Life cycles of agriculturally-relevant ENSO teleconnections in North and South America

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ABSTRACT

The characteristic evolution of ENSO on timescales of months to years means that risks to agriculture have structure between seasons and years. The potential for consecutive ENSO-induced yield anomalies is of particular interest in major food producing areas, where modest changes in yield have significant effects on global markets. In this study we analyze how multi-year El Niño and La Niña life-cycles relate to climate sensitive portions of major crop growing seasons in North and South America.

We analyze the dynamics underlying these life-cycles to illustrate which aspects of the system are most important for agriculture. In North America the same-season teleconnections affecting soybean and maize have been well studied, but we demonstrate the importance of lagged soil moisture teleconnections for wheat in the southern Great Plains. In South America, peak ENSO SST teleconnections are concurrent with, and therefore critical for, wheat and maize growing seasons while soil moisture memory in Argentina plays an important role during the soybean growing season.

Finally, we show that ENSO teleconnection life-cycles are consistent with historical yield anomalies. Both El Niño and La Niña life-cycles tend to force consecutive seasons of either above or below expected yields. While the magnitude of the yield anomalies forced by ENSO are often modest, they occur in major crop producing regions.
1. Introduction

The El Niño Southern Oscillation (ENSO) refers to a coupling between equatorial Pacific ocean and atmosphere anomalies. Although it is fundamentally a tropical Pacific phenomena, both warm (El Niño) and cold (La Niña) events alter atmospheric circulations – and subsequently temperature and precipitation patterns – well into the midlatitudes (Trenberth et al. 1998; Alexander et al. 2002).

ENSO has proven to be a major driver of global crop yield variability, although its impacts on agriculture in a given year are not uniform (Iizumi et al. 2013). Instead, ENSO tends to create agricultural winners and losers. In an El Niño year, drought is likely in many tropical countries while wetter, milder conditions prevail in the northern hemisphere midlatitudes (Mason and Goddard 2001; Diaz et al. 2001). Because every ENSO event is slightly different, however, the consistency and timing of these impacts varies between events (Capotondi et al. 2015).

There is the potential to improve regional and global food security through advanced planning by exploiting robust climate teleconnections in major food producing regions of North and South America. Table 1 illustrates that the reported relation between yield anomaly and ENSO phase is generally consistent across studies despite differences in available data and analytical methods. Although most studies have focused on maize in North America and on maize or soybean in South America, ENSO has a significant impact on maize, soybean and wheat yields in both North and South America. Understanding ENSO teleconnections therefore presents the possibility of providing governments, extension officers and farmers with improved information on seasonal timescales (Messina et al. 1999; Podesta et al. 2002; Iizumi et al. 2013). And while understanding seasonal climate variability is only the first step towards managing climate-induced risks to food security, it is the foundation upon which effective mitigation practices and policies are built. For a
detailed review of how information on climate variability can be used at both the farm and national
scale, see Hammer et al. (2001) and for a more complete case study of how climate forecasts can
improve profit and reduce risks in agriculture see Hammer et al. (1996).

In the past two decades we have seen tremendous progress towards a robust understanding of
ENSO teleconnections, but there are still agriculturally-relevant aspects of the system that are
poorly understood. For example, the relationship between crop yields and ENSO is often im-
plicitly treated as annually independent. However, the dynamics underpinning ENSO produce a
characteristic evolution from one phase to another (Rasmusson and Carpenter 1982; Okumura and
Deser 2010). This multi-year evolution raises the question of whether ENSO poses risks or bene-
fits to consecutive cropping seasons which, in a global economy, are important for market prices
and global food security. As such, this study explores the extent to which El Niño and La Niña
demonstrate a robust life cycle of agriculturally-relevant teleconnections.

a. ENSO life cycle

At the heart of ENSO is the Bjerknes feedback. In the equatorial Pacific prevailing easterly
winds lift the thermocline in the east, bringing cold upwelling water to the surface, and accumulate
warm surface water in the west, which leads to a zonal sea surface temperature (SST) gradient.
These zonal SST gradients reinforce easterly winds, and carry water vapor into the west Pacific
warm pool to fuel deep convection, a process that increases upwelling in the east and completes
the positive (Bjerknes) feedback (Bjerknes 1969). When the easterly trades relax the positive
feedback can run in the opposite direction to create anomalous warming in the east: El Niño
conditions. These El Niño events tend to last 1-2 years and reoccur every 3-7 years. While there
is still debate as to whether ENSO is a self contained oscillatory mode or a stable response to
stochastic wind forcing, both theories agree that ENSO is strongly modified, and to some extent
phase locked, with the seasonal cycle (Thompson and Battisti 2000; Wang and Picaut 2004). Both El Niño and La Niña develop in late spring and peak at the end of the calendar year. Rasmusson and Carpenter (1982) were the first to identify a characteristic multi-year life cycle of SST and zonal wind anomalies during El Niño events. Building on their work, subsequent authors have identified similar life-cycles for La Niña events, although the spatial structure and seasonal evolution differ somewhat between warm and cold events (Okumura and Deser 2010). In our analysis of the evolution of ENSO teleconnections, we therefore evaluate life cycles for warm and cold phases of ENSO separately.

b. Crop stress-sensitivity

The biological response of plants to abiotic stressors, such as extreme heat and drought, depend on the specifics of the stress, the cultivar and the developmental stage at which the stress is applied. While cereals exhibit some degree of sensitivity to abiotic stress at all stages of growth, the final yield of the crop is most stress-sensitive during the periods around flowering and around grain filling (Barnabás et al. 2008). The time around flowering, which determines the number of grains per planted area, is considered more crucial for cereal crop yields than is grain filling, which determines the weight of the grain. As such, our analysis will focus on the flowering portion of the growing season for each crop. The major flowering seasons for North American crops are the late spring and summer: April, May, June (AMJ) for wheat; June, July, August (JJA) for maize and soybean. Flowering seasons in South America are primarily September, October, November (SON) for wheat, November, December, January (NDJ) for maize, and January, February, March (JFM) for soybean. Table 2 lists the major flowering dates by crop and continent.

Our analysis is organized as follows: We present the data in Section 2 and discuss the methods used to create the composite ENSO life cycles, which are used to identify both concurrent
and lagged teleconnections, in Section 3. In Section 4 we analyze the evolution of relevant tele-
connections for each major crop growing season, and demonstrate that these teleconnections are
consistent with observed crop yield anomalies. In Section 5 we summarize our conclusions and
discuss their importance.

2. Data

We aggregate daily mean atmospheric variables from the NCEP-NCAR Reanalysis I up to
monthly quantities for geopotential height, vertical ascent, wind vectors, precipitable water and
maximum temperature on a T62 Gaussian grid for the years 1948-2013 (Kalnay et al. 1996).
For monthly soil moisture, latent heat and sensible heat we use the 1.0°x 1.0° spaced Noah
land surface model version 2.0 from the Global Land Data Assimilation System (GLDAS)
for the years 1948-2010 (Rodell and Kato Beaudoin 2015). Due to the truncated avail-
ability of the GLDAS data, the 2010 composite had to be removed from the La Niña en-
semble in the soil moisture analyses. We use 1.0°x 1.0° monthly precipitation data from the
Global Precipitation Climatology Centre (GPCC) and monthly SST anomaly data from the 2.0°x
2.0° Extended Reconstructed Sea Surface Temperature version 3b (ERSSTv3b), both for 1948-
2013 (Schneider et al. 2011; Smith et al. 2008). El Niño and La Niña events were selected
using the Oceanic Niño index, which is a three-month running mean of SST anomalies in
the Niño 3.4 region (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/
ensostuff/ensoyears_ERSSTv3b.shtml). Crop statistics for the United States for 1949-
2013 were downloaded from the United States Department of Agriculture, National Agricul-
tural Statistics Service (http://quickstats.nass.usda.gov/, accessed August 6 2015). For Ar-
gentina, crop statistics were available for 1969 - 2010 from the Integrated Agricultural In-
formation System (SIIA; http://www.siia.gov.ar/). Crop production data in Brazil were avail-
able from 1976 - 2014, and were downloaded from the Brazilian Companhia Nacional de Abastecimento (CONAB; http://www.conab.gov.br/index.php). Wheat yield data for Canada from 1950 to 2012 was downloaded from the CANSIM database, provided by Statistics Canada (http://www5.statcan.gc.ca/cansim). Maize production data from 1950 - 2008 in Mexico was downloaded from the INEGI Information Databank (http://www3.inegi.org.mx/sistemas/biinegi/). For spatial information on cropland extent in North and South America, a combination of three datasets was used: The Global Agro-Ecological Zones model, the Monthly Irrigated and Rainfed Crop Area dataset and the Spatial Production and Allocation Model (Fischer et al. 2008; Portmann et al. 2010; You et al. 2014). Any cell containing above 0.5% cropland in any of the three datasets is indicated as 'major cropped area', while all other cells containing cropped area fall under 'minor cropped area'. This combined dataset was created as a conservative solution to the significant discrepancies in cropland extent and cropping intensity between datasets (Fritz et al. 2011; Anderson et al. 2015).

3. Methods

a. ENSO ensemble composite construction

An ensemble of El Niño and La Niña composites was constructed from years in which the mean boreal wintertime (October, November, December) SST anomaly amplitude in the Niño 3.4 region exceeded 1/2 standard deviation. This threshold corresponds to an absolute departure in SSTs of just under 0.5°C. Following identification of the events, the calendar years corresponding to the event, prior to the event and following the event were used to construct a complete 'life-cycle' composite. The calendar years for the composites will hereafter be referred to as EN -1, EN 0 and EN +1 for the El Niño composite, and as LN -1, LN 0, and LN +1 for the La Niña composite.
Years were not allowed to be double counted as an ‘event-year’ (EN 0 or LN 0) in one composite and a previous- or post-event year in another composite of the same ensemble. This would happen, for example, when multiple years in a row meet the selection criteria. In these cases the composite centered on the first year to meet the selection criteria is used in the ensemble and the composites for the following years are excluded. Figure 1 illustrates the individual composites (shown in grey), as well as the ensemble mean (shown as the thick colored line).

b. Same-season teleconnections

For the southern hemisphere crops that flower during the boreal winter, the climate sensitive portion of the growing season occurs at the same time as peak ENSO SST anomalies. In these cases, ENSO-induced precipitation and maximum temperature anomalies are identified using the previously defined composite years. The mean composite is plotted for areas in which at least 2/3 of the composite members have the same sign as the composite mean. This limits the focus of the analysis to relatively robust teleconnections. Geopotential height, circulation, and ascent anomalies are then composited as a means of identifying the dynamics that give rise to each teleconnection. In these dynamical analyses, however, all areas are shaded so as to provide a coherent representation of the atmospheric teleconnections.

c. Lagged teleconnections

ENSO teleconnections in boreal spring, during which time SST anomalies are often near neutral, are generally weaker than those in boreal winter and are therefore not likely to play a dominant role in determining growing season temperature and precipitation for boreal spring flowering crops. However, teleconnections during peak ENSO intensity may persist via soil moisture memory and appreciably influence growing season anomalies in the spring. That soil moisture anomalies persist
for weeks to months has been documented in models by Delworth and Manabe (1993) and subse-
sequently confirmed in observations by Vinnikov et al. (1996). Both studies model soil moisture as
a first order Markov process with an exponential autocorrelation function:

\[ r(t) = e^{-\frac{t}{T}} \] (1)

Where \( r(t) \) is the autocorrelation at lag \( t \), and \( T \) is the e-folding time for the damping of soil
moisture anomalies in the absence of forcing, also referred to as the temporal scale of the autocor-
relation. Vinnikov et al. (1996) show that \( T \) may be reasonably approximated as:

\[ T = \frac{1}{ln\left(\frac{r(1)}{r(2)}\right)} \] (2)

Where \( r(1) \) is the autocorrelation at a lag of one month and \( r(2) \) is the autocorrelation at a lag of
two months. Modeling soil moisture memory as a Markov process assumes that the season in
which the anomalies occur is irrelevant. In our analysis we calculate the characteristic temporal
scale of autocorrelation for soil moisture depths 0-10 cm, 10-40cm and 40-100cm to confirm that
the soil moisture data demonstrate persistence lasting up to a season. The ability of soil mois-
ture to perpetuate anomalies, therefore, is a necessary but not sufficient condition for wintertime
ENSO teleconnections to impact springtime soil moisture. For this to happen, a region must have
persistence of soil moisture anomalies from winter to the spring seasons, and ENSO must have a
significant wintertime teleconnections to the region.

To estimate the potential impact of previous winter precipitation on subsequent spring soil mois-
ture we use a partial correlation analysis. The partial correlation between spring soil moisture and
previous winter precipitation with the influence of spring precipitation removed (\( \rho_{SMspPw*Psp} \)), for
instance, would be calculated as:

\[ \rho_{SMspPw*Psp} = \frac{\rho_{SMspPw} - \rho_{PwPsp} \times \rho_{PspSMsp}}{\sqrt{1 - \rho_{PwPsp}^2} \times \rho_{PspSMsp}^2} \] (3)
Where $\rho_{SMsp Pw}$ is the correlation between spring soil moisture and winter precipitation, $\rho_{PwPs}$ is the correlation between spring and winter precipitation and $\rho_{Psp SMsp}$ is the correlation between spring precipitation and soil moisture. Statistical significance ($p<0.1$) is assessed accounting for the number of variables on which the correlation is conditioned. From this analysis we infer the degree to which, in a typical year, winter precipitation anomalies persist through to spring soil moisture. To then analyze whether these relationships are relevant in ENSO years, we first translate precipitation anomalies into volumetric estimates of spring soil moisture anomalies. We use a point-wise multiple linear regression model in which spring soil moisture anomalies are regressed against antecedent winter and concurrent spring precipitation anomalies:

$$SMsp = \beta_0 + \beta_1 \cdot Pw + \beta_2 \cdot Ps + \epsilon \quad (4)$$

where $SMsp$ is the current spring soil moisture anomaly, $Pw$ is the previous winter precipitation anomaly, and $Ps$ is the current spring precipitation anomaly. The $\beta$s for each parameter indicate the relative strength of each term. Finally, we composite the volumetric estimates of spring soil moisture originating from the previous winter months’ precipitation anomalies as was done for the same-season teleconnections. By performing these three analyses rather than directly compositing spring soil moisture we are able to separate the relative impact of previous winter precipitation anomalies on spring soil moisture and confirm that observed soil moisture anomalies occur in areas with sufficient soil moisture memory, as opposed to being identified via spurious correlations between precipitation and soil moisture.

d. Crop yield anomaly analysis

We use historical yield anomalies to demonstrate that observed ENSO-yield relations are consistent with our derived teleconnections from the previous sections. These relations are analyzed
in greater detail in previous studies as referenced in Table 1. In this analysis we consider only states/provinces with an appreciable fraction of national production (>2% of production in 2010). The results are relatively insensitive to the specific threshold chosen to define major producing states. We first correlate sea surface temperature (SST) anomalies with crop yield anomalies to illustrate that the sign of the correlation is consistent with the expected biophysical responses to temperature and precipitation stresses. Yield anomalies were calculated as follows. First expected yields were calculated as the piece-wise linear trends in yield of major crop-producing states/provinces. The trends represent non-climate factors, such as technological advances, which contribute to increases in yield. Deviations from these trends are used to calculate the anomaly as a percent of expected yield, which is correlated with the Niño 3.4 index. The significance (p<0.1) of the correlations is evaluated following the methods of Ebisuzaki (1997) to account for serial correlation in the data. The final correlation coefficients in all countries are relatively insensitive to the choice of using a piece-wise linear trend (having a breakpoint at 1980) or a linear trend without breakpoints. We then aggregate these state-wise yield anomalies into distributions during each phase of the ENSO life-cycle and use a one-tailed Wilcoxon test to identify distributions that are different (p<0.1) from a distribution around zero (Wilks 2011). The choice of the nonparametric Wilcoxon test, as opposed to the normality assumed in a two-tailed t-test, makes little difference in the results.
4. Results

a. Same season teleconnections

1) South America Teleconnections

Sea surface temperature (SST) anomalies during the major flowering seasons for wheat (SON), maize (NDJ) and soybean (JFM) evolve slowly, but precipitation anomalies change sign from one season to the next. In the following sections we will analyze the complete three-year life cycle of ENSO teleconnections for SON, followed by a discussion of why the atmospheric teleconnections evolve rapidly from SON to JFM, despite SST anomalies remaining fairly constant.

(i) Wheat flowering season (SON) teleconnections

Precipitation teleconnections are most robust for the SON season (see Figs 2 for El Niño and Fig 3 for La Niña), when ENSO SST anomalies are at their maximum (see Fig 1). Peak ENSO SST anomalies are associated with a Rossby wave train originating in the tropics and radiating out to the southern tip of South America, often referred to as the Pacific South America mode, which sets up a circulation centered over southeast South America (Mo and Paegle 2001). Precipitation anomalies associated with this circulation are driven by anomalous vertical motion related to the balance between vortex stretching/compression and advection of planetary vorticity. Areas with poleward flow are associated with vortex stretching and ascent, while areas with equatorward flow are associated with vortex compression and descent. Noting the westward tilt with height of the wave trains, figures 2 and 3 indicate that areas of wetting (drying) are associated with anomalous poleward (equatorward) lower-level flow. The upper-level anticyclone centered over southeast South America during El Niño therefore results in lower-level poleward flow and wetting over major agricultural areas. This pattern reverses itself during La Niña. These results are consis-
tent with previous analyses of precipitation teleconnections over southeast South America during ENSO events (Cazes-Boezio et al. 2003; Grimm et al. 2000).

(ii) Maize and soybean flowering season (NDJ and JFM) teleconnections

Owing to the lack of teleconnections during EN -1 (see fig 2), and the similarity of teleconnections between LN 0 and LN +1 (see fig 3), we will discuss the evolution of the circulation from SON to JFM for EN 0 and LN 0 only. This seasonal progression is examined because, while the SST forcing remains of the same sign, the upper-level circulation responsible for precipitation teleconnections over southeast South America is established, persists, and dissipates between September and March.

From SON to NDJ the atmospheric circulation remains much the same for both EN 0 and LN 0 (see figures 4 and 5), but during JFM of EN 0 (LN 0) the upper-level anticyclone (cyclone) has largely dissipated (Figures 4 and 5). However, the northwesterly anomalies in El Niño years over southeast South America remain, as do the wet anomalies, although they are weaker and limited in extent. In La Niña years, on the other hand, the flow becomes primarily poleward, which leads to anomalous ascent and positive precipitation anomalies in southwest Brazil (Fig. 5).

Cunha et al. (2001) attribute negative wheat yields in El Niño years to an excess of rainfall, reduced sunshine, and an over-abundance of soil moisture – conditions favorable to the development of disease in wheat crops – while Podestá et al. (1999) demonstrate that three months later those same wet conditions are beneficial for maize, which requires considerable precipitation and soil moisture during flowering. We therefore expect that South American wheat yields will decrease in response to excess precipitation, while maize and soybean yields will increase in response to excess precipitation.
2) North America Teleconnections

The major flowering season for winter wheat in North America is April, May and June (AMJ). The AMJ season coincides with boreal spring and thus the development or decay of ENSO events. Teleconnections at this time are likely to be weaker than the boreal winter teleconnections observed in the Southern Hemisphere. SST anomalies during June, July, August (JJA) – the critical season for maize and soybean – are also typically weak, providing only modest forcing for summertime teleconnections. Summer basic state flow is also less conducive to strong tropical-extratropical teleconnections (Kumar and Hoerling 1998). Nevertheless, past studies indicate that JJA teleconnections are important for crop yields (see Table 1).

The magnitude and extent of the AMJ teleconnections are limited (not shown). Precipitation teleconnections are also limited during JJA in the midwest, but patterns of lower maximum temperatures in the summer of a developing El Niño event (EN 0 (not shown), LN -1 in Fig. 6) and elevated maximum temperatures in the summer of a developing La Niña event (LN 0; Fig. 6) are clear. The regions of elevated maximum temperature anomalies are associated with anticyclonic lower-level flow (Fig. 6).

Based on these teleconnections, we expect that La Niñas will depress maize and soybean yields. Although the teleconnections are modest, the relation between maximum temperature and yield is strongly nonlinear (Schlenker and Roberts 2006, 2009; Lobell et al. 2014, 2013) and as Phillips et al. (1999) note, La Niñas tend to bring both moisture stress and elevated temperatures.
b. Lagged teleconnections

1) NORTH AMERICA TELECONNECTIONS

To evaluate whether lagged teleconnections exist, we first calculate soil moisture memory to assess whether a physical pathway for sustaining anomalies exists. We next conduct a partial correlation analysis to analyze the season-specific relations, and finally estimate the magnitude of each lagged teleconnection using a multiple linear regression analysis. As described in the Methods section, we calculated the potential soil moisture memory as the e-folding time for the damping of soil moisture anomalies in the absence of external forcing (see Fig. 7, right column). Areas with appreciable soil moisture memory, ranging from 3 months up to 6+ months, coincide remarkably well with major wheat producing regions. These results agree with those of Schubert et al. (2004), who demonstrate the relevance of soil moisture for perpetuating long-term droughts in the Great Plains.

Considering that soil moisture memory does not exceed four months in the 10-40 cm layer over most of the US, we will consider only the season immediately preceding each flowering season. For wheat we analyze the influence of mid-winter (DJFM) precipitation anomalies on spring (AMJ) soil moisture, while for soybean and maize we analyze the influence of early spring (FMAM) precipitation anomalies on summer (JJA) soil moisture.

The partial correlation analysis demonstrates that winter precipitation anomalies are significantly (p<0.1) correlated with spring soil moisture anomalies in the Southwest and also the southern Great Plains, an important wheat production area (see Fig. 7). While the DJFM correlation holds throughout the soil column, the relative importance of winter to spring precipitation for spring soil moisture increases with depth. Early spring (FMAM) precipitation anomalies are also significantly correlated with summertime (JJA) soil moisture anomalies in regions of major
maize and soybean production, although due to weak ENSO teleconnections in the early spring, the ENSO influence on summer soil moisture will be weak (not shown).

Soil moisture memory is therefore unimportant for the summer-season crops, but acts to translate ENSO-induced winter precipitation anomalies into spring growing season soil moisture anomalies (see Figures 8 and 9). Potential evapotranspiration is also lower in the spring than in the summer such that soil moisture can more adequately satisfy the water demands of wheat. As in South America, the winter precipitation anomalies co-occur with maximum SST anomalies and are related to a Rossby wave train originating in the tropics and propagating into the midlatitudes. Peak El Niños (3rd column of Fig. 8) are associated with positive precipitation anomalies in the Southwest and southern Great Plains that cause positive soil moisture anomalies to persist into the following growing season. In contrast, during peak La Niña (3rd column of Fig. 9) negative precipitation anomalies persist from winter to spring, consistently decreasing soil moisture and increasing maximum temperatures. We therefore expect that the southern Great Plains states will demonstrate a positive correlation between SST and wheat yields based on these lagged teleconnections.

2) SOUTH AMERICA TELECONNECTIONS

Owing to the strength of same-season teleconnections during the critical flowering season for wheat and maize in South America (SON and NDJ), lagged teleconnections become important only in the soybean flowering season (JFM). The soil moisture memory in South America was assessed in the same manner as that of North America. The e-folding times for soil moisture in northern Argentina, Paraguay and southern Bolivia were around three months in the 10-40 cm layer and about four months in the 40-100 cm layer, which implies sufficient memory for teleconnections to persist from early boreal winter (SOND) through to JFM (see Fig. 10). The partial
correlation analysis confirms that although the correlation with concurrent precipitation is greatest at depth in the soil column (Fig. 10, left column), there exists a non-trivial partial correlation between JFM soil moisture and previous season precipitation in the same crop-growing regions that demonstrated soil moisture memory.

Figures 11 and 12 illustrate the impact that previous season precipitation has on JFM soil moisture during composite ENSO life cycles. The precipitation forcing remains consistent from SOND into JFM during both the development of El Niño and peak El Niño (see Fig. 4). Precipitation anomalies from the previous season (SOND) therefore act to reinforce those of the current season (JFM) during the onset and peak of El Niño, resulting in significant soil moisture anomalies even when the JFM precipitation anomaly is weak.

Precipitation forcing disappears or weakly reverses sign in southeast South America during peak to decaying La Niñas (see Fig. 5) and in the year following major La Niñas (not shown). The widespread negative precipitation anomalies in Argentina and Uruguay during SOND (Figure 12, LN +1) disappears following the dissipation of the cyclonic circulation in JFM (see Fig. 5 and previous section discussion). However, the dry soil moisture anomalies persist through to total JFM soil moisture anomalies (Fig. 12, LN 0 and LN +1). Soil moisture memory may therefore be important for major soybean producing areas in Argentina, leading to positive correlations with SST.

3) LIFE-CYCLES OF TELECONNECTIONS

Life-cycles of El Niño and La Niña differ in that over the course of a three year life-cycle of a La Niña there are strong teleconnections in each of the three years, while over the equivalent three year life-cycle of an El Niño there tends to be only one or two years with appreciable teleconnections. This discrepancy arises because the strength of ENSO teleconnections are dependent upon, among
other things, the magnitude of concurrent SST anomalies (Kumar and Hoerling 1998). And while all La Niñas form following El Niños, only about half of all El Niños develop into La Niñas.

The development and decay of an El Niño event lasts nearly two years such that two major cropping seasons experience anomalies attributable to El Niño. Teleconnections occurring in EN 0 and EN +1 years tend to have opposite signs to one another. Provided that La Niñas develop following El Niños and persist for two years thereafter, there tend to be appreciable teleconnections for three major cropping seasons during a La Niña life-cycle. And because cold SST anomalies favor dry conditions in major cropping areas of both North and South America, the La Niña life-cycle forces two dry seasons and only one wet season. The southern Great Plains of North America experience wet anomalies during the winter of an El Niño, but experience dry anomalies during the preceding and following winters (see Fig. 9). In South America, wet anomalies during the peak of El Niño preceding La Niña are followed by two years of negative SSTs and dry anomalies (see Fig 3).

c. Teleconnections and yield anomalies

Following from the previous analyses, as well as a much greater body of literature detailing crops’ physiological response to precipitation and temperature anomalies during the growing season, we can infer the sign of yield anomalies attributable to El Niño and La Niña. While most crops respond intuitively to moisture and heat, it’s worth noting that drying implies opposite wheat yield variability in the Americas due to the dry North American wheat flowering months, which benefit from additional moisture, and the wet South American wheat flowering months, in which excess moisture leads to disease (Ferreyra et al. 2001).
1) NORTH AMERICA YIELDS

In the United States both maize and soybean yields correlate with flowering season SST anomalies while wheat correlates with SSTs from the previous winter (see Table 3). This is consistent with our teleconnection analysis and with previous studies on soybean (Iizumi et al. 2014) and maize (Legler and Bryant 1999; Handler 1984; Phillips et al. 1999; Wannebo and Rosenzweig 2003; Izaurralde et al. 1999), summarized in Table 1. In contradiction, Iizumi et al. (2014) find that both El Niño and La Niña events decrease maize yield in the US, although their analysis is based on only twenty years of data. Similarly, the discrepancy between our results and those of Legler and Bryant (1999) for soybean is likely a result of analysis structure. Legler and Bryant (1999) analyze spatial patterns of yield anomalies for crops during the growing season following an ENSO event. Our results indicate that for soybean and maize, yield anomalies are most strongly correlated with flowering season SST anomalies during developing ENSO events (EN 0) rather than decaying events (EN +1). This discrepancy draws attention to the importance of considering ENSO from a life-cycle perspective. There are few studies that analyze connections between ENSO and wheat in the US, but our results agree with those of Mauget and Upchurch (1999), who also come to the conclusion that US wheat yields are correlated with previous season SST anomalies.

Results for Mexico were not statistically significant in major producing regions and mixed in sign for minor production regions, as has been found in previous analyses (Dilley 1997; López et al. 2003). We similarly found no statistically significant correlations between wheat yields in Canada and tropical SST anomalies, which is somewhat in contrast to Hsieh et al. (1999) who found a tenuous linear correlation in the tropics and that both the nine highest and lowest yield
years were associated with negative SST anomalies. This discrepancy points to the complexity of the climate-crop relation in Canada, and a need for further study.

2) South America Yields

Significant correlations exist only in Argentina for wheat and soybean yield anomalies, but correlations with maize yield anomalies exist in both Argentina and Brazil. Consistent with both the location of precipitation teleconnections and with past literature (Iizumi et al. 2014), a negative correlation exists between wheat yield anomalies and El Niño in Argentina. However, maize yield anomalies in Argentina and Brazil are positively correlated with El Niño, which reflects that while precipitation is necessary during the drier NDJ months, excess precipitation in wet SON months during El Niños leads to increased plant disease for wheat. These results agree with those of Ferreyra et al. (2001), Podestá et al. (1999) and Iizumi et al. (2014) (see Table 1). The positive correlation between soybean yield anomalies in Argentina and the El Niño index from the preceding winter is consistent with Podestá et al. (1999), and reflects the combined influence of precipitation teleconnections and soil moisture memory as we demonstrated in the lagged teleconnection analysis. While Cunha et al. (2001) report results for Brazilian wheat, they do not report levels of significance.

d. Life-cycles of yield anomalies

To evaluate the magnitude and timing of the impact of ENSO on crop yields we binned yield anomalies by ENSO phase. We grouped the yield of states that are correlated with ENSO into years corresponding to phases of the El Niño and La Niña life-cycles. Doing so demonstrates that ENSO exhibits a sufficiently strong influence on growing conditions in these regions to force a progression in yield anomalies that reflect the ENSO life-cycle. The progression of yield anomaly-
lies is generally more clear during the La Niña life-cycle than the El Niño life-cycle (see Figures 13 and 14). Teleconnections in both ENSO life-cycles tend to force same-sign yield anomalies across North and South America within a cropping year.

The same-sign yield variability is attributable primarily to same-season teleconnections for maize – and therefore may be obvious from the perspective of agricultural management – but is the combined result of same-season and lagged teleconnections for wheat and soybean. As an illustration of how the phasing of teleconnections and flowering seasons leads to same-sign yield variability, we will first consider a series of yield anomalies for wheat. Following the peak of an El Niño, positive precipitation anomalies in the southern Great Plains from the previous winter force positive flowering season soil moisture anomalies (EN 1 in Fig. 8 and LN 0 in Fig 9), which increases wheat yields (AMJ 1 in Fig. 13, AMJ 0 in Fig. 14). Drier than normal conditions then develop in South America due to negative SST anomalies (LN 0, Fig 3) and force positive yield anomalies due to reduced disease (SON 1 in Fig 13., SON 0 in Fig 14). If we follow the same analysis for soybean yield anomalies during the La Niña life-cycle, same-season teleconnections force negative yield anomalies during JJA 0 and JJA 1 in the US (see teleconnections in Fig. 6, yield anomalies in Fig 14) and lagged teleconnections force negative yield anomalies in JFM 1 due to precipitation deficits from SOND 0 (see Argentina teleconnections in Fig 12 and yield anomalies in Fig 14). The comparable progression for maize is more straight-forward because it is purely same-season teleconnections that are important for yield anomalies, which are strongest during the warm phase of ENSO (JJA 0 and NDJ 0/1 in Fig 13; JJA -1 and NDJ -1/0 in Fig 14).

1) CONCLUSIONS

ENSO significantly affects crop yields in North and South America through both same-season and lagged teleconnections. Same-season temperature and precipitation teleconnections explain
ENSO’s influence on maize and soybean yields in North America as well as wheat and maize yields in South America. Soil moisture anomalies forced by previous-season precipitation teleconnections are important for wheat yields in the United States and soybean yields in Argentina.

In the United States, maize and soybean yields are positively correlated with flowering season SST anomalies while wheat yields are positively correlated with previous winter SSTs. These results are consistent with yields responding positively to increased precipitation. In the summer of a developing La Niña, teleconnections elevate maximum temperatures and decrease precipitation over major crop producing regions of the United States such that they negatively affect maize and soybean yields. Wheat yields are primarily affected by wintertime teleconnections from the previous season when ENSO exhibits a much stronger influence on precipitation. Soil moisture memory in the United States acts to translate ENSO-induced winter precipitation anomalies into spring growing season soil moisture anomalies, particularly in the southern Great Plains. Hence US wheat yields tend to increase following El Niño conditions in the preceding winter.

ENSO-crop correlations over southeast South America in SON and NDJ are a direct result of ENSO precipitation teleconnections overlaid on seasonal climatology. ENSO induces a circulation anomaly centered over southeast South America that forces precipitation anomalies during wheat (SON) and maize (NDJ) flowering seasons. In the relatively wet months of wheat flowering, increased precipitation leads to a higher probability of disease and decreased yields. In the drier months of maize and soybean flowering, additional precipitation likely increases yields. Correlations between El Niño and yield, therefore, are consistently negative for wheat but positive for maize. During the soybean flowering season in Argentina lagged teleconnections become important. Soil moisture memory in parts of Argentina sustains moisture anomalies from SOND into JFM, which affects soybean yields.
An ENSO life-cycle is evident not only in SST anomalies and teleconnections, but also in a sequence of positive and negative crop yield anomalies. The pattern is more obvious in the yield anomalies forced by the La Niña life-cycle than those forced by the El Niño life-cycle. Teleconnections from both ENSO life-cycles, however, tend to impose same-sign yield anomalies across North and South America, which implies that El Niño and La Niña life-cycles can drive progressive sequences of Pan-American yield anomalies. While the magnitude of the yield anomalies forced by ENSO are often modest, the fact that these anomalies occur in major production regions means that they can have a significant effect on global markets. This information may be leveraged to improve food security not only in crop producing countries, but also in import-dependent countries and more generally used as a tool to understand variability in crop production.

Acknowledgments. This material is based upon work supported by the National Science Foundation Graduate Research Fellowship under Grant No. DGE-11-44155. RS acknowledges support from NSF award AGS-1401400. NCEP Reanalysis and GPCC data was provided by the NOAA/OAR/ESRL PSD from their website at http://www.esrl.noaa.gov/psd/. Soil moisture data used in this study was archived and distributed by the Goddard Earth Sciences (GES) Data and Information Services Center (DISC).

References


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<table>
<thead>
<tr>
<th>Region</th>
<th>Years</th>
<th>Methods</th>
<th>Crop</th>
<th>Results</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>central-east Argentina</td>
<td>1931-1996</td>
<td>DSSAT (CERES-Maize) crop model</td>
<td>maize</td>
<td>EN +, LN -</td>
<td>Ferreyra et al., 2001</td>
</tr>
<tr>
<td>central-east Argentina (Pergamino and Pilar)</td>
<td>1900-1999, 1972-1999</td>
<td>tercile analysis, correlation, PCA</td>
<td>soybean</td>
<td>LN -</td>
<td>Podesta et al., 1999</td>
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<tr>
<td>Brazil</td>
<td>1920-1997</td>
<td>composite analysis</td>
<td>wheat</td>
<td>not significant</td>
<td>Cunha et al., 2001</td>
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<tr>
<td>Global (southeast South America)</td>
<td>1984-2004</td>
<td>composite analysis</td>
<td>maize</td>
<td>EN +, LN -</td>
<td>Izumi et al., 2014</td>
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<tr>
<td>Global (Mexico, US)</td>
<td>1984-2004</td>
<td>composite analysis</td>
<td>soybean</td>
<td>EN +</td>
<td>Izaurralde et al., 1999*</td>
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<tr>
<td>Oaxaca, Mexico</td>
<td>1978-1990</td>
<td>regression analysis</td>
<td>maize</td>
<td>EN -, LN +</td>
<td>Dilley, 1997</td>
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<td>Mexico</td>
<td>1960-1989</td>
<td>EPIC crop model, composite analysis</td>
<td>maize</td>
<td>EN +/-, LN +/-</td>
<td>Lopez et al., 2001*</td>
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<td>United States</td>
<td>-</td>
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<td>maize</td>
<td>LN -</td>
<td>Legler et al., 1999*</td>
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<tr>
<td>United States</td>
<td>1868-1982</td>
<td>regression analysis</td>
<td>maize</td>
<td>EN +, LN -</td>
<td>Handler, 1984</td>
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<tr>
<td>United States</td>
<td>1950-1995</td>
<td>lagged regression analysis and DSSAT (CERES-Maize) crop model</td>
<td>maize</td>
<td>LN -</td>
<td>Phillips et al., 1999</td>
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<td>United States</td>
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<td>quartile composite analysis</td>
<td>wheat</td>
<td>EN +, LN -</td>
<td>Mauget and Upchurch, 1999</td>
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<td>Canadian prairie</td>
<td>1960-1997</td>
<td>regression analysis, PCA of SSTs, composite analysis</td>
<td>spring wheat</td>
<td>EN+, LN +/-</td>
<td>Hsieh et al., 1999</td>
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*these studies looked at spatial patterns, not production weighted yield anomalies
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<tr>
<th></th>
<th>North America</th>
<th>South America</th>
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<tr>
<td></td>
<td>First Season</td>
<td>Second Season</td>
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<tr>
<td>Wheat</td>
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<td>JJA</td>
</tr>
<tr>
<td>Maize</td>
<td>JJA</td>
<td>-</td>
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<td>Soybean</td>
<td>JJA</td>
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<table>
<thead>
<tr>
<th>Crop</th>
<th>Country</th>
<th>State/Province</th>
<th>Percent of National Production</th>
<th>Correlation Coefficient</th>
<th>ONI month</th>
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<td>Wheat</td>
<td>AR</td>
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<td>October</td>
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<tr>
<td></td>
<td></td>
<td>Santa Fe</td>
<td>11.5%</td>
<td>-0.30</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Santiago del Estero</td>
<td>5.1%</td>
<td>-0.34</td>
<td></td>
</tr>
<tr>
<td></td>
<td>US</td>
<td>Kansas</td>
<td>16.6%</td>
<td>0.26</td>
<td>December</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nebraska</td>
<td>3.0%</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oklahoma</td>
<td>5.5%</td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Texas</td>
<td>5.7%</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td>Maize</td>
<td>AR</td>
<td>Buenos Aires</td>
<td>35.8%</td>
<td>0.31</td>
<td>December</td>
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<td></td>
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<td>Cordoba</td>
<td>24.9%</td>
<td>0.27</td>
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<td>Santa Fe</td>
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<td>BR</td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td>Iowa</td>
<td>17.3%</td>
<td>0.24</td>
<td>July</td>
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<tr>
<td></td>
<td></td>
<td>Michigan</td>
<td>2.5%</td>
<td>0.24</td>
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<tr>
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<td></td>
<td>South Dakota</td>
<td>4.6%</td>
<td>0.23</td>
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<tr>
<td>Soybean</td>
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<td>31.7%</td>
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<td>November</td>
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<td>14.0%</td>
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<td>July</td>
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<td></td>
<td>South Dakota</td>
<td>4.7%</td>
<td>0.19</td>
<td></td>
</tr>
</tbody>
</table>
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Fig. 1. Three year El Niño and La Niña composites of the Oceanic Niño Index, which is calculated as the three month running mean of sea surface temperatures in the Niño 3.4 region. Ensemble mean shown in bold. Ensemble event years (EN 0 or LN 0) in grey above each panel.

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