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Characterizing Concurrent Hot and Dry Spell Events Across Crucial Breadbasket Regions

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1. Introduction

In regions across the world, from the Americas to Australia, there is evidence of an increasing number of compound climate extremes (Gallant and Karoly 2010; Mazdiyasni and AghaKouchak 2015; Armal *et al.* 2016; Armal *et al.* 2018a; Armal *et al.* 2018b; Najafi and Khanbilvardi 2018a; Najafi *et al.* 2018b; Lima *et al.* 2018; Armal and Al-Suhili 2019). Co-occurring conditions such as high temperatures and dry spells or high temperatures and excess precipitation are considerably more intense and destructive than any one condition individually (Zscheischler *et al.* 2017). In food growing regions, these co-occurring extremes can have negative impacts such as declined yield—a risky consequence in a global society that is fast approaching a population of eight billion people to feed (Najafi *et al.* 2016; Najafi *et al.* 2017; Matiu *et al.* 2017; Zampieri *et al.* 2017; Najafi *et al.* 2018c).

Studies focusing on co-occurring climate extremes in food growing regions have indicated that hot and dry extremes leave more negative impacts than other co-occurring extremes (Troy *et al.* 2015; Lesk *et al.* 2016). Focusing on wheat, the threshold at which wheat begins to be negatively affected by temperature is 30 degrees Celsius (Zampieri *et al.* 2017). With the combination of extreme heat indicated by the number of days that exceed this threshold during the growing season and dry conditions based on the minimum monthly value of the Standardized Precipitation Evapotranspiration Index (SPEI) during the growing season, we characterize the variability and trends of concurrent hot and dry extreme events in every growing region of both spring and winter wheat. By uniquely focusing on global wheat croplands and the risk of these concurrent climate extremes, we draw conclusions about how climate is changing with respect to this crucial crop.

2. Data and methodology

Global wheat croplands were defined based on NASA's MIRCA2000 dataset (https://webmap.ornl.gov/wcsdown/dataset.jsp?ds_id=10015) that displays the locations of irrigated and rainfed wheat lands as well as the number of hectares being grown at each location. This dataset has been widely used in the literature on crop modeling and climate science (Deryng *et al.* 2014; Zampieri *et al.* 2017; Heino *et al.* 2018; Najafi *et al.* 2018c, Najafi *et al.* 2018d, Najafi *et al.* 2019a, Najafi *et al.* 2019b). Only locations that used at least 1% of the land within a grid cell, or at least 67 acres, for crop growth were considered. The irrigated and rainfed lands were combined for analysis in this study; regard for management measures in place such as irrigation were not crucial given our interest in exploring concurrent hot and dry extremes in all significant wheat growing regions.

To make the distinction between spring and winter varieties of wheat, we first used the extrapolated SAGE Crop Calendar Dataset to define the growing season for winter and spring wheat yielding locations (https://nelson.wisc.edu/sage/data-and-models/crop-calendar-dataset/netCDF0-5degree.php) and then narrowed and restricted the areas in consideration by applying Iizumi's Global sowing and harvesting windows of major crops dataset for winter and spring wheat varieties (http://search.diasjp.net/en/dataset/global_crop_calendar_2000). We overlaid the map of global wheat croplands based on the MIRCA2000 dataset onto the medium season, rainfed spring and winter maps based on Iizumi's data set. Cropping all areas that were not common between the data sets, we produced three mappings:

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(1) Locations where only spring wheat is grown, (2) Locations where only winter wheat is grown, and (3) Locations where both spring and winter wheat are suitable for growing.

We defined extreme hot events by the total number of days during a growing season that exceeded 30-degrees Celsius and extreme dry spell events by the minimum monthly SPEI magnitudes during the same growing season (Wang *et al.* 2018). To understand extreme hot and dry events relative to location, we considered the 75th percentile thresholds for each location. We described each location that exceeded the 75th percentile threshold for both temperature (T30) and minimum SPEI during a growing season as having experienced a concurrent extreme event (CEE). The following analyses are focused on the top ten wheat producing countries based on Food and Agriculture Organization of the United Nations (FAO) average production from 2001-2013: China, India, USA, Russia, France, Canada, Germany, Pakistan, Australia, and Turkey.

3. Results

To understand how CEEs have changed over time, we sought to look broadly at the differences in impacts experienced between the IPCC's baseline period from 1961-1990 and the most current decades since 1990 (1991-2013) for spring and winter varieties of wheat. Despite the shorter period after 1990 (only 23 years as opposed to 29), we still observe a surge of concurrent extreme events across the growing areas. We have separated the spring (winter) wheat growing locations into locations that grow only the spring (winter) variety and locations that are suitable for growing both varieties. The respective growing seasons were used for the locations that are suitable for growing both varieties. Thus, "spring (only)" and "winter (only)" will refer to locations that do not include the areas suitable for both varieties and "spring (total)" and "winter (total)" will refer to locations that include the areas suitable for both varieties.

Beginning with the spring wheat variety, a significant difference in the means was found in the frequency of CEEs for spring (only) growing areas. However, more "extreme" CEEs, based on the number of days exceeding 30 degrees Celsius in dry growing areas, were found in the baseline period. Looking at the major producing regions of wheat globally, India experienced more events along its western coast line and less events in the eastern region of the country in the period after 1990. Furthermore, Australia experienced more CEEs in the eastern part of the country in the period after 1990. Transitioning to the spring (total) growing areas, we found the difference in the frequency of CEEs was insignificant. However, the additional affected major producers were China and the United States. After 1990, China observed an increase in the number of seasons impacted by CEEs, most notably post-2000. In the United States we observed a spatial shift in the concentration of impacted locations before and after 1990. During the baseline period, the events are generally concentrated in the north, and in the period after 1990, there is a greater number of CEEs in the southern United States.

In general, the winter wheat growing season was found to experience less hot and dry extreme conditions as compared to the spring wheat growing season. Overall, though, we found a significant increase in the frequency of CEEs across winter (total) growing areas in the period after 1990 compared to the baseline period. Focusing on the major wheat producing countries, we observed a spatial shift in the United States with the dispersion of extreme events after 1990. We also observed a spatial decrease in the number of impacts in southern Australia after 1990. Finally, the location of impacts in Turkey remained essentially the same in the decades before and after 1990. It is important to note that these observations were made for locations considered suitable for both spring and winter wheat, and not croplands exclusive to winter wheat. The winter (only) growing areas also experienced a significant increase in the frequency of CEEs in the period after 1990 compared to the baseline period and the observations made are the same as those for the winter (total) growing areas but on a smaller scale. In particular, the expansion of CEEs to the northwest region of the United States and southern Canada in the last decade is a common feature of both growing area maps.

Looking into the individual extremes over the entire time period considered, 1961-2013, we note that there is lack of significant trends in T30 or SPEI, leading us to conclude that these extremes are not necessarily driven more by temperature or dryness in any one area but are unique events.

CEEs are unique occurrences that affect spring and winter wheat croplands in different places at different times. With a focus on the major producers of wheat worldwide, Asian countries (China, India, and Pakistan) experienced CEEs only during the spring growing season while the United States and Australia experienced CEEs in both the spring and winter growing seasons. This study confirms that as climate changes, the co-occurrence of hot and dry extreme events will increase. Furthermore as observed, they will increase in croplands that grow essential grains for food security. The croplands affected by these CEEs are different for spring and winter varieties of wheat, and from these results, agricultural scientists in industry can recommend improvements for management practices based on expected conditions. Our focus on the major producers of wheat can be studied further by analyzing the potential economic effects these climate extremes have had on global grain prices. Alternatively, similar work can be done focusing on food-insecure nations and the spatio-temporal effects of CEEs there. Considering CEEs during different stages of crop growth rather than just the full growing season is another way the data can be transformed to tell another story about how compound hot and dry extremes are affecting croplands and global food security.

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