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Trans-Pacific ENSO teleconnections pose a correlated risk to agriculture

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ABSTRACT

The El Niño Southern Oscillation (ENSO) is a major source of interannual climate variability. ENSO life cycles and the associated teleconnections evolve over multiple years at a global scale. This analysis is the first attempt to characterize the structure of the risk posed by trans-Pacific ENSO teleconnections to crop production in the greater Pacific Basin region.

In this analysis we identify the large-scale atmospheric dynamics of ENSO teleconnections that affect heat and moisture stress during the growing seasons of maize, wheat and soy. We propose a coherent framework for understanding how trans-Pacific ENSO teleconnections pose a correlated risk to crop yields in major agricultural belts of the Americas, Australia and China over the course of an ENSO life cycle by using observations and a multi-model ensemble of climate anomalies during crop flowering seasons.

Trans-Pacific ENSO teleconnections are often (but not always) offsetting between major producing regions in the Americas and those in northern China or Australia. El Niños tend to create good maize and soybean growing conditions in the US and southeast South America, but poor growing conditions in northern China, southern Mexico and the Cerrado in Brazil. The opposite is true during La Niña. Wheat growing conditions in southeast South America generally have the opposite sign of those in Australia. Furthermore, multi-year La Niñas can force multi-year growing season anomalies in Argentina and Australia.

Most ENSO teleconnections relevant for crop flowering seasons are the result of a single trans-Pacific circulation anomaly that develops in boreal summer and persists through the following spring. During the late summer and early fall of a developing ENSO event, the tropical Pacific forces an atmospheric anomaly in the northern midlatitudes that spans the Pacific from northern China to North America and in the southern midlatitudes from Australia to southeast South America. This anomaly directly links the soybean and maize growing seasons of the US, Mexico and China and the wheat growing seasons of Argentina, southern Brazil and Australia. The ENSO event peaks in boreal winter, when the atmospheric circulation anomalies intensify and affect maize and soybeans in southeast South America. As the event decays, the ENSO-induced circulation anomalies persist through the wheat flowering seasons in China and the US.

1. Introduction

In a global economy, food insecurity can be caused not only by local crop failures, but also by crop failures in distant food-exporting regions (Puma et al., 2015; Marchand et al., 2016). Crop failures in major producing regions can increase food prices globally with greatest impact on import dependent trade partners (d'Amour et al., 2016). Understanding the food security of any nation, region, or the world, therefore, requires that we understand production variability globally and how this impacts food availability via the global food trade system. Of particular interest is the co-variability of major food producing regions – do they tend to vary in-phase or out-of-phase generating compounding or offsetting global-scale production variability?

Climate variability, although only one of many factors that determines food security, is one process that can affect the crop yields of geographically distant regions simultaneously or in sequence. The El Niño Southern Oscillation (ENSO), as a major source of temperature and precipitation variability, is among the most important modes of climate variability for global food security (Trenberth et al., 1998; Mason and Goddard, 2001). Spatially, both El Niño and La Niña have distinct patterns of teleconnections to climate at a global scale (Bjerknes, 1969; Trenberth et al., 1998; Alexander et al., 2002). From an interannual perspective, ENSO exhibits a characteristic multi-year life cycle of sea surface temperature (SST) and zonal wind anomalies

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(Rasmusson and Carpenter, 1982). Furthermore, the transition from an El Niño state to a La Niña state tends to be phase locked to the seasonal cycle (Wang and Picaut, 2004), and therefore intersects crop flowering seasons in a predictable manner. By creating unfavorable growing conditions in many regions simultaneously or in sequence (Anderson et al., 2016), ENSO can pose a correlated risk to crop production in our globalized agricultural economy (Anderson et al., 2017).

Recent studies have detailed the impacts of ENSO on crop yields globally (Iizumi et al., 2014), but we lack a unified framework for understanding the mechanisms behind how these yield anomalies relate to one another. This is, in part, because the climate analyses of global ENSO teleconnections often focus on the season when teleconnections are strongest rather than the seasons when crops are most vulnerable to climate anomalies. And while there are studies that analyze the dynamic processes by which ENSO affects crop yields, these tend to be regional analyses that focus on one specific season. Fragmenting the literature in this way makes it difficult to understand how ENSO-induced crop yield anomalies relate to one-another.

For example, when considering major soybean producers we might be interested in how ENSO-induced yield anomalies in the United States relate to those in China and Southeast South America. Are they all part of a single circulation pattern that spans the basin and persists throughout the year or is each region affected by independent teleconnections that develop locally at different times of the year? Do El Niño or La Niña events (hereafter generalized as ENSO events) have the same impacts on production in all regions or are losses in one region and at one time compensated for by gains elsewhere and at other times? Answering these questions is critical for understanding how closely linked the yield anomalies are, but doing so requires considering both spatial variations in the climate teleconnections and the timing of each circulation anomaly in relation to major crop growing seasons.

In this analysis we will address two main questions: (1) How are ENSO climate teleconnections during the growing seasons in the Americas, China and Australia related to one another? and (2) Within a single growing year, are ENSO-forced heat and moisture stress anomalies generally compounding or offsetting across major producing regions?

In the following sections we will first identify the trans-Pacific atmospheric teleconnections relevant during the growing seasons of maize, wheat and soy. Next, we translate the climate variables into measures that are relevant for agriculture (soil moisture and killing degree days). We then use a multi-model ensemble to identify which teleconnections from the observational analysis are most robust. Through these analyses we construct a coherent framework, which we summarize in the final section, for understanding how trans-Pacific ENSO teleconnections affect crops over the course of an ENSO life cycle.

2. Methods and data

To analyze how life cycles of ENSO affect crop growing conditions in the greater Pacific basin region, we (1) identify relevant ENSO years, (2) define the climate sensitive months of the local growing season at each location during those years, and (3) define metrics of heat and moisture stress during those months to use in a composite analysis. To analyze the global atmospheric dynamics that give rise to local growing season teleconnections, we define a discreet number of seasons that include the climate-sensitive portions of local growing seasons. We then create composites of atmospheric variables during these seasons for each year in the ENSO life cycle. Finally, we estimate how robust observed teleconnections during local growing seasons are by using an ensemble of SST-forced atmospheric models. In the following sections we describe the methods and data used in each of these analyses.

2.1. Defining ENSO life cycles

The first step in our analysis is to construct ENSO life cycles. To do so, we identify years in which the October-November-December SST anomaly in the Niño 3.4 region as measured by the Oceanic Niño Index[1] exceeded 0.5 standard deviations, which corresponds to an absolute departure of just under 0.5 °C. These ENSO `event years' are listed in grey above panels 1 and 2 of Fig. 1. Each life cycle consists of three years: an `event year' as well as one year preceding and one year following the event. Years were not allowed to be double counted as an `event year' in one life cycle and as a following or preceding year in another life cycle. Because SST anomalies in the Niño 3.4 region tend to develop and decay in boreal spring (Rasmusson and Carpenter, 1982; or see Fig. 1), we use a May-April 'ENSO year'.

2.2. Identifying climate sensitive portions of the growing season

How crop yields respond to an abiotic stress depends on the stage of development at which the stress is applied. Many crops are relatively insensitive to stresses applied during the vegetative stages of development but respond strongly to stress applied around the time of flowering, which determines the number of grains that develop per planted area (Siebers et al., 2017; Barnabás et al., 2008). We use the global crop calendar of Sacks et al. (2010) to estimate crop harvest dates by location and consider the three months prior to harvest as the season around flowering. We use the primary harvest dates from the Sacks et al. (2010) data where multiple harvest dates are available for maize. For wheat, we use winter wheat harvest dates in all countries except Australia and Canada, where we use spring wheat harvests. While both the US and China grow a spring wheat crop, we choose to focus our analysis on the larger winter wheat crop. These data constraints prevent our analysis from addressing nuances within individual countries, such as teleconnections to regions growing alternate season wheat. Our results instead focus only on the primary growing season of each crop in each country. We furthermore use the static harvest dates of Sacks et al. (2010), although in practice planting and harvest dates will be variable and may depend on the growing conditions for that year. The dataset is largely interpolation in some regions, such as northeast Brazil and parts of China (see Sacks et al., 2010 for details), which may bias our results in these areas. Although the crop calendars in Sacks et al. (2010) are subnational, we include a simplified country-level approximation of the crop calendars in the bottom three panels of Fig. 1 for comparison to the ENSO life cycles in the top two panels.

To mask out minor and non-producing regions, we only plot teleconnections for locations in which the harvested area of a given crop corresponded to at least 0.1% of the total area for that pixel according to the Monfreda et al. (2008) dataset of global harvested areas. While the Monfreda et al. (2008) dataset represents harvested areas around the year 2000, actual harvested areas may have changed over time in some regions (most notably in Brazil).

2.3. Calculating crop-relevant variables

Even when climate teleconnections exist during crop flowering seasons, they do not always translate to yield anomalies. Crop yields respond not to variations in precipitation directly but rather to soil moisture anomalies. We use 0–1 m soil moisture estimates from the Noah Land surface model version 3.3 in the Global Land Data Assimilation System version 2 (Rodell and Kato Beaudoing, 2015), which is available from 1948 to 2010, to calculate the average soil moisture anomaly during the flowering season. We average the flowering season soil moisture over the years identified in Fig. 1 to estimate ENSO teleconnections for each year in the life cycle.

In terms of temperature, crop yields benefit from increases in growing season temperature up to a biophysical threshold, at which

[1] Data available from https://catalog.data.gov/dataset/climate-prediction-center-cpcoceanic-nino-index.