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Changes in concurrent monthly precipitation and temperature extremes

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Abstract
While numerous studies have addressed changes in climate extremes, analyses of concurrence of climate extremes are scarce, and climate change effects on joint extremes are rarely considered. This study assesses the occurrence of joint (concurrent) monthly continental precipitation and temperature extremes in Climate Research Unit (CRU) and University of Delaware (UD) observations, and in 13 Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate simulations. The joint occurrences of precipitation and temperature extremes simulated by CMIP5 climate models are compared with those derived from the CRU and UD observations for warm/wet, warm/dry, cold/wet, and cold/dry combinations of joint extremes. The number of occurrences of these four combinations during the second half of the 20th century (1951–2004) is assessed on a common global grid. CRU and UD observations show substantial increases in the occurrence of joint warm/dry and warm/wet combinations for the period 1978–2004 relative to 1951–1977. The results show that with respect to the sign of change in the concurrent extremes, the CMIP5 climate model simulations are in reasonable overall agreement with observations. However, the results reveal notable discrepancies between regional patterns and the magnitude of change in individual climate model simulations relative to the observations of precipitation and temperature.

Keywords: concurrent extremes, precipitation, temperature, CMIP5, simultaneous extremes, climate change

S Online supplementary data available from stacks.iop.org/ERL/8/034014/mmedia

1. Introduction

The interaction and dependence between precipitation and temperature, mainly due to the thermodynamic relations between the two variables, have been recognized in numerous studies. Precipitation and temperature data are generally interdependent, and their co-variability has been explored at different spatial and temporal scales (Zhao and Khalil 1993, Trenberth and Shea 2005, Adler *et al* 2008, Liu *et al* 2012). Various parametric and non-parametric joint distribution functions also have been used to represent this interdependence (Tebaldi and Sansó 2008, Sexton *et al* 2012, Watterson 2011, Estrella and Menzel 2012, Srikanthan *et al* 2001).

While extreme values of precipitation and temperature often are addressed independently by employing univariate statistical methods (Cooley *et al* 2007, Katz 2010, AghaKouchak and Nasrollahi 2010, Zhang *et al* 2011, AghaKouchak *et al* 2010), analyses of concurrence of climate extremes are scarce, and climate change effects on joint extremes are rarely investigated. The 2003 European and 2010 Russian drought and heatwave are examples of concurrent precipitation and temperature extremes which resulted in significant loss of life and substantial economic impacts (Fink *et al* 2004, Trenberth and Fasullo 2012). Nicholls (2004) argues that changes in the relationship between precipitation and temperature may be more important than changes in one or the other individually.

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Simultaneous occurrences of such precipitation and temperature exceedences are often described in terms of warm/wet, warm/dry, cold/wet, and cold/dry climate combinations (Zhang *et al* 2000, Beniston *et al* 2009, Estrella and Menzel 2012). Zhang *et al* (2000), for example, analysed the trends of precipitation and temperature, as well as the areas affected by the joint abnormal conditions in Canada, based on the four combinations of wet–dry and warm–cold climate extremes. Beniston *et al* (2009) also investigated trends in the joint quantiles of precipitation and temperature across Europe using the same four climatic combinations. Most previous joint extreme studies have investigated warm/dry conditions for specific extreme events (e.g., Albright *et al* 2010, Lyon 2009, Trenberth and Fasullo 2012, Fink *et al* 2004). This study assesses the occurrence of concurrent warm/wet, warm/dry, cold/wet, and cold/dry precipitation and temperature extremes in ground-based observations and global climate model simulations.

The joint representation of climate extremes may reveal information that is not apparent from analysis of individual extremes. The objectives of the present study are to (a) assess changes in concurrent precipitation and temperature extremes based on both observations and multiple Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor *et al* 2012) simulations; (b) provide a stringent assessment of how well model simulations of historical climate replicate the statistics of observed concurrent precipitation and temperature extremes.

2. Data and method

In this study, ground-based observations and 13 CMIP5 historical simulations (1951–2004) of precipitation and temperature are used to investigate concurrent extremes. Monthly 0.5° × 0.5° gridded observationally based continental precipitation and temperature data for the same period provided by the Climatic Research Unit (CRU; Version 3.1) are used as validation references (New *et al* 2000, Mitchell and Jones 2005). Since observations are also subject to uncertainties (Thorne *et al* 2005, Morice *et al* 2012), the gridded monthly terrestrial air temperature and precipitation data sets for the period 1951–2004 from the University of Delaware (UD) are used as an alternative source of ground-based observation (Nickl *et al* 2010). The UD data include a large number of stations from both the Global Historical Climate Network (GHCN) and the archive of Legates and Willmott monthly and annual station records (Legates and Willmott 1990a, 1990b). These data are interpolated to a 0.5° × 0.5° resolution and have been used in a variety of studies (Rawlins *et al* 2012, Sheffield *et al* 2012). It is acknowledged, however, that the ground-based observations are subject to their own biases and uncertainties, especially over more remote African, Asian, and South American regions where measurements are comparatively sparse, as well as in the first half of the 20th century generally (New *et al* 1999, 2000, Tanarhte *et al* 2012). This study therefore is limited to the second half of the 20th century for which more reliable ground-based observations are available. For consistent comparison, the ground-based observations and the mostly coarser-resolution CMIP5 climate simulations are all remapped onto a common 2° × 2° global grid.

The 25% and 75% quantiles of precipitation and temperature are used as threshold levels for defining the joint extremes. Following (Beniston *et al* 2009), the combination of the precipitation and temperature quantiles T75/P75, T75/P25, T25/P75, and T25/P25 represent the four climate combinations: warm/wet, warm/dry, cold/wet, and cold/dry, respectively. In other words, concurrent extremes are defined as being simultaneously in an outer quartile of both temperature and precipitation. Here, P75 (T75) indicates precipitation (temperature) occurrences above the 75% quantile, while P25 (T25) denotes occurrences below the 25% quantile. For purposes of this study, the term ‘extreme’ thus denotes a rather modest departure from the mean, i.e. above the 75% percentile or below the 25% percentile. However, the joint precipitation–temperature statistics are found to be relatively insensitive to the choice of quantile levels, since similar patterns of changes to concurrent extremes are obtained when alternatively 90/10% thresholds are used—not presented here for brevity. The joint occurrences of extremes during the late 20th century (1978–2004) are compared with the period (1951–1977) at each 2° × 2° grid point, where the joint occurrences in each period are obtained by counting the frequency of occurrences of T75/P75, T75/P25, T25/P75, and T25/P25 combinations. The per cent change in the joint occurrence of extremes (as well as the absolute number of occurrences) during 1978–2004 relative to 1951–1977 are then obtained for the ground-based observations and each CMIP5 climate simulation. Here the per cent change is defined as 100× the difference between the number of occurrences in the two periods divided by the number of occurrences in the first (base) period.

3. Results

The per cent changes in occurrence of concurrent extremes (warm/wet, warm/dry, cold/wet, cold/dry) based on ground-based observations and CMIP5 historical simulations are presented in figures 1–4. The changes in the absolute number of concurrent extremes are also provided as supplementary material (Figures S1–S4 available at stacks.iop.org/ERL/8/034014/mmedia).

The per cent changes in the warm/wet combinations for ground-based observations (CRU and UD data) and for each selected CMIP5 historical simulations between the two periods are shown in figure 1 (white areas indicate no data in either precipitation or temperature). The CRU and UD data sets indicate that the joint occurrence of warm/wet combinations has significantly increased in the 1978–2004 period relative to that of 1951–1977. This result is consistent with previous findings that extremely hot days and heavy precipitation events have become more common since 1950 (Field *et al* 2012, Easterling *et al* 2000). Also, numerous studies have shown that the global surface temperature (both

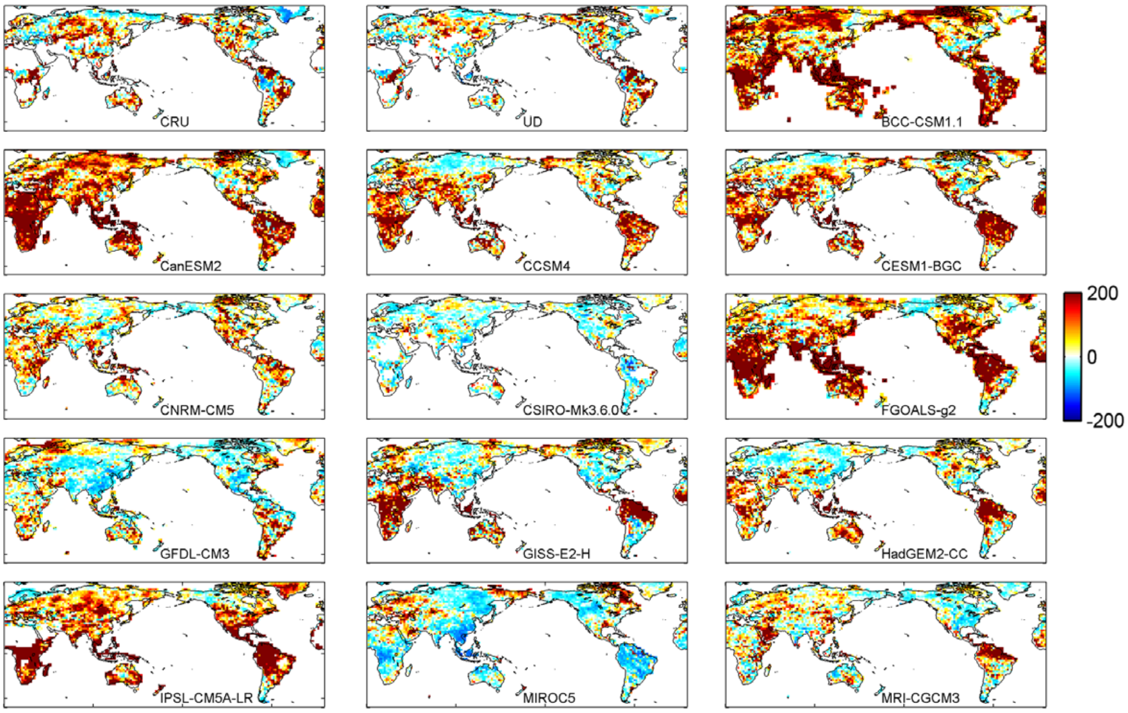

Figure 1. Percentage change in the occurrences of the warm/wet extremes for the period 1978–2004 versus 1951–1977 in the CRU and UD observations (top left panels) and in each selected CMIP5 model simulation.

mean and extreme values) and precipitation extremes have increased in the second half of the 20th century (e.g., Nicholls *et al* 1996, Easterling *et al* 2000, Vose *et al* 2005, Alexander *et al* 2006, Hansen *et al* 2010, Lawrimore *et al* 2011, Jones *et al* 2012, Smith *et al* 2012). The joint analysis of these extremes from the CRU and UD data highlights that, at high latitudes (e.g., Canada and Siberia), as well as in tropical regions (central Africa and Amazon), the occurrences of warm/wet extremes has increased substantially in 1978–2004 relative to 1951–1977, while a few areas, such as parts of southern China, and eastern United States, exhibit a decrease in these occurrences.

Generally, most of the CMIP5 climate simulations are in qualitative agreement with CRU and UD observations and show an increase in the occurrence of warm/wet combinations across the globe, although the magnitude of the increase differs by individual model at a regional scale. For example, the patterns of change in warm/wet extremes simulated by the MIROC5 model differ substantially from those of the CRU and UD observations. Figure 1 also demonstrates that most, but not all, models agree with the CRU and UD observations that the warm/wet combinations have increased over particular parts of the world, including the western United States, central Africa, Australia and the Middle East. On the other hand, the CMIP5 models exhibit regional discrepancies in representing the observed warm/wet extremes, particularly over parts of China, and the Amazon region.

The simulation of warm/dry extremes (high temperature and low precipitation) is of particular concern because of their association with occurrences of heat waves and droughts that can cause tremendous environmental and societal damage (Sivakumar 2006, Lyon 2009, Albright *et al* 2010). Figure 2 displays the per cent change in occurrence of the warm/dry extremes in 1978–2004 relative to 1951–1977. As shown from the CRU and UD observations, the joint occurrence of warm/dry extremes has increased in recent years in many areas across the globe, including central Africa, eastern Australia, and parts of Russia. Most CMIP5 climate simulations roughly agree with the locations of observed warm/dry extremes, especially over central Africa, Amazonia and the Middle East; however, notable discrepancies also exist between individual climate simulations and the CRU and UD observations. For example, while the observations and several CMIP5 simulations (e.g., BCC-CSM1.1, IPSL-CM5A-LR, and GISS-E2-H models) indicate an increase in warm/dry combinations across eastern Australia, other simulations (e.g., by the MIROC5, CSIRO-Mk3.6.0) imply a slight decrease in occurrences of warm/dry combinations in eastern Australia.

The per cent change in the cold/wet combinations is shown for the CRU and UD observations and for each CMIP5 simulation in figure 3, where it is seen that most of the simulations are consistent with the observed patterns of change in cold/wet extremes. Overall, ground-based observations and CMIP5 model simulations indicate that the concurrence of the cold/wet combinations has decreased over most parts of the globe, except over the eastern United States and parts of China where the cold/wet combinations have increased. However, regional simulation discrepancies also are evident. For instance, the ground-based observations exhibit a decrease in the cold/wet combinations in eastern

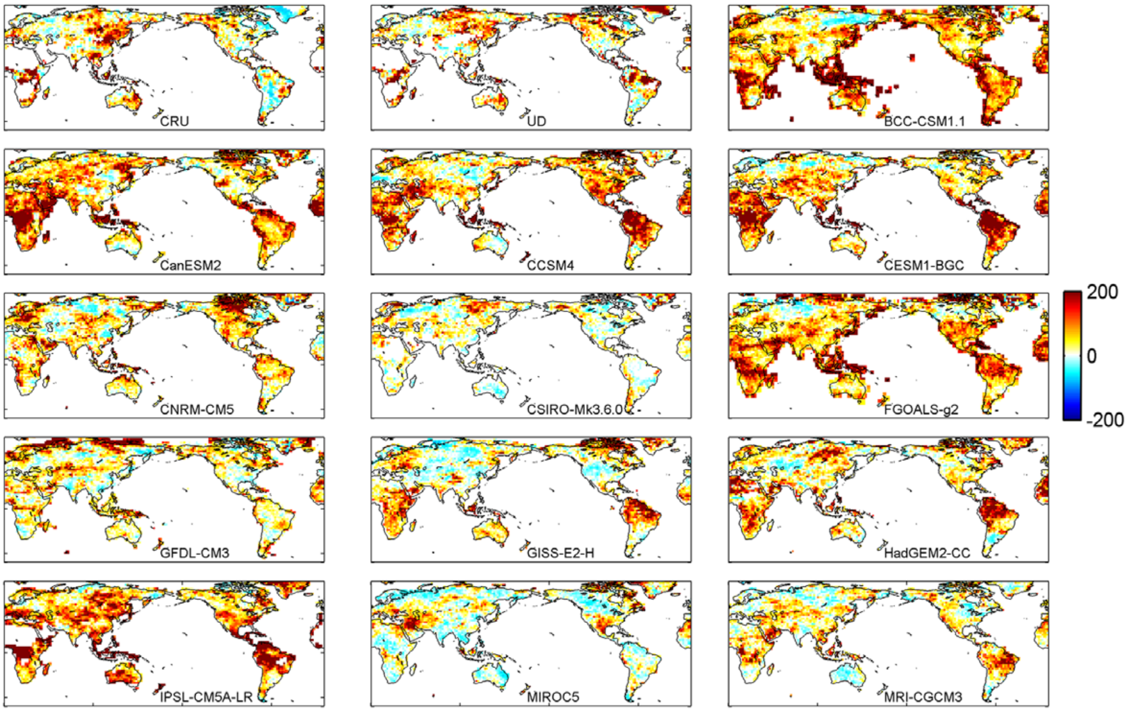

Figure 2. Percentage change in the occurrences of the warm/dry extremes for the period 1978–2004 versus 1951–1977 in the CRU and UD observations (top left panels) and in each selected CMIP5 model simulation.

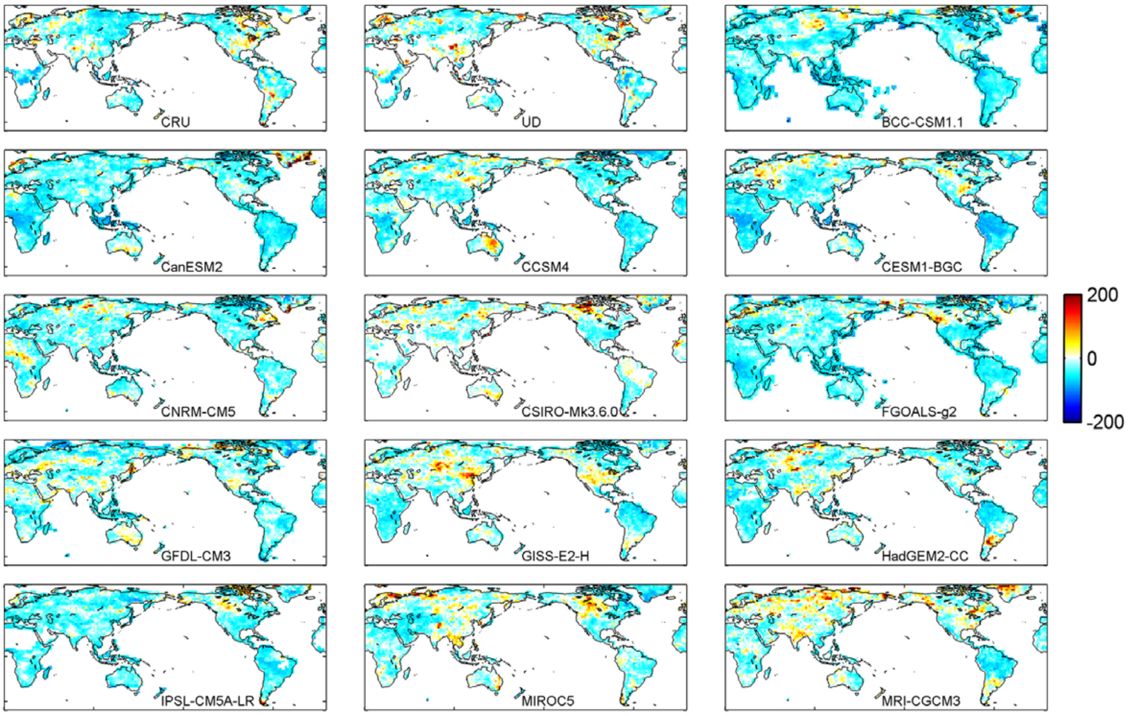

Figure 3. Percentage change in the occurrences of the cold/wet extremes for the period 1978–2004 versus 1951–1977 in the CRU and UD observations (top left panels) and in each selected CMIP5 model simulation.

Australia that is replicated by most model simulations, while the CCSM4 and GFDL-CM3 show an increase in the cold/wet combinations. The ground-based observations show an increase in the cold/wet combinations in the eastern to northeastern United States, whereas the opposite is indicated in some of the CMIP5 model simulations.

Similar to the cold/wet cases, both observations and CMIP5 simulations indicate a decrease in the concurrence of cold/dry conditions over most parts of the globe. However, there are substantial and widespread differences between CMIP5 simulations of cold/dry extremes and those of the CRU and UD data (figure 4), with the BCC-CSM1.1,

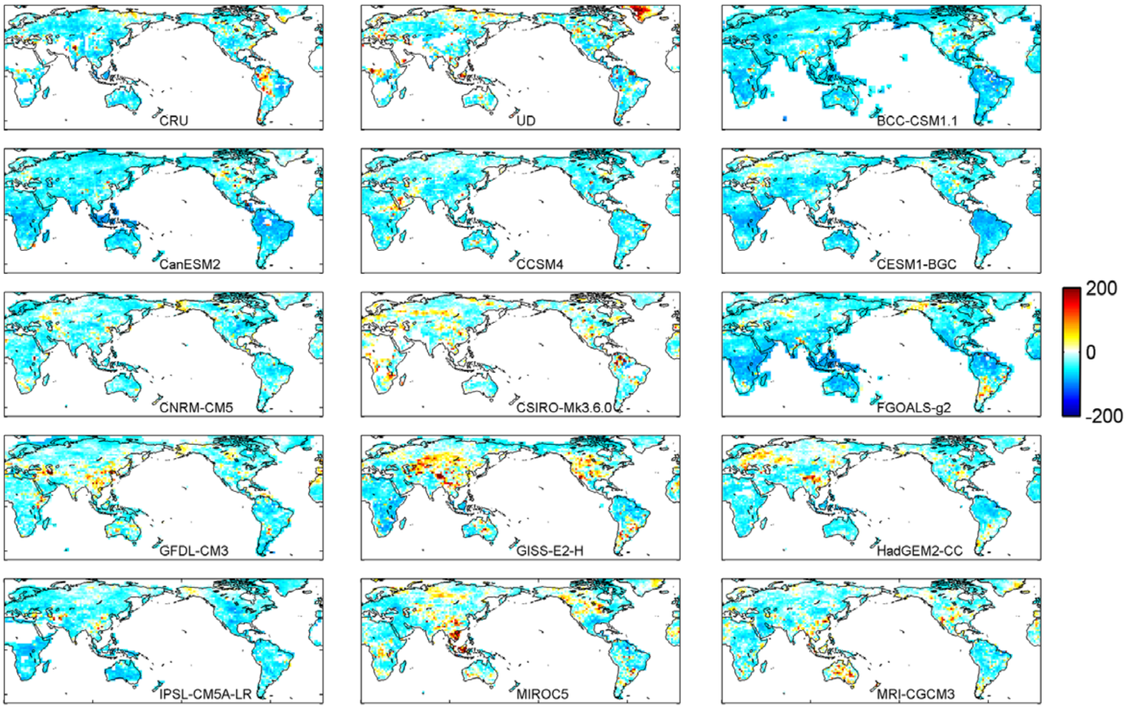

Figure 4. Percentage change in the occurrences of the cold/dry extremes for the period 1978–2004 versus 1951–1977 in the CRU and UD observations (top left panels) and in each selected CMIP5 model simulation.

CanESM2, and CCSM4 simulations showing better overall agreement with the CRU and UD observations. One can see that there are inter-model variations in the sign of change (decrease/increase in cold/dry conditions) over certain regions including Australia, Eurasia and eastern China. It is worth mentioning that both figures 3 and 4 indicate that even over high latitudes and cold regions, the occurrence of joint cold/dry and cold/wet extremes have decreased in 1978–2004 relative to 1951–1977.

Figure 5 summarizes the probability of detection (POD) of the sign of change in the CMIP5 climate model simulations for the four combinations of warm/wet, warm/dry, cold/wet, and cold/dry extremes with respect to CRU observations. Here, the POD is defined as the fraction of grids in which the sign of change in the number of joint occurrences (increase, decrease, neutral) in CMIP5 model simulations agrees with the ground-based observations. The POD values of the CMIP5 climate models for the four combinations of the extremes range between about 0.55 and 0.85, indicating 55% and 85% agreement in the sign of change. However, the magnitudes of changes in the extremes and their detailed patterns may be substantially different from one model to another. Not shown here for brevity are the POD values of CMIP5 models against the UD data. Overall, models exhibit similar qualitative performance with respect to both CRU and UD data sets (i.e., a relatively poorly performing model with a low POD score relative to CRU also scores low relative to UD).

It is worth noting that the CMIP5 coupled ocean–atmosphere models cannot be expected to reproduce the historically observed sea surface temperature magnitudes and patterns, nor the historical sequences of associated El Niño Southern Oscillation, Pacific Decadal Oscillation, and the Atlantic Multidecadal Oscillation events. Because these events affect the continental precipitation and temperature extremes, the CMIP5 simulations also cannot be expected to reproduce the observed geographical distribution of these climatic extremes in a given year (Peterson *et al* 2012, Kenyon and Hegerl 2010). It is anticipated that the patterns of climatic extremes on land would instead be simulated more reliably by the participating Atmospheric Model Intercomparison Project (AMIP) models in which observed sea surface temperatures are prescribed (Taylor *et al* 2012).

4. Conclusions

The observed increase in heat waves, droughts and floods which have severely impacted the environment and society over the past several decades, has brought much-needed attention to the analysis of climate extremes (AghaKouchak *et al* 2012, Hegerl *et al* 2011, Field *et al* 2012). Numerous studies have addressed univariate changes in climate extremes, but the concurrence of observed climatic extremes and their simulation by climate models has received considerably less scientific attention.

The concurrences of precipitation and temperature extremes are assessed using ground-based CRU and UD observations and the CMIP5 climate model simulations for the following four combinations of joint extremes: warm/wet (high temperature and high precipitation), warm/dry (high temperature and low precipitation), cold/wet (low temperature and high precipitation), and cold/dry (low temperature and low precipitation). The per cent change in the joint occurrence of extremes (and in the absolute number of occurrences)

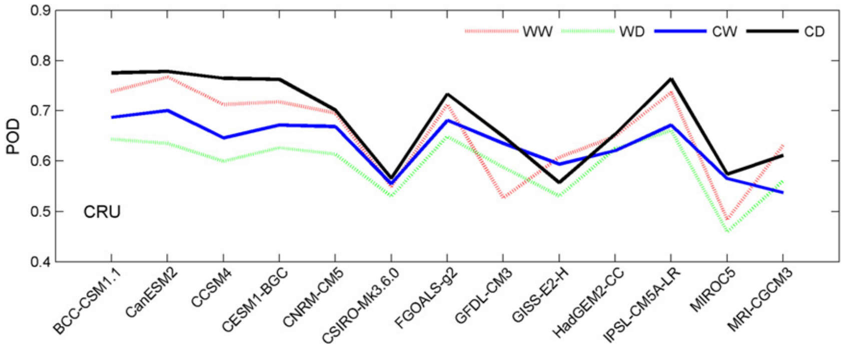

Figure 5. The probability of detection (POD) of the sign of change in the CMIP5 climate model simulations from the period 1951–1977 to the period 1978–2004 for the four combinations of warm/wet, warm/dry, cold/wet, and cold/dry extremes with respect to CRU observations. The POD is defined as the fraction of grids in which the sign of change in the number of joint occurrences (increase, decrease, neutral) in CMIP5 model simulations agrees with the ground-based observations.

during 1978–2004 is compared with the baseline (1951–1977) extreme occurrences at each global grid point. Based on the CRU and UD data sets, the occurrences of joint warm/dry and warm/wet extremes are observed to have increased substantially across the globe. The warm/wet extremes have particularly increased over high latitudes and in tropical regions, whereas the warm/dry extremes also have increased in many areas, including central Africa, eastern Australia, northern China, parts of Russia, and the Middle East. On the other hand, the cold/wet and cold/dry extremes combinations have decreased over most parts of the globe.

Quantitative agreement between the CMIP5 climate model simulations of concurrent extremes and the ground-based observations is assessed by means of the probability of detection (POD) of the sign of change, defined as the fraction of grids in which the sign of change in the number of joint occurrences of extremes (increase, decrease, neutral) in CMIP5 model simulations agrees with the ground-based observations. The results show that with respect to the sign of change in the concurrent extremes, the CMIP5 climate model simulations are in reasonable agreement with observations. However, there are notable discrepancies in regional patterns as well as biases in the magnitudes of change in individual climate model simulations relative to the observations of precipitation and temperature extremes. Further details of the statistical characteristics of the CMIP5 simulations that may account for these issues are currently under investigation.

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