IMPACT OF ENSO-RELATED CLIMATE ANOMALIES ON CROP YIELDS IN THE US

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ABSTRACT

Historical daily thermal and precipitation data from selected stations across the United States are composited into climate scenarios for the three phases of ENSO: Warm Events (El Niño), Cold Events (El Viejo or La Niña), and Neutral. Using these scenarios, yields of 7 field crops were simulated using the EPIC biophysical model during the one-year period coincident with maximum SST anomalies in the equatorial Pacific. The response of simulated agricultural productivity to the ENSO-related climate-variability parameters, is presented.

A sensitivity calculation confirms the relevance of precipitation totals/medians and suggests ENSO-related yields are sensitive to changes in statistical properties characterizing precipitation distribution and occurrence. Results are spatially dependent, with the southwest and northern plains regions indicating the highest sensitivity to the inclusion of additional precipitation characteristics. The southeast yields are not as sensitive.

The yield deviations (expressed as normalized differences to neutral yields) associated with the two extreme ENSO phases (Warm Events and Cold Events) are spatially and crop dependent with ranges up to ±120%. The largest yield deviations are in the south, southwest, and northern plains. Overall, Cold Events demonstrate larger impacts in the southern regions and Warm Events have a larger impact in the north. Additionally, the notion that climate anomalies associated with Cold and Warm Events and subsequent impacts on yields should be of opposite sign (ie, linear) is not valid in many regions. For the eastern half of the US, modeled yield deviations under Warm Event conditions are nearly all less than neutral. Conversely, in the western half, results are more mixed. Under Cold Event conditions, yields in the east are enhanced in the south, but worsened in the north; while in the western half, yields have decreased in general.

The results highlight the critical role of climate and production-related data on station or county levels in quantifying the impact of ENSO climate anomalies on yields. Both the diverse nature of the ENSO-related yield deviations as well as their sensitivity to monthly frequency distribution and occurrence characteristics imply that ENSO-related *seasonal* precipitation forecasts might be beneficial for agricultural application only if details were provided regarding not only totals, but also predicted changes in temporal and spatial variability of a more comprehensive suite of characteristics.

INTRODUCTION

The tropical Pacific atmosphere-ocean phenomenon known as the Southern Oscillation can be described as a variation between normal conditions and two extreme states, Warm Events (El Niño), and Cold Events (El Viejo or La Niña). This system is commonly referred to as ENSO. The most commonly noted characteristics of ENSO are the Warm (Cold) SST's anomalies associated with El Niño (La Niña); in the eastern half of tropical Pacific basin. Because naming conventions have varied over time, in this paper we will refer simply to Warm and Cold Events. A plethora of studies have linked global anomalous climatic variability of temperature and precipitation to these anomalous SST's using a variety of approaches and datasets, e.g. Douglas and Englehart (1981), Douglas and Englehart (1981), McBride and Nicholls (1983), Ropelewski and Halpert (1986), Ropelewski and Halpert (1987), Ropelewski and Halpert (1996), Sittel (1994), Green (1996).

These climatic anomalies also have detectable signatures in other natural indicators. Streamflow anomalies in the US associated with Warm Events indicate regionally dependent patterns of precipitation increases/decreases during the subsequent year (Cayan and Webb (1992), Kahya and Dracup (1993)). There is a reduced frequency of occurrence and amount of acreage burned from naturally occurring wildfires in Florida during Warm Events (Sweetnam and Betancourt (1990), Brenner (1991), Brenner (1991), and Jones, et al. (1992)).

The ENSO-global climate connection can be explored for more practical applications. For example, ENSO-related climate anomalies during the warm phase in some regions of Africa seem related to less than normal agriculture yields (Cane, et al. (1994)). Futures pricing has also indicated the presence of an ENSO signature (Keppenne (1995)). Questions regarding potential economic value of ENSO *prediction*s on the agriculture sector are beginning to be addressed. Improving forecasting skill for predicting ENSO events (Chen, et al. (1995)) leads naturally to the exploration of mitigation alternatives. The value of an improved ENSO forecasts for agriculture in the Southeast US exceeds $100 annually (Adams, et al. (1995)). Similarly, for the entire US market, this estimate increases to exceed $200 million annually (Solow, et al. (1998)).

This is a companion paper to these latter works. The focus here is exploration of the yields associated with mean ENSO climate anomalies. In this paper, the sensitivity of yields for seven crops, as simulated by an agricultural productivity model, to ENSO-related climate anomalies identifies the geographic regions and magnitudes of ENSO-related impacts in agricultural productivity.

There are some parallels in our approach to those in the climate change community. To take advantage of the tools utilized in these climate change studies we tailor our experimental design to facilitate their usage. However, because detailed historical climate data are available, realistic estimates of ENSO-related climate anomalies can be produced without the intermediate and potentially misguided step of prediction.

We determine that yields can vary widely according to crop, location, and ENSO phase. The largest yield anomalies associated with ENSO occur in the southwest and northern plains during

Warm Events. However, there are a number of regions where anomalous yields occur in one or both extremes. The yield results are sensitive to the inclusion of higher-moment precipitation statistics and occurrence information which more completely describes ENSO-related changes of daily rain events.

The methodology to calculate the ENSO scenarios for all the climate-related input to the bio-physical model is described first. The yield model is then discussed, especially with regards to the input parameters and determination of plant production. The sensitivity of the yields to input parameterization will be addressed, with particular emphasis on the quantitative impact of daily precipitation variations. Results of this model for seven crops; cotton, corn, grain sorghum, soybeans, wheat, barley and rice, are presented with emphasis on the relation to the ENSO climate anomalies. Finally, results of the yield and sensitivity results will be addressed in light of the need for improved historical data and future ENSO impact studies.

ENSO CLIMATE SCENARIOS

Climate Data

Daily precipitation, maximum and minimum temperature data for 54 US stations for the period 1948 - 1987 are compiled, Figure 1. These stations were selected from a much larger database to achieve a balanced areal distribution and for their proximity to agriculturally significant areas.

Data for 19 of these 54 stations are from a specially selected subset (Hughes, et al. (1992)) of the base data in the monthly Historical Climatology Network (HCN) dataset (Karl, et al. (1990)). These daily data were selected for inclusion in the HCN dataset after consideration of the following: the degree to which each station maintained a constant observation time for maximum and minimum temperatures, completeness of the pre-1951 data holdings, low potential for heat island bias over time, and above average data quality (Appendix A, Karl, et al. (1990)).

The daily HCN data for these 19 stations are not adjusted or otherwise altered to correct historical artifacts or to fill in data voids as is the case with the monthly HCN data. Thus, daily HCN data and monthly HCN data do not always provide identical monthly means/totals. Daily data for the remaining 35 stations were selected from the historical records at the National Climatic Data Center.

Description of ENSO Index

Various statistical parameters (described later) are calculated from the daily data for each month at each station. Each monthly set of statistics are categorized by ENSO phase; Warm Event, Cold Event, or Neutral according to an index based on tropical Pacific sea surface temperature (SST) anomalies, i.e. is the Pacific ocean west of Galapagos warm, cold, or normal.

The particular index chosen is that from the Japan Meteorological Agency (JMA) because it selects well the known ENSO events. The index is a 5-month running mean of spatially averaged

SST anomalies over the tropical Pacific: 4°S-4°N, 150°W-90°W. If index values exceeded 0.5°C for 6 consecutive months including Oct.- Nov.-Dec (OND), the ENSO year of October through the following September is categorized as Warm Event (index values greater than +0.5°C), Cold Event (index values less than -0.5°C), or Neutral (all other values), Table 1. Comparing this selection of ENSO years to other such lists (e.g. Kiladis and Diaz (1989)), the year of 1953 was not categorized as a Warm Event in this study as the SST anomalies were weaker for this event than for the others. For the Cold Event year selections, several differences are noted: the classification of Cold Event years is less agreed upon. We chose a symmetric definition.

The specific choice of ENSO year definition, i.e., October through following September was based on prior analyses of ENSO-related climate anomalies (e.g., Sittel (1994)) where anomalies in the year following the SST anomaly maximum were indicated. Additionally, we made a decision to bracket both the winter and traditional growing seasons within the ENSO year, thus our choice of October - September. The impact of ENSO-related climate anomalies on yields in the year following the SST anomaly maximums has been demonstrated (Hansen, et al. (1998)). No doubt there is much confusion in the literature regarding the details on how many have compared agricultural statistics and ENSO climate anomalies. We provide explicit details here to insure clarity on the application of the results.

Statistical Properties

Most previous works examining ENSO-related climatic anomalies focused on monthly means (totals). A recent study suggests that variations in daily precipitation and temperature play an important role in simulated yields (Mearns, et al. (1996)). Additionally, without daily data, it is difficult to characterize changes of both monthly precipitation distribution (which are typically not normally distributed) and precipitation occurrence. We maximize utilization of information from the daily data and minimize need for assumptions.

Several mean statistical quantities were calculated subsequently for each of the 480 months for each station: mean and standard deviation of daily minimum and maximum temperature; monthly total and standard deviation of daily precipitation values; skewness of daily precipitation values; given a wet day, the probability of a wet day following (PWAW); given a dry day, the probability of wet day following (PWAD); and number of days in the month with rain (NDR). Then a canonical 12-month sequence of these mean monthly statistics is generated for each of the three scenarios, Warm, Cold, and Neutral, based on the entire described climate record. This sequence of statistics covers the ENSO year, October through the following September. Thus for Warm Event October, the 12 statistical characteristics for Octobers of 1951, 1957, 1963, 1965, 1969, 1972, 1976, 1982, and 1986 were averaged.

EPIC Yield Model

A mathematical model called EPIC (Erosion Productivity Impact Calculator) was developed to determine the relationship between soil erosion and soil productivity (Williams, et al. (1984)). EPIC simulates these processes using a daily time step function and readily available inputs. Its components include weather simulation, hydrology, erosion-sedimentation, nutrient cycling, plant growth, tillage, soil temperature, economics, and plant environmental control. EPIC has been used in numerous scientific studies for a variety of purposes and has gained popularity across disciplines in agriculture.

EPIC has the ability to simulate many different crops. A single crop growth model simulates all the crops considered. Each crop has unique values for the model parameters. The potential increase in plant growth for a day is estimated as the product of intercepted energy and a crop parameter for converting energy to biomass and is adjusted with a daylight hour function. Interception of energy (solar radiation) is estimated as a function of the crop's leaf area index. This leaf area index is simulated with equations dependent upon heat units, the maximum leaf area index for the crop, a crop parameter that initiates leaf area index decline, and five stress factors (Williams, et al. (1989))

Crop yield is calculated as above ground biomass times a harvest index. The harvest index increases as a nonlinear function of heat units from zero at planting to the optimal value at maturity. The harvest index may be reduced by high temperature, low solar radiation, or water stress during critical crop stages (Williams, et al. (1989)).

The potential biomass is adjusted daily if one of five plant stress factors is less than 1.0 using the product of the minimum stress factor and the potential biomass. The water-stress factor is computed by considering supply (soil, air, runoff) and demand (that needed for biomass production). The temperature stress factor is computed with a function dependent upon the daily average temperature, the optimal temperature, and the base temperature for the crop. The nitrogen and precipitation stress factors are based on the ratio of accumulated plant nitrogen and precipitation to the optimal values. The aeration stress factor is estimated as a function of soil water relative to porosity in the root zone.

Water stress reduces yield in EPIC by reducing accumulated biomass and reducing the harvest index. Water stress is only allowed to reduce the harvest index over the later portion of the growing season. This is consistent with findings that many crops have developmental phases (such as pollination and grain filling) in which water stress is more critical. A parameter for each crop specifies what portion of the growing season water stress is allowed to reduce the harvest index. Thus, EPIC simulates early-season water stress through accumulated biomass reduction, and mid- and late-season water stress through reductions in both components of crop yield (Bryant et al. 1992).

Accuracy of the EPIC Model

The plant growth model in EPIC has been tested throughout the U.S. and in several foreign countries. The most comprehensive work validating the ability of the EPIC model to simulate crop yields accurately was conducted by Williams, et al. (1989). In this study the model was tested with data from several locations with considerable variation in soil and weather characteristics. The authors conducted four tests in all, one of which compared measured and simulated grain yields for six crop species at 20 locations in the United States and 15 locations in other countries. EPIC's mean simulated yields were always within 7% of the mean measured yields. The standard deviations of the simulated yields were similar to the standard deviations of the measured yields but were not as close as the means. The simulated yields had smaller standard deviations than did the measured yields. The authors conclude that the simulation of crop yield by EPIC adequately predicted the response of long-term yield to various management strategies.

More recently, a study by Kiniry, et al. (1995) compared simulated cereal, oilseed and forage yields to measured yields in the northern Great Plains region of North America. Forage and cereal crops were simulated for six locations and canola was simulated for four locations. When measured yields were plotted against simulated yields, the values were generally close to a line through the origin with a slope of 1.0. Only a few simulations had large differences from the measured yields. The authors conclude that EPIC produced satisfactory simulations.

Two studies that were more cite specific compared simulated wheat, grain sorghum and corn yields to measured yields at Bushland, Texas (Steiner, et al. (1987), Bryant, et al. (1992)) . In both studies the authors conclude that the simulation model adequately reproduced the measured yields.

Finally, a very recent study by Rosenberg, et al. (1997) attempted to validate the EPIC model for the study of ENSO effects. The authors compared simulated crop yields from representative farms in North America to actual yield data averaged across crop districts or counties. The analysis utilized 17 years of historical weather and crop yields for the United States and 26 years for Canada. Their results show that the temporal agreement between actual and simulated crop yields was less than perfect. On the 9 test farms simulated, yields match rises and falls in the annual time series of historic yields in 50-88% of the years. They also observed that the EPIC model performs much better for corn than for wheat, leading to the conclusion that wheat simulations in the EPIC model are problematic - especially for warmer, more southerly climates (Rosenberg, et al. (1997)).

Additional validation work was not undertaken for this study. The number of sites and crops simulated would prohibit a validation effort at each location for each crop. However, the simulated yields were compared to state average yields in an effort to guard against gross errors in yield simulations.

Methodology of Producing ENSO-Related Yields

Crop yields are simulated for each of 48 sites examined in this study, for all four climate scenarios for seven row crops. The crops included were cotton, corn, grain sorghum, soybeans, wheat, barley and rice. An EPIC dataset consists of weather data, wind data, soil data, and crop management data for a specific location. One EPIC dataset was constructed for each site. The soil data were constructed from existing databases for each location, and were not varied by ENSO phase. For management, nitrogen was added as needed, and irrigation was not available. Planting date was allowed to vary based on heat units accumulated since the beginning of the calendar year. This last feature allows for early planting in years with warm spring weather, thus providing the opportunity for early harvest and higher yields, and delayed planting in years with cool spring weather, thus increasing the probability of a late maturing crop and a lower yield.

Each site has a corresponding representative climate station selected from the eligible 54 stations. The weather simulation component of EPIC requires daily values of precipitation, maximum temperature, minimum temperature, relative humidity and solar radiation to simulate plant development each day. The sample size of monthly climate data used to calculate the canonical (ENSO-phase specific) climate scenarios is relatively small. To simulate a wider range of potential climate variations and to provide ancillary (humidity and solar radiation) daily weather information, a stochastic weather simulator was used to generate station-dependent, and ENSO-phase specific daily weather from the canonical climate scenarios. The generator utilizes the thirteen temperature and precipitation statistical parameters calculated for each canonical month to simulate the five daily weather parameters needed by the crop growth model. Daily solar radiation and relative humidity were generated based on a climatological parameters for each station, but were modified by the weather generator based on the temperature and precipitation data inputs (e.g., reduced solar radiation is associated with precipitation).

Yields were simulated for 30 years, for each crop, for each climate scenario, for each sector of the United States where the crop could normally grow. Thus the resulting yields from the 30 years of simulation reflect not only the mean ENSO climate anomalies but also a distribution of probable weather sequences for each specific ENSO phase. These 30 years of weather simulations and resulting yields can include extreme events such as extreme temperatures or droughts/heavy rains, and certainly the occurrence of such events in the climate data would affect the climate statistics (means and distribution characteristics) but these extremes and their impacts are not addressed here and remain a subject for further exploration. Means of the 30 years of simulated yields are examined here and reflect the mean potential yields for the Cold, Warm, Neutral, and All-Year phases of ENSO at each station. From our definition of an ENSO year, yields here are from the year *following* maximum SST anomalies (ie, maximum SST anomalies occur in December).

The phase and amplitude of the climate anomalies, intersecting with the critical phases (flowering, grain filling, ripening) of plant development generates a considerable range of yield amplitudes. These intersection points fluctuate according to a variety of inputs described previously. The simulations examined here parameterize consistently these inputs in order to focus on the role of climate variability.

Climate Anomalies Associated with ENSO extremes

The US climate anomalies associated with ENSO extremes vary both in magnitude and spatial distribution (Sittel (1994) and Green, et al. (1997)). Warm events are characterized by cooler (1-2°C) wintertime temperatures in the southeast and southwest and warmer (1-3°C) temperatures in the central and northern plains states, Figure 2. The warm anomalies continue into the spring and early summer months for the north with maximum anomalies shifting to the east, but the south returns to near-normal conditions. Precipitation anomaly patterns following Warm Events indicate the gulf coast states encounter wetter (2-5 cm. per month) than normal winters and the west coast receives slightly more winter-time rain in the south (California) and less rain in the north (Washington). By the spring, the entire eastern seaboard shows increased precipitation, with the west coast (Oregon and N. California) being dry. In summer, climate impacts of Warm Events are more localized, e.g. south Texas is colder and Michigan, Minnesota are warmer than usual. Additionally, drier conditions are found along eastern coastal regions, north Texas to northern Alabama and large regions of the plains states (South Dakota, Iowa, and Wisconsin).

For Cold Events, the anomalies are sometimes reversed from those associated with Warm Events, but not everywhere. Above average wintertime temperatures (1-3°C) are present east of the Mississippi and below average temperatures (1-2°C) are seen in the west and northwest. By spring, the warmer anomalies in the east are focused in the Ohio Valley and northern Florida, Georgia, and South Carolina, and cooler temperatures are most evident in the northern plains states. Wintertime precipitation patterns associated with Cold Events show much enhancement (3-7cm per month) in the band stretching from northern Mississippi to southwest Pennsylvania, and along the Oregon and Washington coasts, but much decreased precipitation totals along the California coast. In the spring, these drier conditions in California spread inland, gulf coast regions have increased precipitation as northwest states have increased precipitation (only in western Washington). In summer, only the extreme south US and also coastal Washington are colder than normal. Illinois, Wisconsin and coastal zones in Pennsylvania, New York and New England states are warmer. Enhanced precipitation occurs in the southeast and also covers parts of Oklahoma. Dry to very dry conditions exist for parts of Texas and Louisiana as well as large areas of Iowa, South Dakota, Wisconsin, and Minnesota. Thus as suggested by these results, the climate anomalies associated with opposite phases of ENSO are not necessarily linear. For example, climate anomalies at the Florida station are nearly opposite (for Cold and Warm Events) while those in many of the states adjacent to the Great Lakes are of the same sign for both precipitation totals and temperatures for most seasons. Further evidence demonstrates that climate anomalies associated with strong Warm Events are not amplifications of normal Warm Events (Rosenberg, et al. (1997)). Indeed these findings have been show to be the case in other places such as New Zealand (Mullan (1995)).

Sensitivity of Yields to Monthly Precipitation Characteristics

While monthly precipitation totals provide a first order indication of hydrologic changes associated with ENSO, additional details regarding monthly precipitation distributions and occurrence offer a more complete picture of ENSO-related precipitation changes. The motivation is rooted in climate change analysis, where secondary statistics detailing changes of frequency and daily precipitation totals have detectable effects on yield simulations (Nonhebel (1993), Semenov and Porter (1995)). There is also evidence of linkages of mean yields over interannual time periods to frequency of rainfall (Riha, et al. (1996)).

To quantify the potential impact on yield changes of higher order precipitation characteristics associated with ENSO climate variability, two sets of yields were calculated for the cold, warm neutral, and all-year cases. Baseline yields were estimated using only monthly temperature profiles and totals as well as monthly standard deviations (other required parameters were estimated from these values). An additional set of yields, hereafter referred to as the complete scenario incorporated not only the monthly means/totals but also the corresponding monthly statistics of skewness, transitional probabilities, and number of days of rain. The yield deviations (extreme phase minus neutral normalized by all-year case) for both the baseline and complete scenarios are compared. We find yields can correspond to more or less precipitation totals, but they can also be highly sensitive to changes in distribution and occurrence characteristics. In other words the EPIC simulation model is sensitive to the higher order precipitation characteristics. The added information gives a different simulated daily rainfall pattern, thus impacting runoff, leaching, solar radiation, etc..

In referencing the baseline and complete scenario results, the discussion focuses on changes resulting from *inclusion* of the additional statistical parameters. Changes in the yield deviations resulting from this inclusion are expressed as percentage deviations from neutral year yields.

Adding complete statistics increased slightly the standard deviation of the Warm Event yield deviations (all crops and locations), indicating the additional statistics increase the likelihood of larger yield deviations. For Warm Events, the impacts of including secondary precipitation statistics are largest, in an absolute sense, for southwest and northern plains stations, e.g. Figure 3. For the northern plains stations (Montana–MT and North Dakota–ND), the complete ENSO-specific statistics increased yield deviations by a factor of 50-100% (Montana–MT corn; 117%complete, 59% baseline). In contrast, the southern California –CA station indicated (in one case a dramatic factor of 3/4) reductions of yield deviations, especially for winter crops, for the complete scenario. Increased spring precipitation totals (which resulted in yield increases exceeding 30%) during the growing season were accompanied by higher PWAW, and reduced skewness - indications that precipitation is coming in multi-day larger rainfall events, which lead to more dramatic decreases of production. In the SE (Alabama–AL, Georgia-GA, Tennessee–TN), the secondary statistics increased yield deviations by factors of one-half for winter crops (absolute yield differences are still quite small), while for spring crops the results were mixed.

Complete scenario information for Cold Events increased the frequency of occurrence of large negative yield deviations. As for Warm Events, the largest absolute changes in yield deviations are encountered in the southwest; but more specifically north Texas–TX, California, and

Washington. In northern Texas and in Oklahoma for example, the complete scenario indicated more frequent small-rain-total events and fewer sequential days of rain, which compound reduced yields resulting in even larger (negative) yield deviations. In the southeast, Cold Events yield deviations increase by up to an additional one-quarter of their magnitudes for winter crops, but decrease (exception is FL where there is a large increase) by similar amounts for summer crops. In the Michigan–MI, Wisconsin–WI region, where yield deviations are reduced during Cold Event years, these deviations generally increase when adding complete precipitation statistics, i.e. less frequent rain and a higher probability of larger daily totals.

COMPLETE–SCENARIO YIELDS

The yield deviations (difference of warm or cold phase yields from neutral yields, normalized by all-year yields) associated with the two ENSO complete scenarios (Warm and Cold) are spatially and crop dependent with ranges up to 120%. The largest values are in the southwest, and northern plains states.

With a few exceptions (primarily at southern stations), at each station yield deviations for winter crops are of the same sign as those for traditional spring to fall crops. This is true for both warm and cold events. This implies climate anomalies during both growing seasons are similar or the growing seasons coincide for more than one month. The growing seasons for winter and spring-fall crop in the northern states have spring/summer months in common. This is not the case for southern states where we note the exceptions.

For convenience we have identified regions demonstrating similar response characteristics with regards to yield deviations during ENSO events. Not all stations in this study could be associated with one of these regions, Table 2. These summaries indicate for example in the north and central plains states the ENSO related yields are often of the same sign for both Cold and Warm Events, but otherwise are generally opposite in nature (but not necessarily equal in magnitude).

Winter Crops

The impact of ENSO on U.S. climate is typically largest and most significant during the winter months. For the SW, SE, and NE/E regions Warm and Cold events elicit oppose signs for yield deviations. In contrast, the NP and ME show similarly-signed yield response to ENSO, Table 2. However, note that the amplitudes of response indicate that Cold Events have a larger impact in the SE, SW, and NE/E regions, but in the NP and ME regions, Warm Events are more important.

Marked changes of simulated yields for Warm Events for winter crops are concentrated in Texas, the southwest, and northern plains states, Figure 4. Decreased yields occur in Michigan–MI, Wisconsin–WI, Illinois–IL, South Dakota–SD in contrast to increased yields at nearby stations in Montana–MT and North Dakota–ND. Stations in this 6-state region all encounter warmer temperatures in the winter-summer period, however the striking difference in climate means between these two groups of stations occurs during the summer months where cooler temperature and precipitation anomalies occur in the Montana–MT and North Dakota–ND stations as compared to the precipitation deficiencies and warmer temperatures at the other stations. Increased yields are indicated for Arizona–AZ, southern California, and western TX. During the growing season for this region (approx. October-March) note the cooler temperatures and near normal or slightly above normal precipitation. The southernmost TX stations (Alice and Corpus Christi) have similar climate conditions, yet Alice has reduced yields while Corpus Christi has slightly better yields under Warm Event conditions. In the southeast, yields are consistently slightly below normal (except for the Florida-FL station). These depressed yields occur despite near normal or slightly above normal precipitation totals and generally cooler temperatures during the growing season.

Most significant changes (decreases of 10-25%) in winter crop yield deviations for Cold Event yields are in California and the southwest Figure 5. The Cold Event climate anomalies for this region are, cooler but drier. In TX, yields are opposite (except for northwest TX) of those for Warm Events, i.e., larger yields in the south, and smaller yields for the mid and northern TX stations. The southern TX stations do indicate large spring precipitation surpluses as compared to the other TX stations. In the southeast, yields are larger in amplitude than for Warm Events, i.e. increases of 5-10%, yet in Florida, production is lessened (10-15%). Yields for the northern states (Montana–MT, North Dakota–ND, Wisconsin–WI, and Michigan–MI) show same-sign (i.e. reduced) yields for both Warm Events and Cold Events. The linkage between ENSO-related climate anomalies and yields seems to be evident in some cases. For Clark, SD, Warm Event yields are much larger in magnitude (still negative) than for a Cold Event. Warm Events have decreased precip totals and much warmer temperatures throughout the year whereas Cold Events have slightly warmer temperatures and positive precipitation anomalies in the spring.

Spring/Summer/Fall Crops

Climate variations associated with ENSO during the summer months are not as large as those during the winter. For these crops, the NP and ME regions respond with same sign yields for both Warm and Cold events. In the south and east (SE, SW, and NE/E), Warm and Cold events lead to yield deviations with opposite signs. The mean yield deviations for the Warm Events case are notably larger than for the Cold Events case in the NP, ME and NE/E regions. However, for the SW and SE regions, Cold Events have more impact than Warm Events. Yields for corn are markedly larger than for the other spring/summer crops in NP, thus strategies for utilizing ENSO predictions for maximizing profit in this region might be easier.

The largest changes of yields for the warm case for spring/fall crops are concentrated in Texas, but other regions such as the northern plains, and eastern seaboard show consistent responses. In Texas–TX, the south (north) is dominated by increased (decreased) yields. Southern TX stations have increased yields for both cold and Warm Events, and the larger Warm Event yields can probably be linked to increased precipitation and cooler temperatures, i.e. less water and temperature stress throughout the *entire* growing period. In southern California, larger yields for Warm Events are likely the result of larger precipitation totals and cooler temperatures encountered during the growing season. In the southeast, yields are less than neutral for many of the stations in spite of larger precipitation totals yet sometimes warmer temperatures during much of the growing season. Eastern seaboard stations show reduced yields (5-20%), no doubt due to reduced (25-50%) summertime precipitation and warmer temperatures. For all stations, the correlation (significant at 5%) between corn yield deviations and monthly temperature (precipitation totals) for the warm phase peaks in July-Aug (May and July) with values of -0.27 (0.53 and 0.27) indicating the role of temperatures and moisture for these months in production. Montana–MT and North Dakota–ND stations both show increased yields whereas South Dakota–SD has large decreased yields. Climate differences between the two sets of stations are most noticeable in summer where summer precipitation totals are larger and temperatures near normal or colder for the Montana–MT and North Dakota–ND stations, in contrast to precipitation deficiencies and warmer temperatures for South Dakota–SD .

Just as for Warm Events, the largest changes of yields for Cold Events for spring/fall crops are concentrated in the southwest U.S. In TX, the extreme northern stations have reduced yields which corresponds to yearlong reduced precipitation. The mid-TX stations also indicate reduced yields, but not as large as for the northern stations, perhaps somewhat mitigated by cooler spring/summer temperatures and a few months of larger precipitation totals. The southern TX stations have increased yields, perhaps due to greater spring precipitation and cooler summer temperatures. For the Arizona station, negative yield deviations are larger than for the Warm Events case. This is not unexpected as Cold Event precipitation deficits are larger than for the Warm Events case. Reduced precipitation totals-as much as 50% less in winter/spring months-contributed to much lower yields in southern California. Yields are up (in the 5-15% range) for the cold phase in the southeast. This is confirmed by Hansen, et al. (1998).

Discussion and Summary

Using historically founded monthly mean climate conditions for the three phases of ENSO, Warm Event, Cold Event, and Neutral, yields of 7 crops were simulated during the one-year period coincident with maximum SST anomalies in the equatorial Pacific, i.e. the growing season during and following maximum SST anomalies associated with ENSO extremes. The climate variables which determined phase-specific yield deviations included minimum and maximum temperatures, precipitation totals as well as information regarding monthly distribution characteristics and rainfall occurrence.

Our results confirm the relevance of precipitation totals/medians and additionally indicate that monthly precipitation totals alone are inadequate to accurately quantify the entire spectrum of ENSO-related yield deviations. Our simulations suggest ENSO-related yield deviations are sensitive to changes in statistical properties characterizing precipitation distribution and occurrence.

The added information gives a different simulated daily rainfall pattern, and the EPIC model is sensitive to the higher order precipitation characteristics, i.e., the resulting simulated crop yield estimates are different from those obtained when the higher order characteristics were not used.

It is recognized the EPIC model oversimplifies reality. The failure of this study to consider different crop varieties as a way to manage yield differences due to anticipated weather, may over estimate yield variability. In addition, failure to fully capture the interactions of weather events at critical phases in plant development might under estimate yield variability.

Yield deviations had wide ranges, and varied considerably over a variety of spatial scales. The yields were more homogeneous in the eastern half of the US. This most likely reflects the better availability of precipitation to sustain agricultural activities. For the eastern half of the US, modeled yield deviations under Warm Event conditions are nearly all less than neutral. Conversely, in the western half, results are more mixed. Under Cold Event conditions, yields in the east are enhanced in the south, but worsened in the north; while in the western half, yields have decreased in general.

The impact of ENSO on U.S. climate is typically largest and most significant during the winter months. For winter crops, yields in the SW, SE, and NE/E regions have opposite signs for Warm and Cold events, and highlight the larger impact of Cold Events. In contrast, the NP and ME/E show similarly-signed yield response to ENSO but Warm Events have larger impact.

For spring-to-fall crops, the NP and ME regions respond with same sign yields for both Warm and Cold events, and the impact of Warm Events are notably larger. In contrast, for the southwest and southeast regions (SE, SW), Warm and Cold events lead to yield deviations with opposite signs; however, the Cold Events have more impact than Warm Events. In the NE/E, Warm and Cold events also lead to yield deviations with opposite signs, but in this case Warm Events have larger impacts.

Overall, Cold Events demonstrate larger impacts in the southern regions and Warm Events have a larger impact in the northern stations. Additionally, the notion that climate anomalies associated with Cold and Warm Events and subsequent impacts on yields should be of opposite sign (ie, linear) is not valid in many regions.

Yield deviations can vary substantially over relatively small distances. For example the two southern Texas stations are separated by only 100-km, yet yield deviations - particularly for Warm Event winter crops, were of opposite sign, even when climate anomalies were similar in sign, and to a lesser extent, magnitude. Thus it is difficult to fully interpret the impact of ENSO climate anomalies on yields without climate and production-related data on station or county levels. Additionally, the location-specific results here highlight the potential difficulties in relating ENSO-related state average yields to smaller (local) scales (e.g. Phillips, et al. (1996)).

Collective results have implications for potential ENSO-prediction applications in agriculture. In some regions yield magnitudes were very crop dependent, thus crop selection could maximize gains (or minimize potential losses) if ENSO predictions were available far enough in advance and if mitigation alternatives were quantified to such a degree as to guide accurately the decision process. Results indicate the largest impact of ENSO climate anomalies on yields would be in the southwest and northern plains regions. These are regions of relatively low precipitation totals, thus a small change in precipitation could no doubt have this effect. However, in many of these areas, water available for agricultural activities is provided through irrigation, thus lessening the immediate impact of ENSO-related climate variability (ignoring questions regarding the impacts of market pricing and long-term availability/storage of irrigation water). In regions of supplemental irrigation (e.g. southeast US) ENSO climate variability would be felt more as cropping systems typically must rely much more on precipitation rather than on irrigation.

Realizing the estimated value of improved ENSO forecasts depends to a great deal on identification of mitigation options and subsequent decisions by agricultural stakeholders to adopt alternative farm management and cropping practices. Both the diverse nature of the ENSO-related yield deviations as well as their sensitivity to monthly frequency distribution and occurrence characteristics highlighted here imply that ENSO-related *seasonal* precipitation forecasts might be beneficial for agricultural application only if details were provided regarding not only totals, but also predicted changes in temporal and spatial variability of a more comprehensive suite of characteristics. Continued development of a bias-free historical dataset of daily values or of monthly precipitation characteristics would be a welcomed contribution for further examination of this point.

Finally, expanded analysis including more stations will greatly improve the robustness of our results. Additionally planned sensitivity tests will detail the role of each variable on ENSO-related yield deviations. The results of these efforts will be reported elsewhere.

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Table 1. Table of ENSO categorization based on JMA tropical Pacific SSTA index. The year listed corresponds to the first three months of the ENSO year. For example 1948 refers to the ENSO year October 1948-September 1949.

Neutral Years	**Warm Event Years**	**Cold Event Years**
1950	1951	1947
1952	1957	1948
1953	1963	1949
1958	1965	1954
1959	1969	1955
1960	1972	1956
1961	1976	1964
1962	1982	1967
1966	1986	1970
1968		1971
1974		1973
1977		1975
1978		
1979		
1980		
1981		
1983		
1984		
1985		

Table 2. Mean/RMS variation of normalized yield deviations (in %), e.g. (Cold phase yield-Neutral yield)/All-year-yield in six regions of the US. ALL, NP, SW, SE, ME, and NE/E refer to groupings* of stations as indicated below and as illustrated in Figure 1.

	ALL-COLD	ALL-WARM	NP-COLD	NP-WARM	ME-COLD	ME-WARM	SW-COLD	SW-WARM	SE-COLD	SE-WARM	NE/E-COLD	NE/E-WARM
Winter Wheat	-1.9/10.7	1.0/16.3	10.7/13.5	17.8/22.5	-0.5/ 5.3	-7.9/ 8.8	-16.3/17.5	16.3/17.1	5.4/ 5.8	-1.6/ 3.1	3.3/ 5.9	-2.6/ 3.2
Barley	-4.2/12.7	-1.3/19.9	7.9/11.4	15.6/22.2	-3.0/ 6.6	-9.5/10.4	-18.8/19.5	11.0/11.8	7.3/ 7.4	-2.6/ 3.1	5.5/ 8.2	-2.7/ 2.8
Corn	2.1/23.2	-6.2/32.4	14.5/22.9	51.6/69.8	-10.5/13.9	-6.6/ 7.6	0.3/29.4	-1.8/38.2	4.4/ 4.9	-4.1/ 9.0	-0.8/ 4.3	-6.9/ 8.6
Soybeans	-0.5/13.0	-6.6/20.1	2.4/ 2.4	14.3/15.4	-9.0/12.8	-13.9/19.2			5.1/ 6.0	-6.0/ 9.0	-1.2/ 5.1	-10.9/12.7
Spring Wheat	-2.5/12.0	-3.7/14.8	10.1/13.9	8.00/17.5	-3.2/ 3.2	-10.1/10.1	-19.5/19.5	-1.10/1.1				
Sorghum	-2.6/12.5	-3.8/16.9	9.4/ 9.4	10.8/10.8	-6.0/ 8.2	-5.3/ 6.2	-19.7/22.3	5.50/16.2	4.5/ 5.4	-2.1/ 4.1	1.4/ 4.1	-9.0/ 9.8
Cotton	-0.7/14.2	-0.8/16.3					-20.5/22.6	6.10/12.2	4.5/ 5.3	-2.9/ 5.3	0.2/ 6.1	-8.5/10.3

*ALL all stations

NP stations in North Dakota and Montana

SW stations in California and Arizona

SE stations in Kentucky, Tennessee, Arkansas, Alabama, Georgia, and Mississippi

ME stations in Wisconsin, Michigan, Iowa, Illinois, Missouri, and South Dakota

NE/E stations in Ohio, Pennsylvania, North Carolina, Delaware, West Virginia, and Virginia.

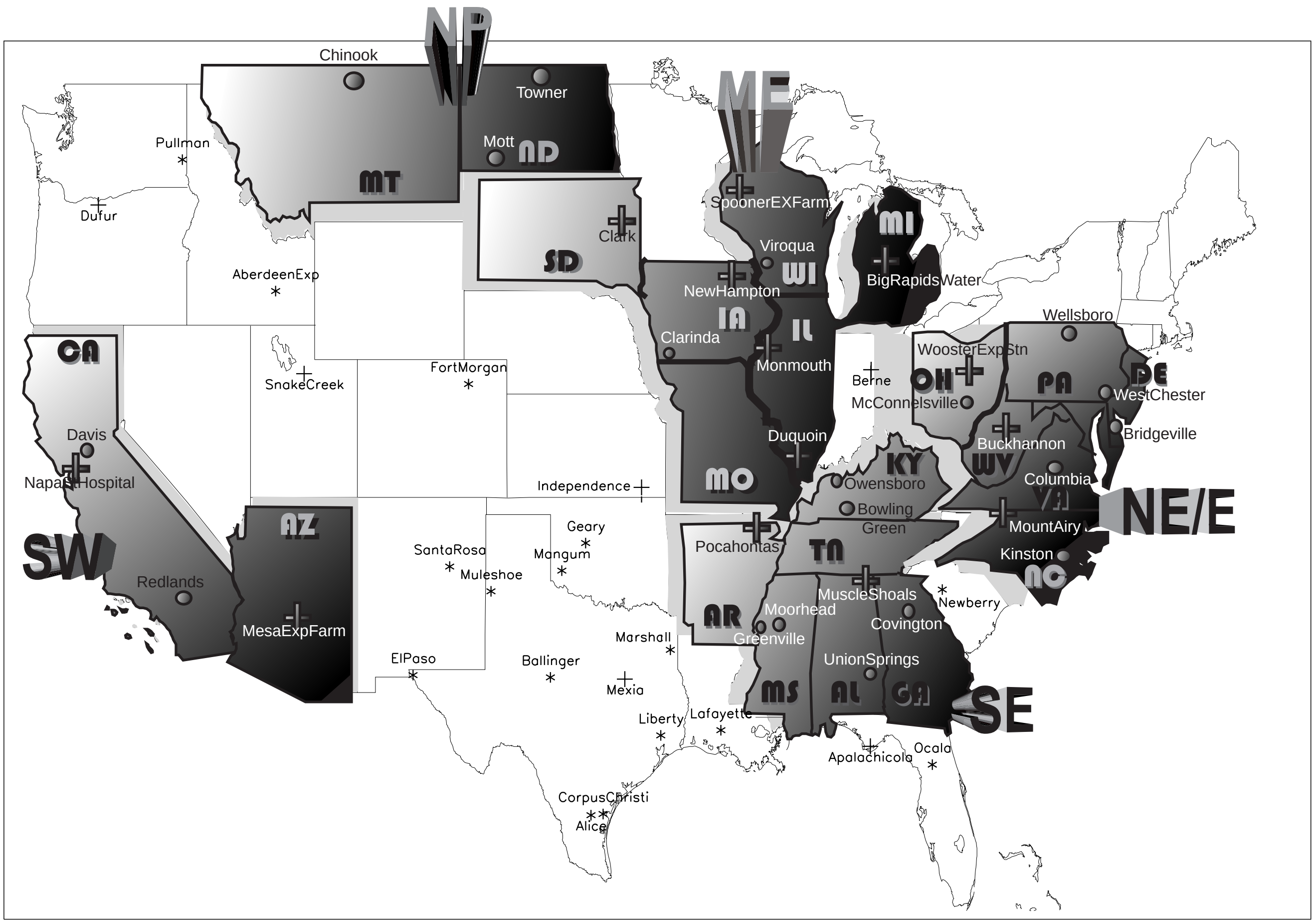
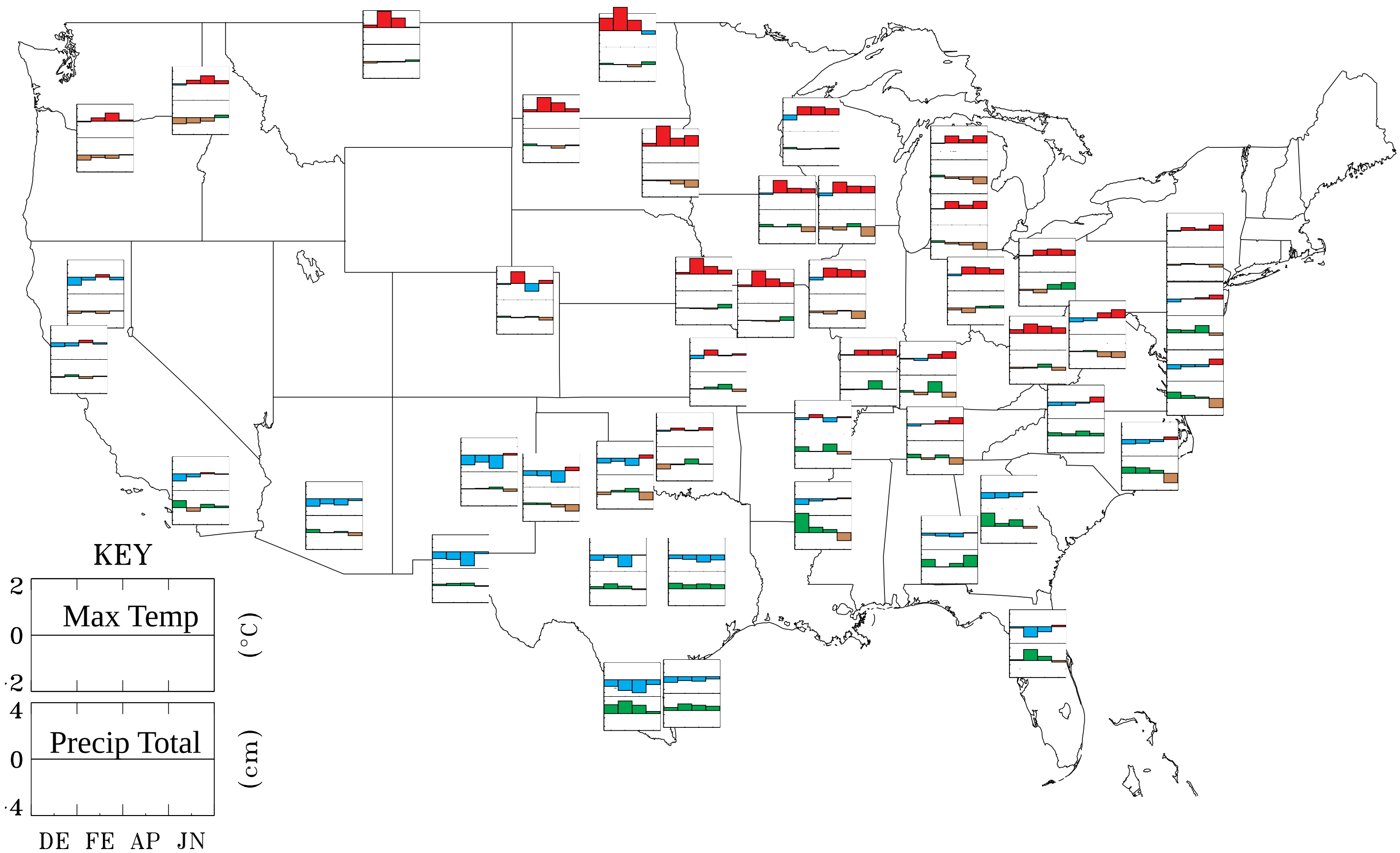


Figure 1. Location of stations where daily historical temperature and precipitation climate data are available to form scenarios for EPIC simulations (*). Stations from the HCN dataset are indicated by (+). Highlighted regions correspond to those in Table 2.



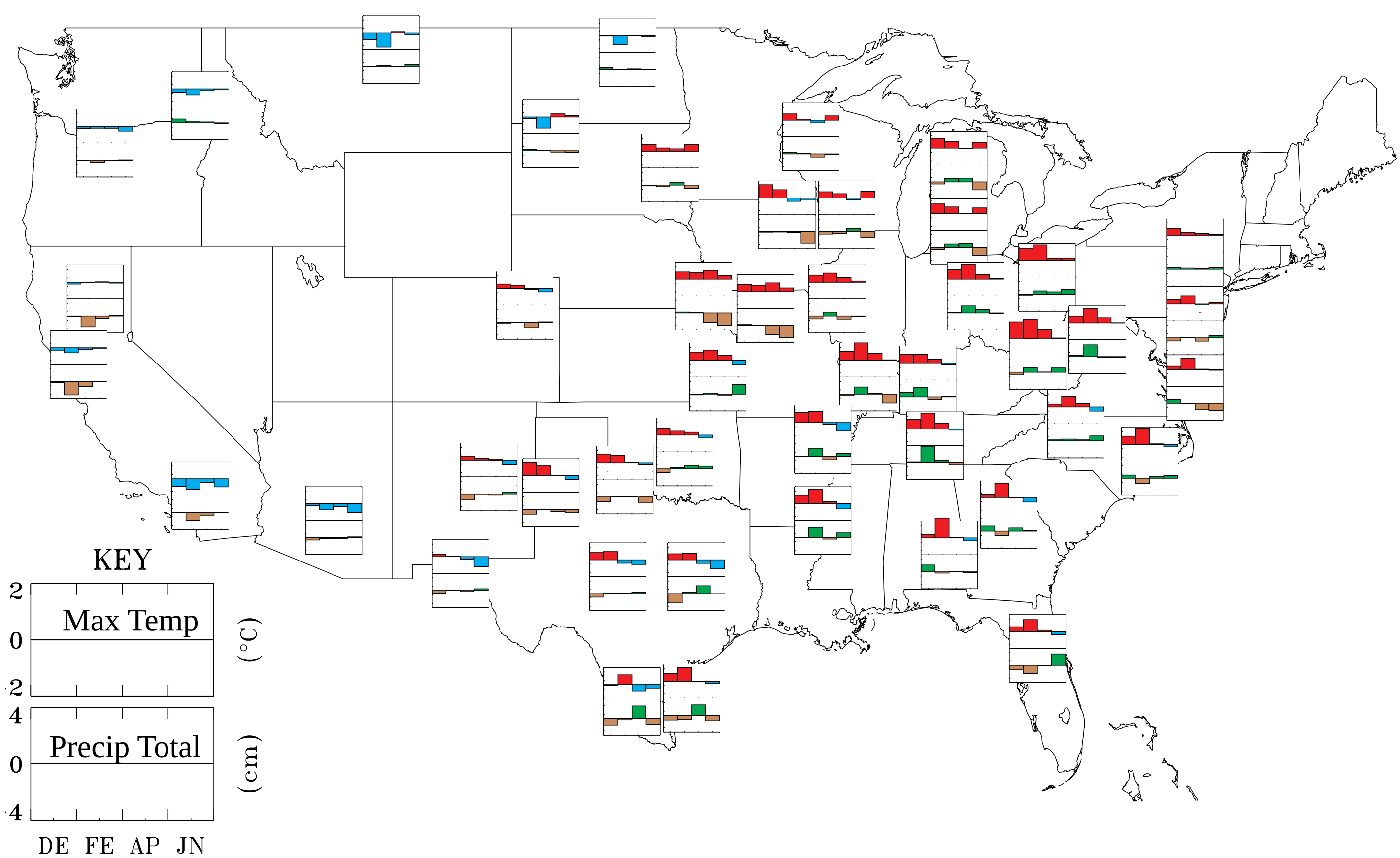


Figure 2. Mean climate anomalies (departure from neutral) of maximum temperature and precipitation totals for four 3-month seasons for Warm Events (top) and Cold Events (bottom)

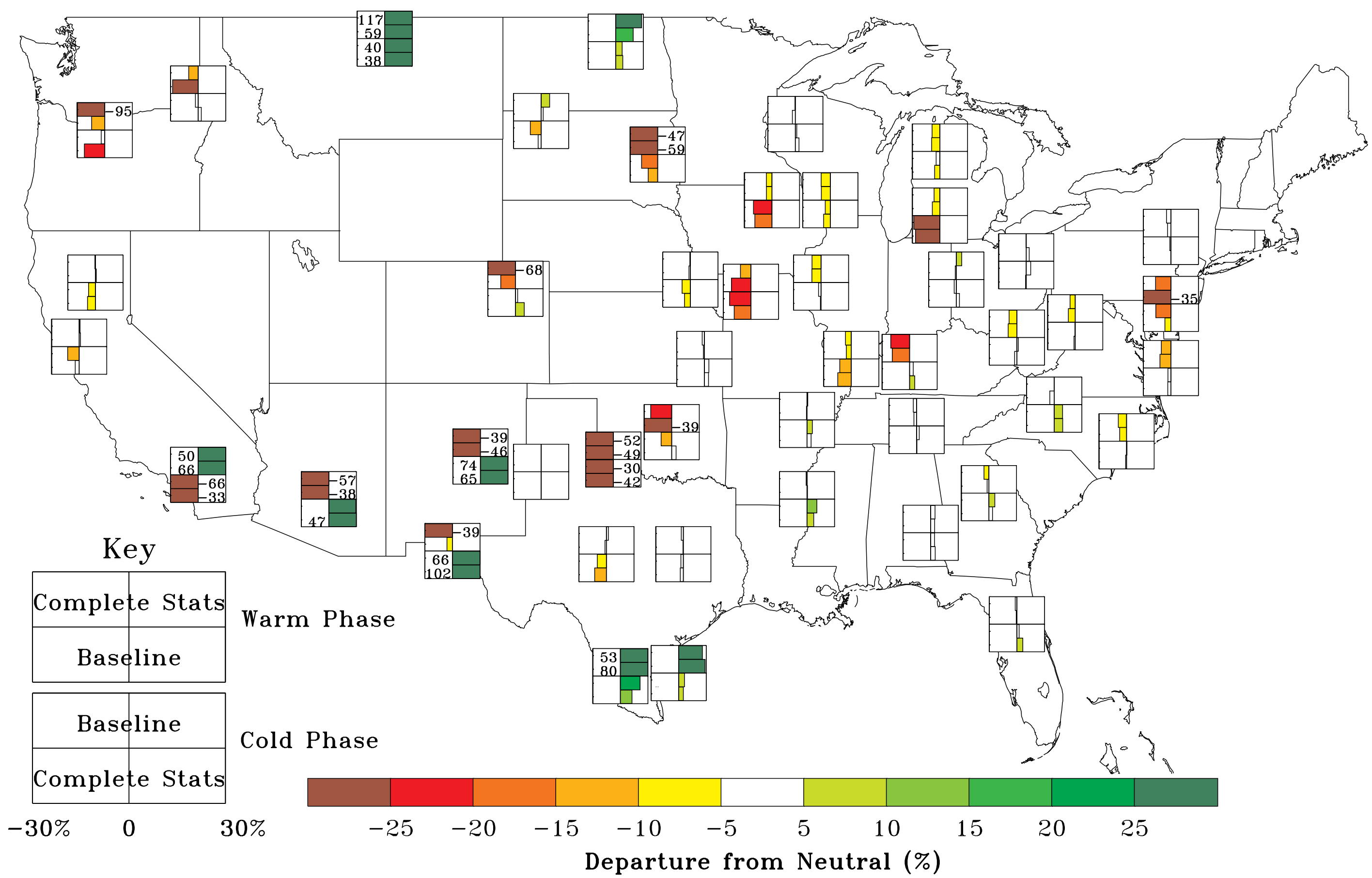


Figure 3. Crop yield deviations for corn for Warm and Cold Events (extreme phase-neutral normalized by All-Year) simulated by EPIC. Results for baseline and also complete-scenario are shown (see Key).

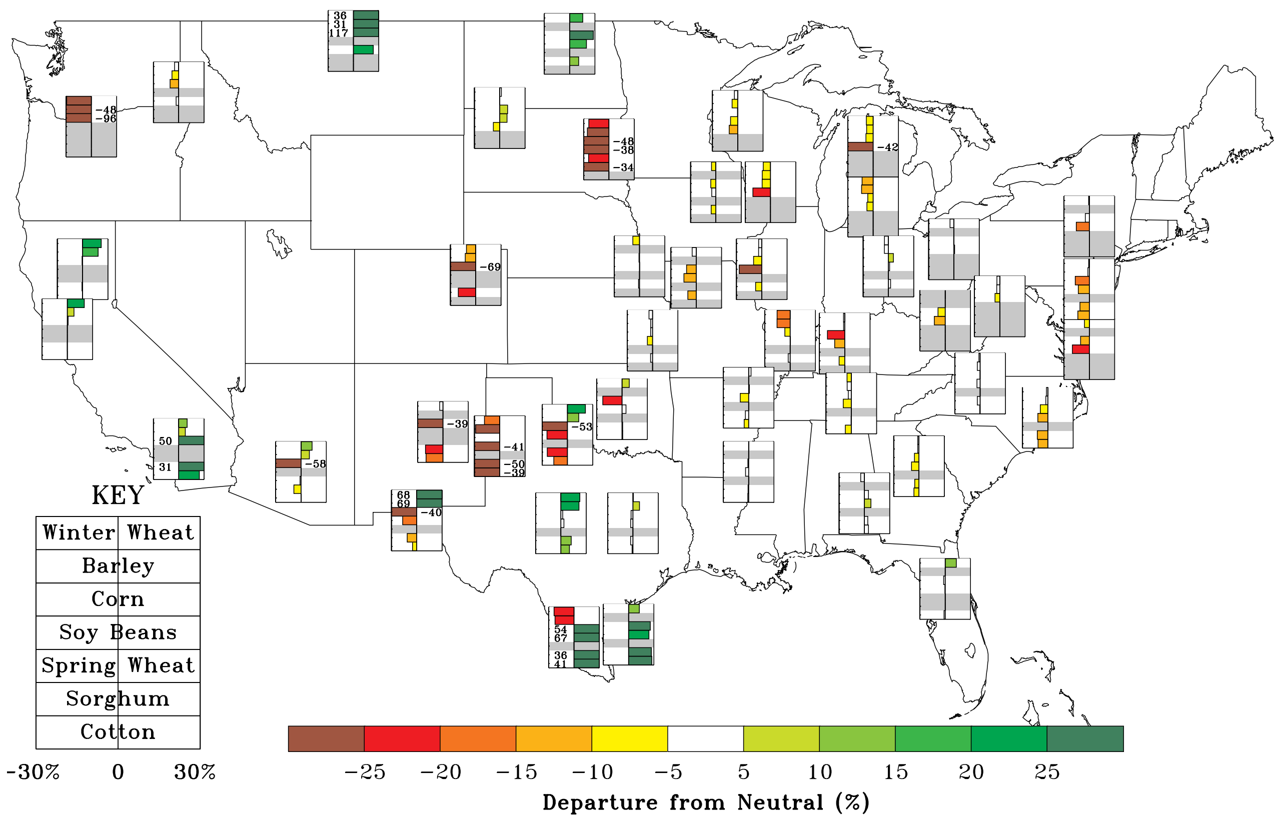


Figure 4. Crop yield deviations for Warm Events (Warm Event case-neutral normalized by All-Year) simulated by EPIC

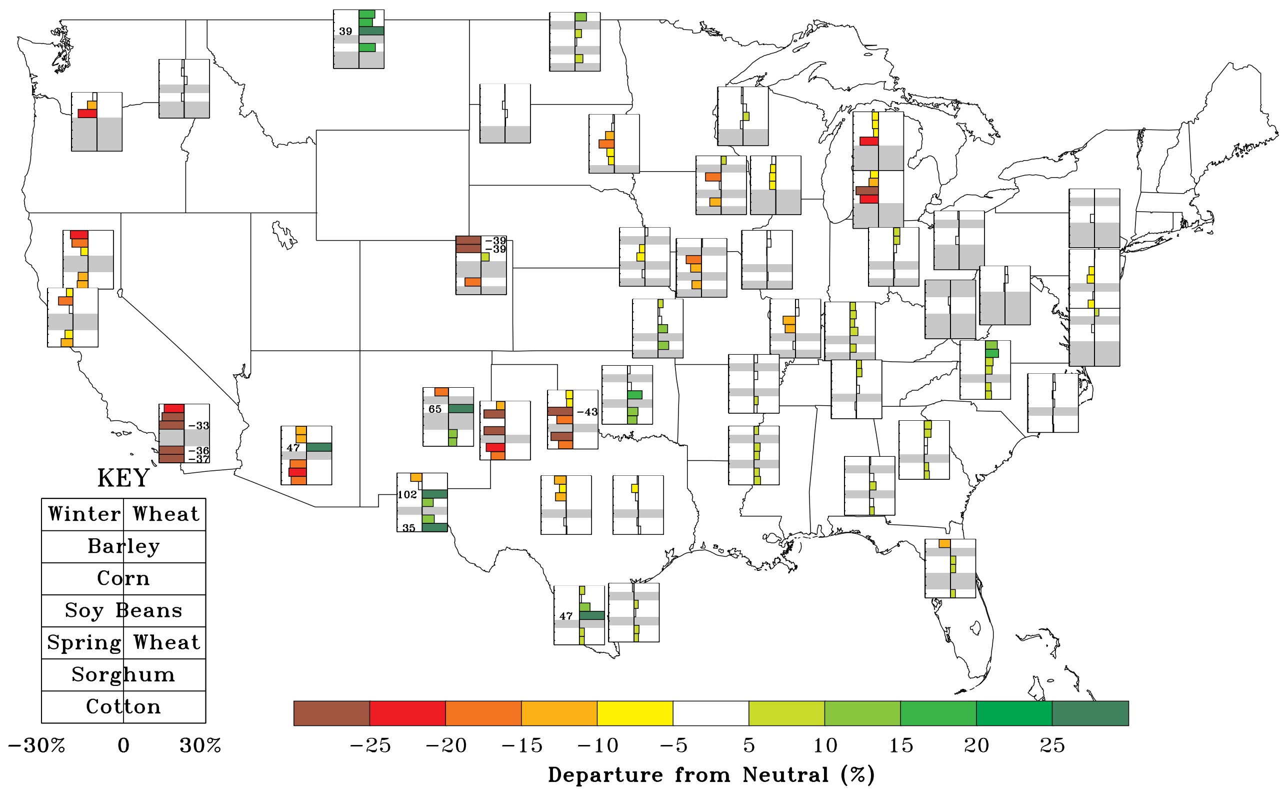


Figure 5. Crop yield deviations for Cold Events (Cold Event case-neutral normalized by All-Year) simulated by EPIC