurring up to 20 days earlier in the later period. Taken in combination these changes imply a relative increase of precipitation during spring. Clearly, the link between changes in precipitation receipt and streamflow is a function of many non-linear processes, which are a function of precipitation phase and parameters such as elevation and temperature (where snow-melt is a major source of streamflow) [*Maurer et al.*, 2007]. However, these results are to some degree consistent with prior research that reported a tendency in the seasonal streamflow distribution in the western United States and Missouri River Basin during the past decades toward earlier maxima [*Groisman et al.*, 2001; *Stewart et al.*, 2005]. The spring streamflow peak in the western USA has shifted one or two weeks earlier over the last 50 years, "while mean annual flows have remained constant or marginally increased" [*Stewart et al.*, 2005]. One study in the Sierra Nevada showed "center timing" (CT) (i.e., the day when accumulated streamflow achieved half the annual flow, i.e., the 50th percentile of total discharge) is occurring earlier [*Maurer et al.*, 2007]. While, much of the change in the timing of CT and streamflow peak is attributable to snowmelt induced by rising temperature, and there are divergent trends in streamflow timing in the western USA with elevation [*Regonda et al.*, 2005], these changes may also be linked to changes in precipitation reported herein. The day of year on which the 75th percentile accumulation are attained in California are also shifted earlier in the 1971–2000 period. This implies the relative increase in precipitation receipt extends into early summer.

[31] 2. Shifting of precipitation regimes in the southeastern USA (Georgia, and North and South Carolina). The 10th and 25th percentiles were achieved earlier in 1971–2000 than either of the previous periods, while the timing of the 50th percentile exhibits a mixed response (with stations showing both earlier and later attainment) and the 75th percentile accumulation is generally reached slightly later in the 1971–2000 period. In total these changes imply a relative increase in precipitation early in the year (January – March), but relative declines in precipitation receipt during the latter portion of the spring and early summer.

[32] 3. A shift in the timing of precipitation receipt along a southwest to northeast swath extending from eastern Texas through Ohio. The day of year on which the 25th percentile accumulation is attained is consistently later in 1971–2000 than in either of the earlier period by, at many sites, 20 days. This tendency is much less evident in the timing of CT. Much of this region attained the 25th percentile between year day 80 and 110 in 1970–2000 this coupled with the timing of the 50th percentile imply late winter and spring exhibited lower relative precipitation receipt at the end of the C20th. The geographic region of change is consistent with, but displaced south of, the mean Colorado cyclone track [*Mercer and Richman*, 2007], in the region of consistently highest near-surface moisture content [*Marshment and Horn*, 1986] and may be linked to the decline in Colorado cyclone frequency in April and May over the period 1961–1990 [*Bierly and Harrington*, 1995].

Figure 3. Results of analysis of the observational time series in terms of percentile day of year. Left-hand frames show the mean percentile day of year for the (a) 10th, (b) 25th, (c) 50th, (d) 75th, and (e) 90th percentiles, as computed using data from 1971–2000. The second column shows the difference in mean percentile day of year values computed for 1971–2000 versus 1911–1940, and the third column shows the difference in mean percentile day of year values computed for 1971–2000 versus 1941–1970. If the later time period exhibits significantly later achievement of the specified percentile than that of the earlier time period, the station is shown by a solid circle. If the later time period exhibits significantly earlier achievement of the specified percentile than that of the earlier time period, the station is shown by an open circle. In each case, the diameter of the circle scales linearly with the difference in mean percentile day of year (see legend in the lowest frames). If the mean percentile day of year from the 1911–1940 or 1941–1970 periods lie within the middle 900 values in an ordered sequence of the distribution of 1000 bootstrap realizations from the 1971–2000 period, the mean percentile day of year values are deemed to be not significantly different at the 90% confidence level and the station is shown by a plus symbol. The right-hand column shows results of the trend analysis applied to the percentile day of year annual values. If the trend is toward an earlier achievement of the percentile that is significant at the 90% confidence level, an open symbol is shown; if it occurs later, a solid circle is shown; and if the trend is not significantly different to zero at the 90% confidence level, then the station is denoted by a plus symbol.

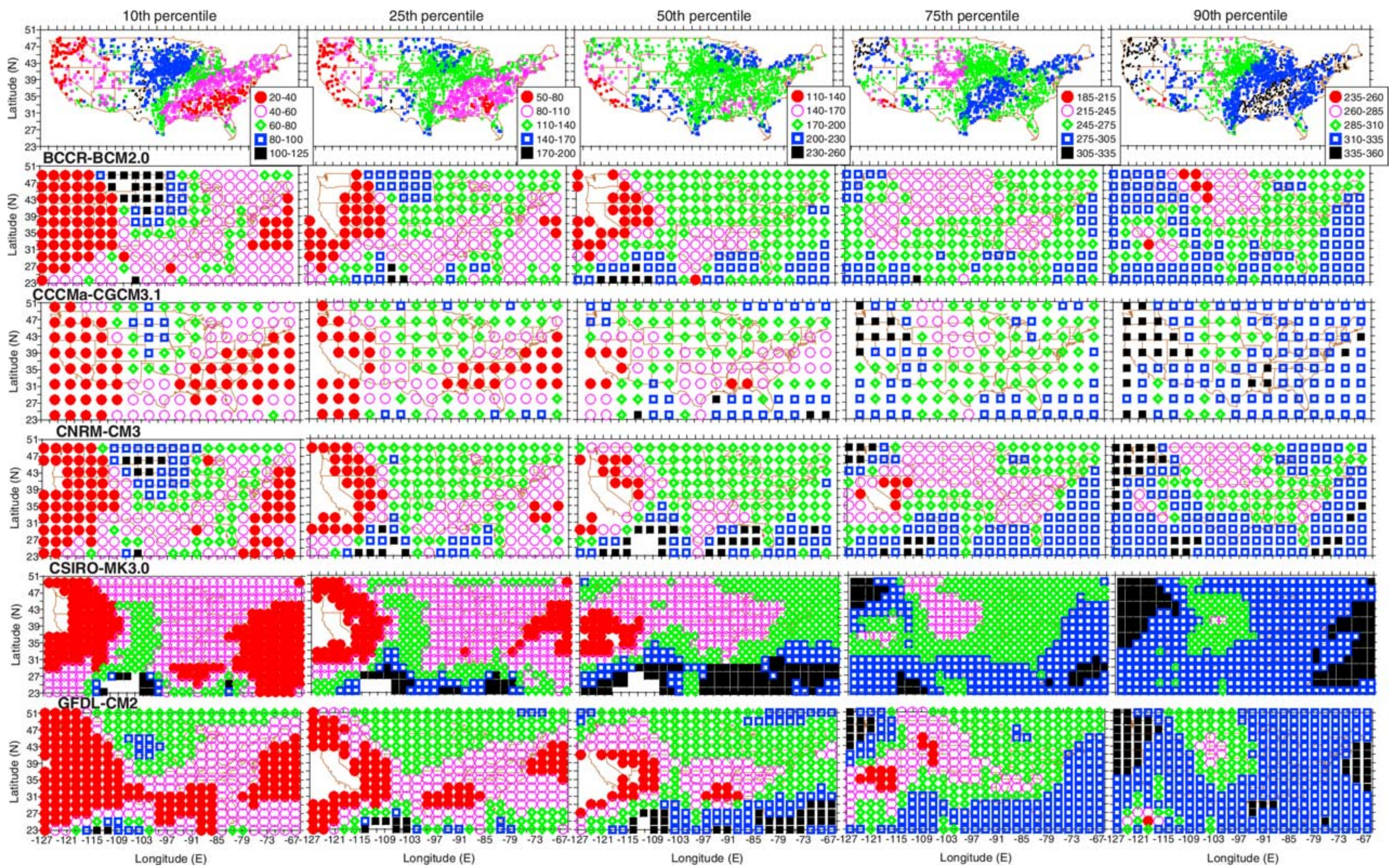

Figure 4. Spatial depictions of mean percentile day of year results for observations (top row) and each of the 10 AOGCMs. The columns depict the five percentile levels used herein. (First column) Tenth percentile to the (middle column) 50th percentile and the (right-hand column) 90th percentile. The scale and symbols used in each frame are consistent for each percentile level. Where no symbol is shown in depicting the AOGCM simulations, this denotes that the AOGCM results lie outside the range of values computed from the observational records.

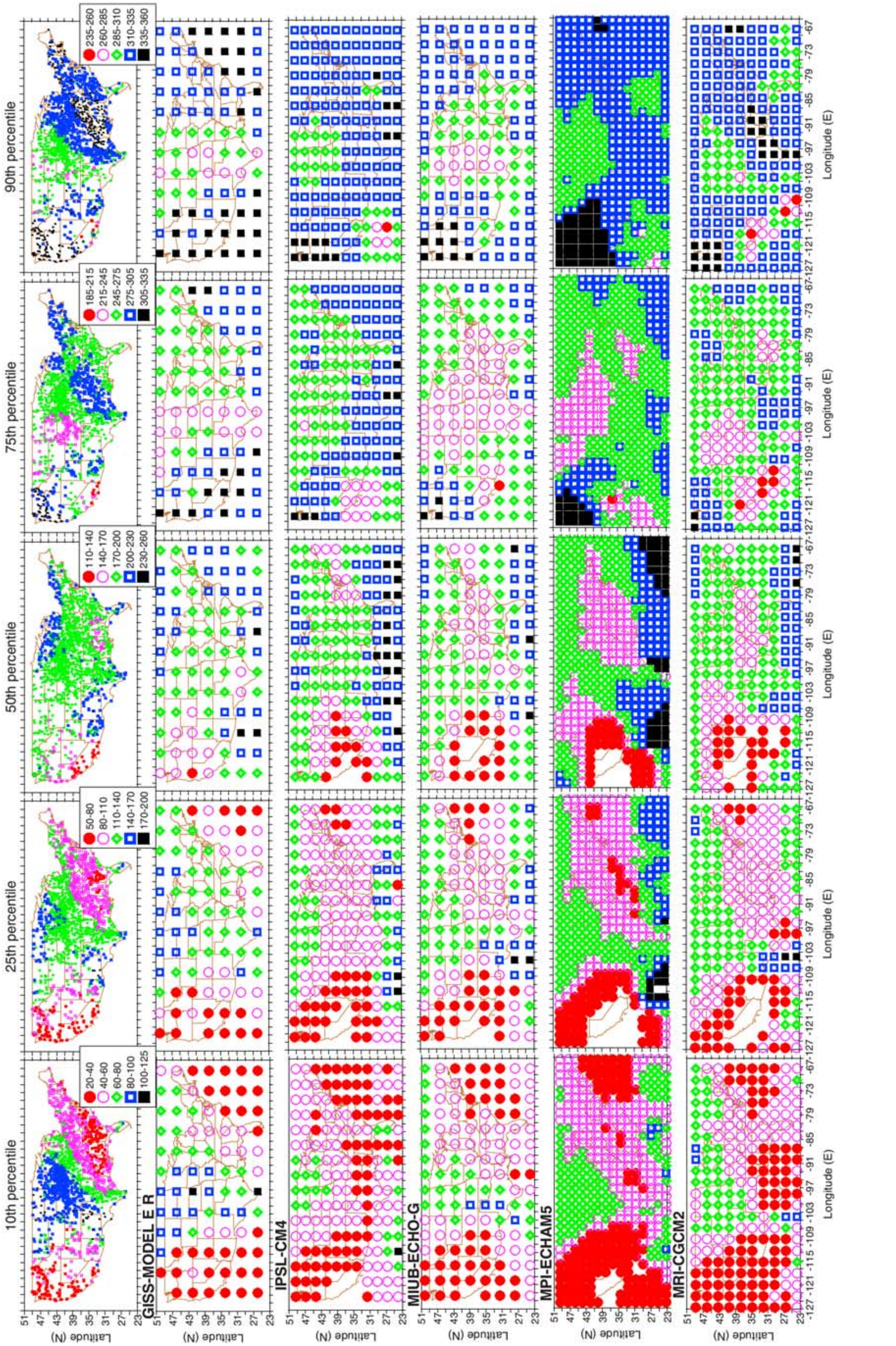

Figure 4. (continued)

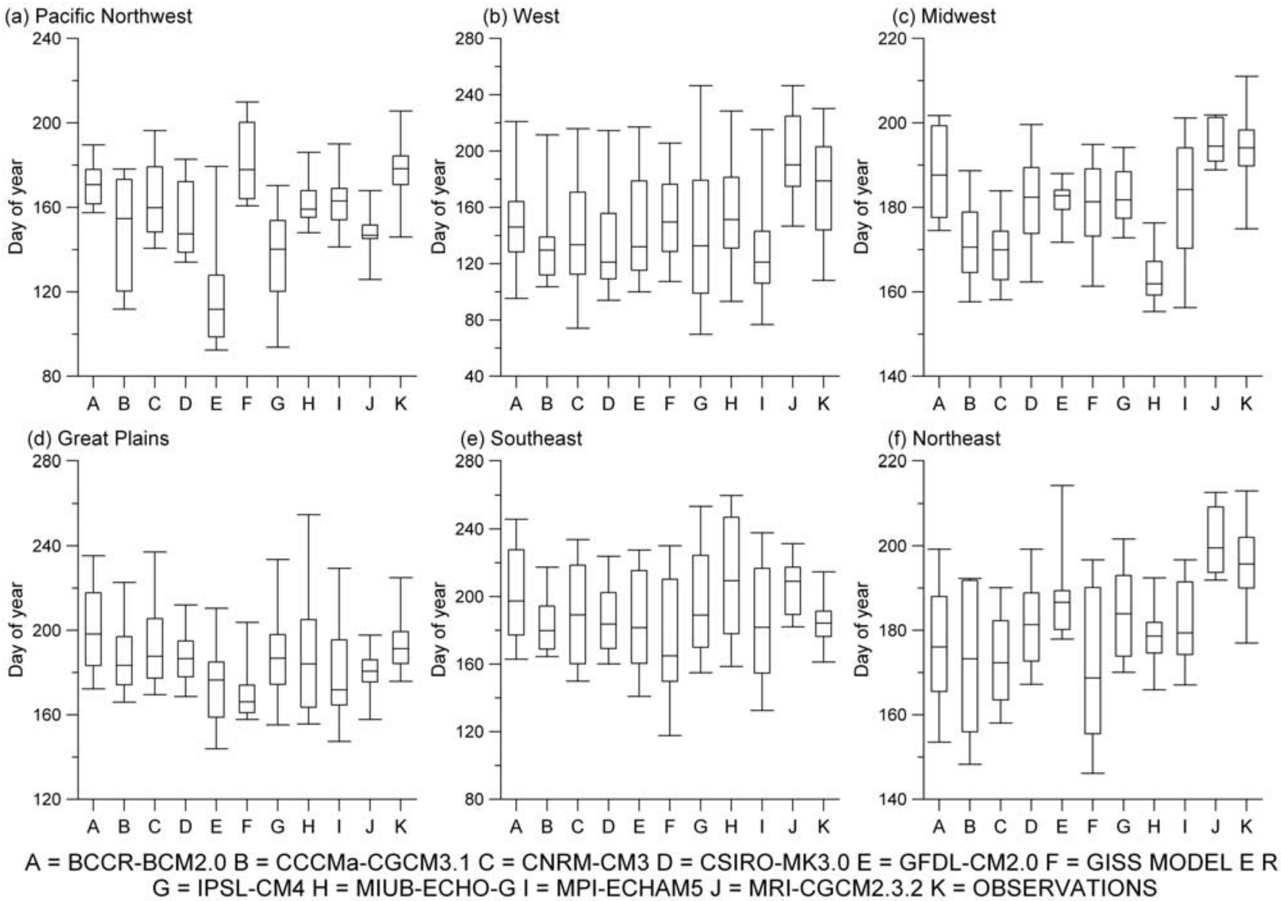

Figure 5. Box-and-whisker plots of regionally aggregated estimates of the mean day of year on which 50% of the annual total accumulated precipitation is achieved during 1971–2000. The regions are as defined in Figure 1. Note that the *y* scales vary between individual frames.

[33] 4. The 25th percentile of annual total precipitation was attained earlier in the year during 1971–2000 over the Great Plains while this region showed little or no change in the timing of CT. This implies this region has seen a tendency toward increased relative precipitation receipt in year days between 80 and 130 (i.e., March and April) but a slight decline in May and June.

[34] 5. In the states of Kansas, Oklahoma, Missouri and Illinois the 75th percentile of annual total precipitation was attained later during 1971–2000 (by up to 20 days at some sites). This implies that in 1971–2000 there was a relative drying of summer and early fall and a relative increase in precipitation during the remainder of the fall. This is consistent with regionally and seasonally averaged results based on gridded data that indicated the largest magnitude trends in precipitation receipt over the C20th occurred during the fall (during September, October and November) [*Li et al.*, 2005].

[35] It should emphasized that the changes in seasonality reported here describe relative shifts in seasonal precipitation receipt, and that they need not be associated with changes in total annual precipitation. Further, in considering these results it should be acknowledged that the latter period (1971–2000) includes the time since the "regime shift" in atmospheric and oceanic conditions over the North Pacific during the winter of 1976–1977 [*Hare and Mantua*, 2000], while the two former periods contain "two particularly noteworthy dry decades (1930s and 1950s)" at the national level [*Groisman et al.*, 2004].

4.3. Simulations of 1971–2000 by AOGCMs

[36] When output from the 10-AOGCMs are analyzed in terms of the percentile day of year from 1971–2000, almost all of the AOGCMs exhibit clear similarity to spatial patterns evident in the observations. However, there are some discrepancies. Almost all AOGCMs tend to underestimate the number days that elapse prior to attainment of 25% of the year total precipitation in California, and in many other states in the western USA (Figure 4). In the observations all of the western states (California, Oregon Washington, Nevada, Idaho, Utah and Arizona) achieve 25% of annual total accumulation 50 to 120 days after the start of the year, while several of the AOGCMs achieve this fraction of the annual total prior to mid-February. Many of the AOGCMs also achieve 50% of the annual total precipitation in these states before the date implied in the observations; however several of the AOGCMs (e.g., GISS-MODEL E R) tend to achieve the 75th and 90th percentile accumulation over southern California considerably later than is indicated by the observations. This implies the

AOGCMs are over-emphasizing the relative dominance of wintertime precipitation relative to summer receipt.

[37] In the upper Midwest (Minnesota, Wisconsin and Michigan) most of the observational sites achieve 50% of the annual total accumulation between year days 200 and 230 (i.e., mid-July to mid-August), but some of the models, most notably CSIRO-MK3.0 and MPI-ECHAM5 achieve 50% of total accumulation prior to year day 180 (i.e., the end of June) and indeed with the exception of GISS-MODEL E R and IPSL-CM4 the AOGCM simulations do not match the observed dates for the percentile day of year in this region.

[38] To provide a synthesis of AOGCM performance the simulated day of year on which the 50% accumulation of annual total precipitation was achieved were compiled for each of the six regions defined in Figure 1 (Figure 5). In considering the implications of this analysis it is important to note the following caveats; the observational locations are not evenly distributed in the regions or between regions, and the spatial resolution of the models will critically determine the number of grid cells in each region and hence the potential for variability. Nevertheless, the results indicate:

[39] 1. In all regions the range of simulated grid-cell percentile day of year lie within the range of values from the observational sites. However, in accord with the discussion above, virtually all of the AOGCM underestimate the percentile day of year on which CT is attained in both the Pacific Northwest and the West. The majority of AOGCMs also underestimate the number of days that are required to attain CT in the Midwest and the Northeast. In the case of the Midwest this discrepancy is particularly pronounced in the case of the MIUB-ECHO-G model. In the case of the Southeast the AOGCMs scatter both above and below the observed percentile day of year.

[40] 2. Several of the AOGCMs exhibit some skill is differentiating regional behavior and in the absolute magnitude of percentile day of year estimates. The MRI-CGCM2.3.2 simulations tend to be biased toward later 50th percentile day of year than the other AOGCMs in the West, Midwest and Northeast, but actually exhibit greater accord with the observations in these regions.

[41] 3. Biases in the AOGCMs relative to the observations do not appear to be regionally consistent. For example, the BCCR-BCM2.0 simulations tend to exhibit relatively early attainment of the 50th percentile precipitation accumulation in the Pacific Northwest, West and Northeast, but are biased toward late attainment of the 50th percentile in the Great Plains and Southeast.

[42] Despite some of the shortcomings indicated in this synthesis, the AOGCM were considered sufficiently skillful that an analysis of possible future seasonality was warranted.

4.4. Simulations of 2046–2065 and 2081–2100 Relative to 1971–2000

[43] Analysis of changes in percentile day of year from the three AOGCM simulation periods resolves (Figure 6):

[44] 1. There is considerable divergence in terms of the AOGCM simulation of possible changes in percentile day of year in the two future simulation periods. For example, GFDL-CM2.0 simulated from 2046–2065 and 2081–2100 indicate considerably earlier achievement of 25th percentile over much of the contiguous USA than in 1971–2000, while CSIRO-MK3.0 implies that over much of the southern Great Plains, there will be a substantial delay in achieving this accumulation.

[45] 2. CCCMa-CGCM3.1, GISS MODEL E R and MIUB-ECHO-G exhibit the fewest grid-cells with significant differences in the percentile day of year in the three time periods. Conversely, GFDL-CM2.0 and IPSL-CM4 exhibit the largest fraction of grid cells with differing percentile day of year in 1971–2000, 2046–2065 and 2081–2100.

[46] 3. GFDL-CM2.0 exhibits a tendency toward earlier attainment of the 25th and 50th percentile accumulation in the central Great Plains – implying a continuation of the relative increase in the winter and early spring and relative drying of the summer observed in the historical period. However, this feature is not replicated in the other AOGCMs.

[47] Analyzing the AOGCM simulations for 2046–2065 relative to 1971–2000 and aggregating the output to the regions defined in Figure 1 indicates (Figure 7):

[48] 1. In all cases (i.e., for all AOGCM and all regions) the 25th to 75th percentiles of the date of attainment of the CT precipitation in 2046–2065 overlap those from 1971–2000.

[49] 2. In no region are the AOGCM simulations consistent in terms of changes in the mean percentile day of year.

[50] a. In the Pacific Northwest, six AOGCM indicate a tendency toward later attainment of the 50th percentile accumulation in 2046–2065 than during 1971–2000.

[51] b. In the West seven AOGCM indicate later attainment of the 50th percentile accumulation in the 2046–2065 period.

[52] c. In the Midwest, five AOGCM indicate earlier (later) attainment of the 50th percentile accumulation in 2046–2065.

[53] d. In the Great Plains, six AOGCM indicate later attainment of the 50th percentile accumulation in 2046–2065.

[54] e. In the Southeast, seven AOGCM indicate later attainment of the 50th percentile accumulation in 2046–2065.

[55] f. In the Northeast, six AOGCM indicate later attainment of the 50th percentile accumulation in 2046–2065.

Figure 6. Changes in the day of year on which the 10th (leftmost column), 25th, 50th (middle column), and 75th and 90th (right-hand column) percentiles are achieved in each of the 10-AOGCM (each row represents results from one AOGCM) in 2046–2065 and 2081–2100 relative to 1971–2000. If the symbol is red, the percentile is achieved earlier in the year in the future simulations. If it is blue, that percentile level is achieved later in the year in the future time period. If no symbol is shown, the projections lay within the 90% confidence level bounds computed from the 1971–2000 time period. The triangles show results of 2046–2065 versus 1971–2000, while the circles show 2081–2100 versus 1971–2000. If a grid cell is denoted as "earlier," this indicates that in the future time period that percentile was achieved on an earlier date than during 1971–2000.

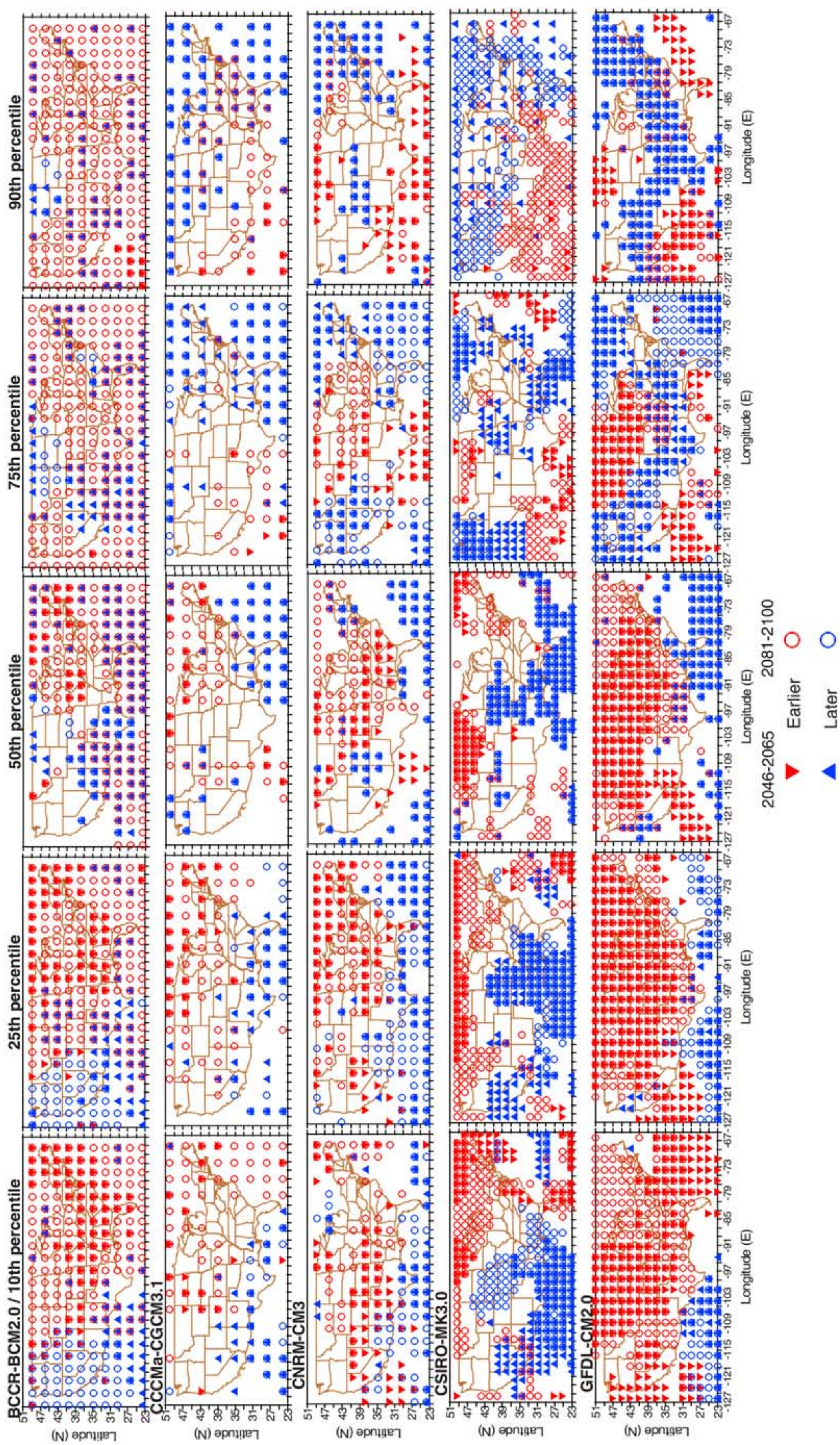
BCCR-BCM2.0 / 10th percentile
25th percentile
50th percentile
75th percentile
90th percentile
CCCMa-CGCM3.1
CNRM-CM3
CSIRO-MK3.0
GFDL-CM2.0
Latitude (N)
Longitude (E)
2046-2065
2081-2100
Earlier
Later

Figure 6

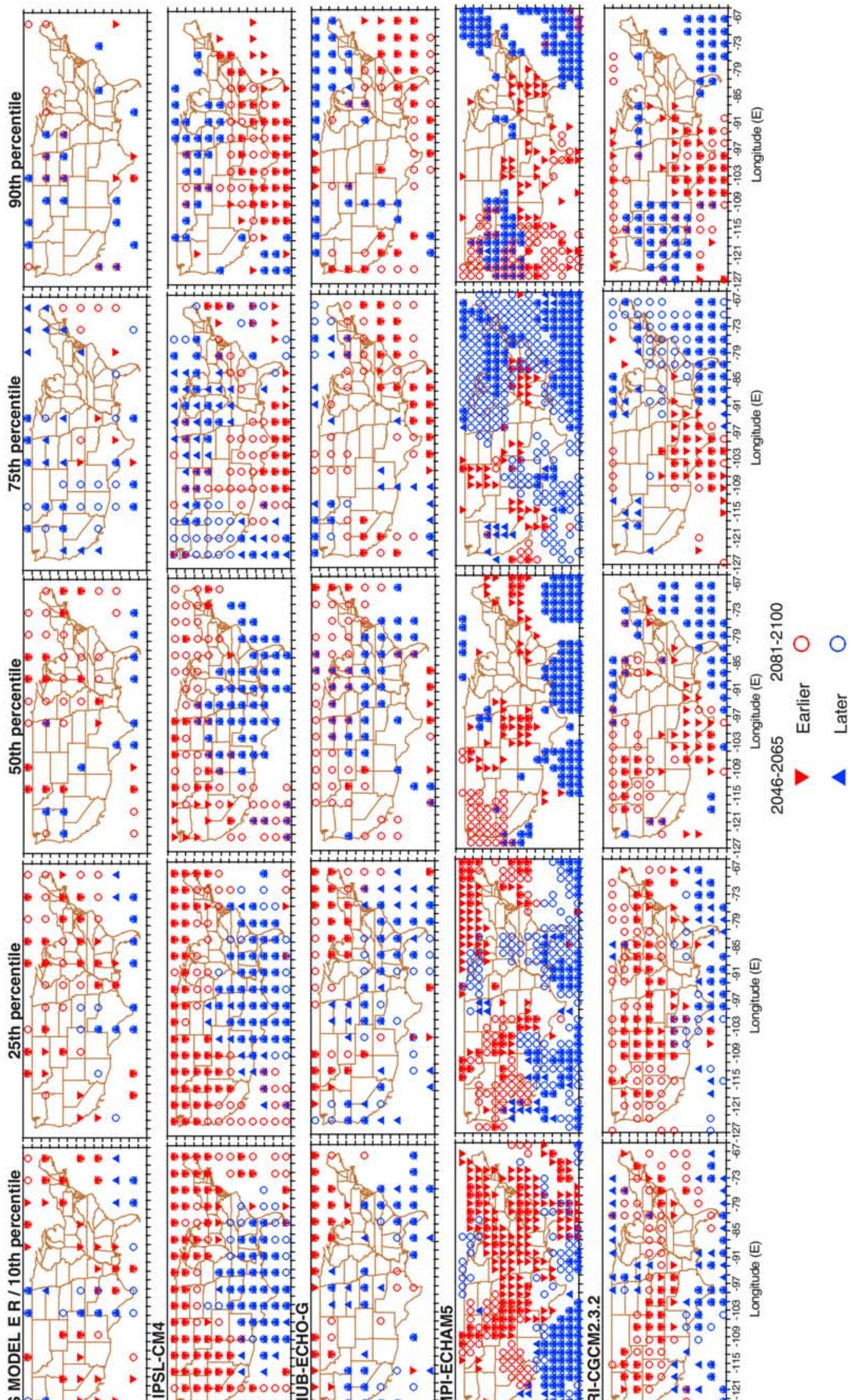

Figure 6. (continued)

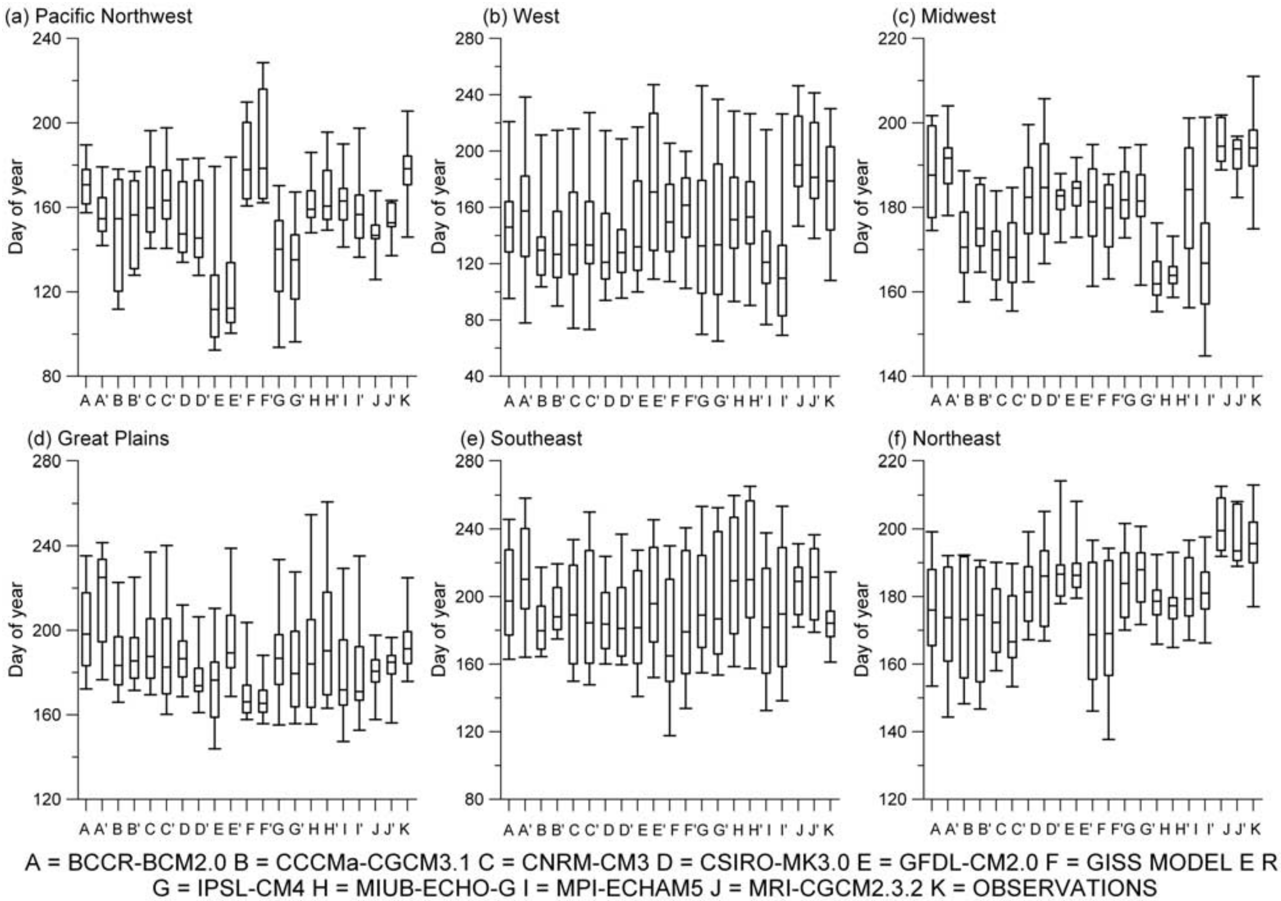

Figure 7. Box-and-whisker plots of regionally aggregated estimates of the mean day of year on which 50% of the annual total accumulated precipitation is achieved in 1971–2000 and 2046–2065. The results for 1971–2000 and each AOGCM are denoted by the letter shown in the legend, the prime indicates results for 2046–2065. For comparative purposes, the observationally derived percentile day of year are shown in column K. The regions are as defined in Figure 1. Note that the *y* scales vary between the individual frames.

[56] As indicated by this summary there is thus a general tendency toward later attainment of the CT in the middle of the C21st relative to the end of the C20th. This implies a continuation of the tendency in gridded data from the C20th toward largest increases in fall precipitation across USA [*Li et al.*, 2005].

[57] 3. There is some commonality in AOGCM simulations across regions. For example, both GFDL-CM2.0 and MIUB-ECHO-G output indicates a tendency toward later attainment of the 50th percentile accumulation in 2046–2065 than in 1971–2000 except in the Northeast.

[58] Thus in short, for no region are changes in the 50th percentile day of year timing (i.e., shift toward an earlier of later date) consistent across all AOGCM. However, in the West and Southeast, seven of the 10 AOGCMs imply later attainment of the 50th percentile accumulation in the middle of the C21st relative to the end of the C20th.

5. Summary and Concluding Remarks

[59] Prior research has generally indicated a historical trend toward increased annual total precipitation across the contiguous US and amplification of extreme or intense events. While there is tremendous regional variability, there is some evidence that these tendencies may persist into the future. The impacts of such changes are strongly coupled to the timing and nature of precipitation received. Changes in the seasonal receipt of precipitation influences partitioning of the water into runoff, evapotranspiration and infiltration and thus flood forecasting and ecosystem responses. While the mean seasonality of precipitation receipt for stations across the contiguous USA as measured using a standard seasonality index does not indicate substantial changes during the C20th, analyses based on the day of the year on which certain percentiles of the annual total precipitation were achieved do indicate spatially coherent patterns of change. As shown, many of the observed differences span climatological seasons and may offer a partial explanation for the paradox of differential trends in precipitation and streamflow in climatological seasons [*Small et al.*, 2006]. These temporal shifts in seasonality are more clearly defined using a percentile-based approach.

[60] In some regions the mean day of the year on which the 50th percentile of annual precipitation was achieved differed by 20–30 days between 1971–2000 and two prior 30-year periods in the century (1911–1940 and 1941–

1970). For example, in accord with the seasonal analyses of *Li et al.* [2005] there is evidence of a relative increase in spring precipitation in the west coast over the course of the C20th.

[61] Many AOGCMs qualitatively capture spatial patterns of seasonality during 1971–2000 but also achieve the 25th and 50th percentile of the annual total precipitation before the date implied in observations particularly over the western states. There is considerable divergence between AOGCMs in terms of future changes in the seasonal distribution of precipitation, but for all regions considered there is a tendency for more AOGCM to imply a shift toward later attainment of the 50th percentile accumulation.

[62] Atmosphere-Ocean General Circulation Models are proving ever more skillful in terms of simulation of past climates even at the regional scale [*Christensen et al.*, 2007]. Many AOGCMs qualitatively capture patterns of seasonality during 1971–2000 but all 10 examined herein achieve the 25th percentile of annual total precipitation over California prior to the date indicated by the observations. Equally most AOGCMs achieve 50% of the annual total precipitation before the data implied in observations over the upper Midwest. The discrepancies with observations from the historical period and the divergence of simulations from differing AOGCMs imply great caution should be taken in using direct output from AOGCMs for analysis of possible future hydrologic states.

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S. C. Pryor, Department of Geography, Atmospheric Science Program, Indiana University, 701 E. Kirkwood Avenue, Bloomington, IN 47405, USA. (spryor@indiana.edu)

J. T. Schoof, Department of Geography and Environmental Resources, Southern Illinois University, 1000 Faner Drive, Carbondale, IL 62901, USA.