Interactions of Mean Climate Change and Climate Variability on Food Security Extremes

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Abstract

Recognizing that climate change will affect agricultural systems both through mean changes and through shifts in climate variability and associated extreme events, we present preliminary analyses of climate impacts from a network of 1137 crop modeling sites contributed to the AgMIP Coordinated Climate-Crop Modeling Project (C3MP). At each site sensitivity tests were run according to a common protocol, which enables the fitting of crop model emulators across a range of carbon dioxide, temperature, and water (CTW) changes. C3MP can elucidate several aspects of these changes and quantify crop responses across a wide diversity of farming systems.

Here we test the hypothesis that climate change and variability interact in three main ways. First, mean climate changes can affect yields across an entire time period. Second, extreme events (when they do occur) may be more sensitive to climate changes than a year with normal climate. Third, mean climate changes can alter the likelihood of climate extremes, leading to more frequent seasons with anomalies outside of the expected conditions for which management was designed. In this way, shifts in climate variability can result in an increase or reduction of mean yield, as extreme climate events tend to have lower yield than years with normal climate.

C3MP maize simulations across 126 farms reveal a clear indication and quantification (as response functions) of mean climate impacts on mean yield and clearly show that mean climate changes will directly affect the variability of yield. Yield reductions from increased climate variability are not as clear as crop models tend to be less sensitive to dangers on the cool and wet extremes of climate variability, likely underestimating losses from water-logging, floods, and frosts.

1. The Coordinated Climate-Crop Modeling Project (C3MP)

The Coordinated Climate-Crop Modeling Project (C3MP; Ruane et al., 2014) was developed as an initiative of the Agricultural Model Intercomparison and Improvement Project (AgMIP; Rosenzweig et al., 2013) to mobilize the worldwide network of crop modeling experts for a distributed climate impact study. Participants document their crop modeling sites and then run a set of 99 sensitivity tests using climate data from the 1980-2010 period provided either by the AgMERRA climate product (Ruane et al., 2015) or local observations. Tools and protocols on www.agmip.org/c3mp facilitate the simulations and submission of results. To date 1138 simulation sets have been submitted, representing more than 50 countries, 20 crop models, and nearly 20 crop and pasture specie (McDermid et al., 2015). Additional results are still coming in, and the C3MP network has connected researchers around the world. The C3MP protocols have also been adapted by AgMIP's regional integrated assessments (Antle et al., 2015), Global Gridded Crop Model Intercomparison (Elliott et al., 2015), and AgMIP's Livestock Modeling Team.

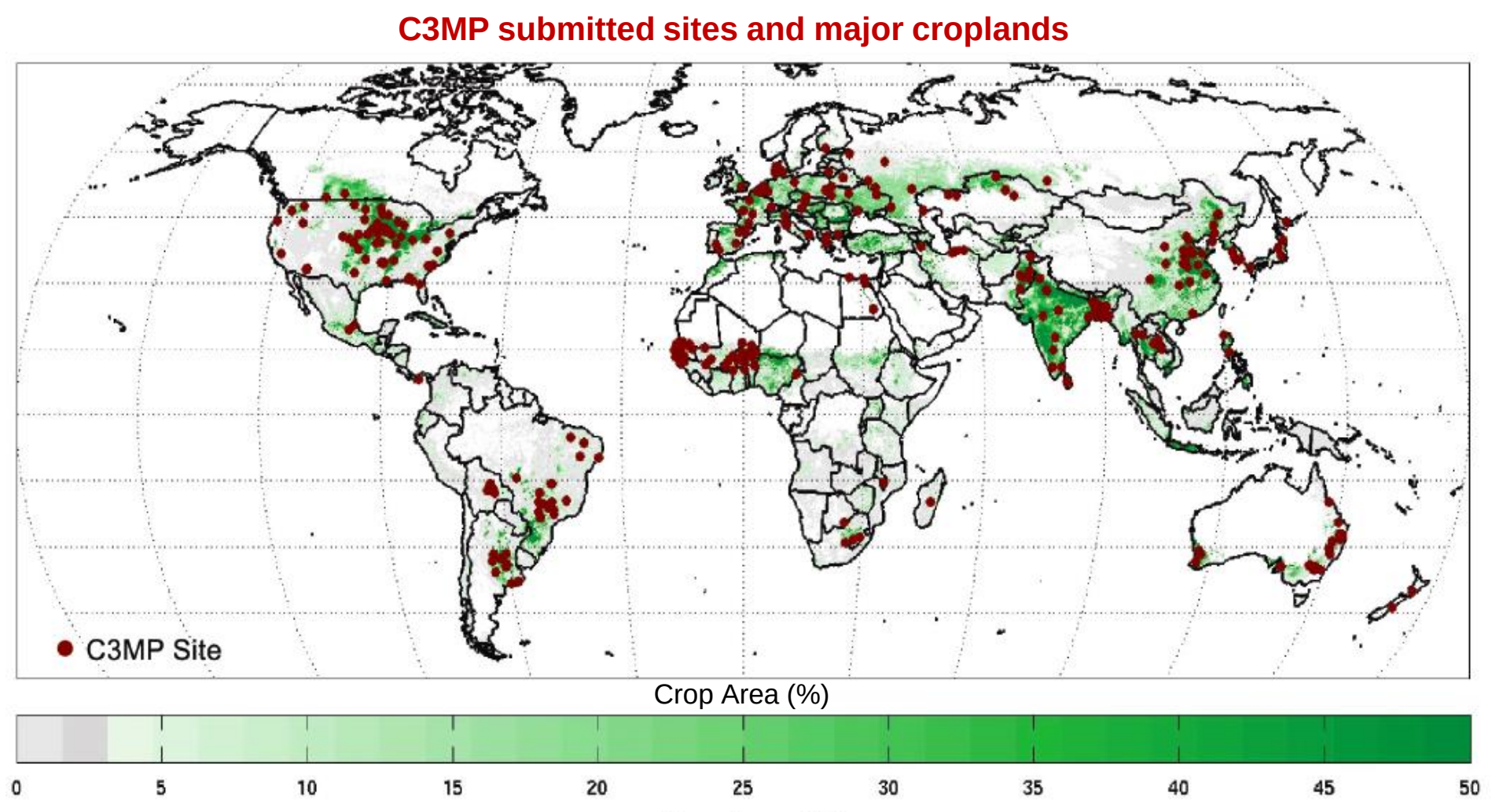


Figure 1: Sites of C3MP simulation sets (red dots) overlaid on major crop area fraction from Monfreda et al. (2008).

2. Mean Climate Change Affects Mean Yields

C3MP sensitivity tests are used to fit emulators capturing the core crop model response to a range of temperature changes (T=-1 to +8˚C), precipitation changes (P = -50 to +50%), and CO$_2$ concentrations ([CO$_2$] = 330 to 900 ppm).

- **These emulators take the form:**

$$Q(T,P,[CO_2]) = a + bT + cT^2 + dP + eP^2 + f\,[CO_2] + g\,[CO_2]^2 + h\,[T{*}P] + i\,[T{*}CO_2] + j\,[P{*}CO_2] + k\,[T{*}P{*}CO_2] \qquad (Eqn.\ 1),$$

and are similar to those used by Crimp et al. (2008), for example, but add cross terms that allow for climate factor interactions (Ruane et al., 2014). These emulators have demonstrated strong fidelity to the raw crop model sensitivity test simulations, as evidenced by correlations and RMSE (McDermid et al., 2015).

- **Crop model emulators may be visualized through impact response surfaces showing mean yield response as well as uncertainty across analyzed simulation sets (Figure 2). Across 126 rainfed maize sites there is a clear detrimental response to warmer and drier conditions, with a minor benefit from elevated [CO$_2$] (maize=C4). This quantifies the straight-forward mean yield response to mean climate change that has been the focus of most impacts assessments.**

- **Uncertainties remain large, particularly in response to temperature increases (right side of Figure 2). Uncertainty across sites can come from many sources, including: soils, cultivars, management, crop models, baseline climate conditions, and fertilizer. These results underscore that crop response to climate is not universal (Bishop et al., 2015).**

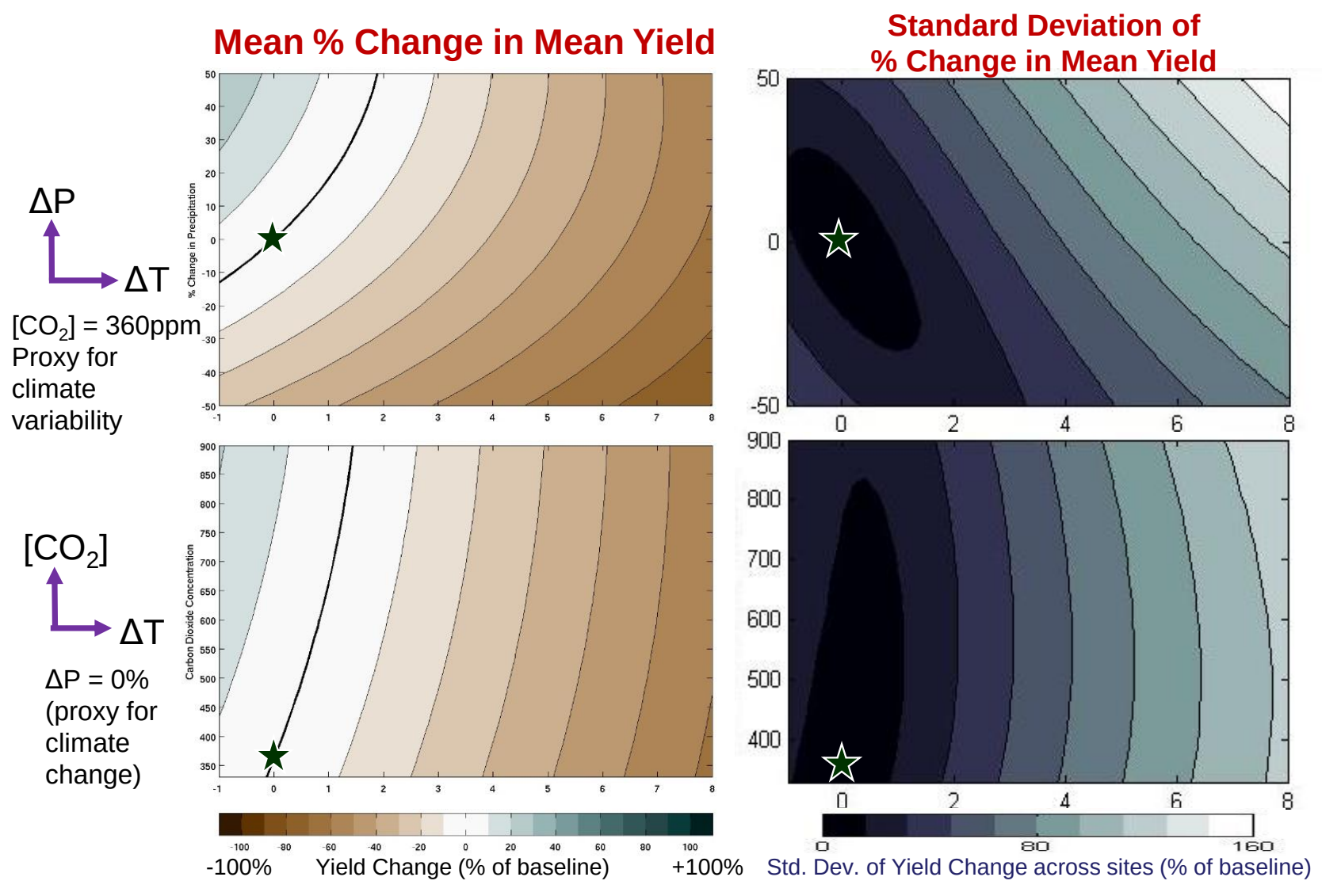


Figure 2: Impacts response surfaces describing key cross-sections of emulated CTW response space for 126 rainfed maize sites simulated by C3MP participants. (left) mean yield response (as % of 1980-2009 mean yield); (right) uncertainty represented by standard deviation across all 126 simulation sets of emulated mean yield changes for any CTW change. Stars represent 1980-2009 (~current) climate conditions. These figures are included in Mavromatis et al. (in preparation), which also examines other C3MP crops in comparison to experimental observations.

3. Global Climate Model Projections

- **Emulators derived from C3MP sensitivity tests offer a mechanism to quickly assess any new climate scenario, providing a number of climate impact metrics. Figure 3 presents projected changes in growing season temperature and precipitation in Ames, Iowa, USA, from the corresponding grid-box in 29 CMIP5 GCMs. CO2 concentrations for future periods are determined by the time period and Representative Concentration Pathway (RCP; Moss et al., 2010) as listed in Table 1. These CTW changes provide the inputs for emulators such as Eqn. 1.**

- **While the sign of precipitation change is unclear in Ames, the overall warming trend is clear. Projections show a general pattern where warmer models tend to also be drier, while relatively cooler models are wetter.**

- **As some AgMIP activities are limited by computational power and resources to analyze the huge number of possible models and scenarios that are possible (across climate/crop/economic/emissions/adaptation options), the cool/wet, cool/dry, hot/wet, hot/dry, and middle regions of projected change provide a strong basis for sub-setting the larger CMIP5 GCM ensemble. The number of GCMs in each region also can serve as a relative weight in understanding the probability of each GCM in the subset.**

- **Similar projections can also be made from regional climate models, statistical projections, and future iterations of CMIP.**

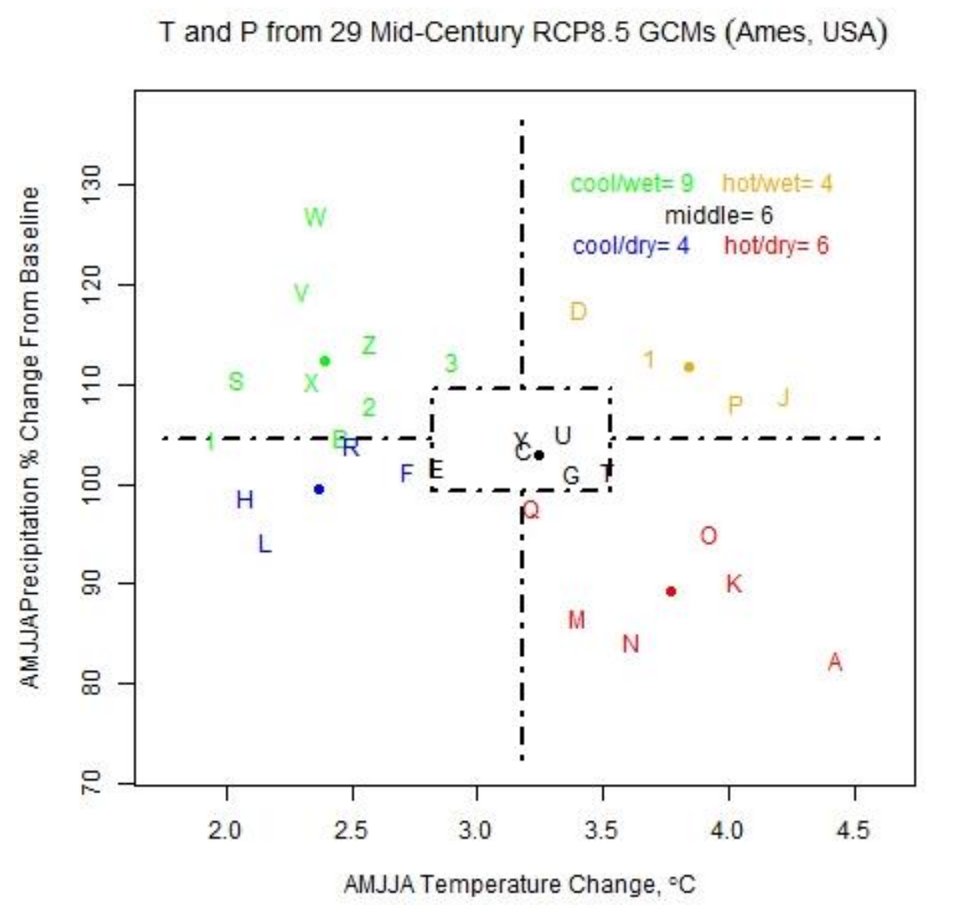


Figure 3: Projected changes in growing season temperature and precipitation for Ames, Iowa, USA. 29 CMIP5 climate models are represented as A-Z and 1-3. The climate change space has been divided into 5 regions to facilitate representative sub-setting, as is done for AgMIP regional integrated assessments in Sub-Saharan Africa and South Asia. Dots represent the mean of models within each region, and the table in the upper right indicates relative weights determined by the number of GCMs in each region.

Table 1: CO$_2$ concentrations for various future time periods and RCPs across various AgMIP activities.

Scenario and Time Period	Planting Year Coverage	Mid-year	[CO2]
Current	1980-2009	1995	360 ppm
RCP4.5 Near-term	2010-2039	2025	423 ppm
RCP8.5 Near-term	2010-2039	2025	432 ppm
RCP4.5 Mid-Century	2040-2069	2055	499 ppm
RCP8.5 Mid-Century	2040-2069	2055	571 ppm
RCP4.5 End-of-Century	2070-2099	2085	532 ppm
RCP8.5 End-of-Century	2070-2099	2085	801 ppm

4. Mean Climate Change Affects Yield During Extreme Events

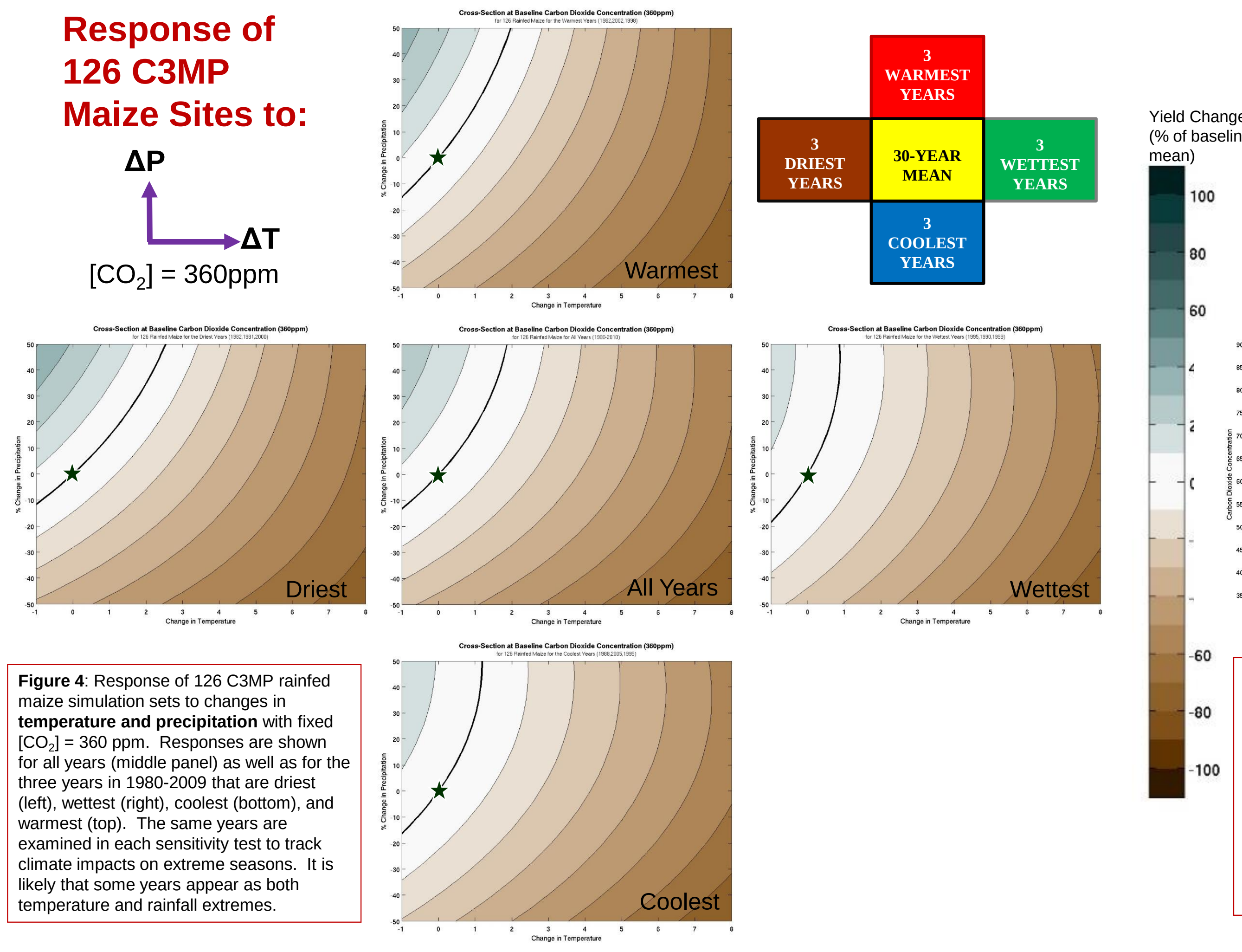


Figure 4: Response of 126 C3MP rainfed maize simulation sets to changes in **temperature and precipitation** with fixed [CO$_2$] = 360 ppm. Responses are shown for all years (middle panel) as well as for the three years in 1980-2009 that are driest (left), wettest (right), coolest (bottom), and warmest (top). The same years are examined in each sensitivity test to track climate impacts on extreme seasons. It is likely that some years appear as both temperature and rainfall extremes.

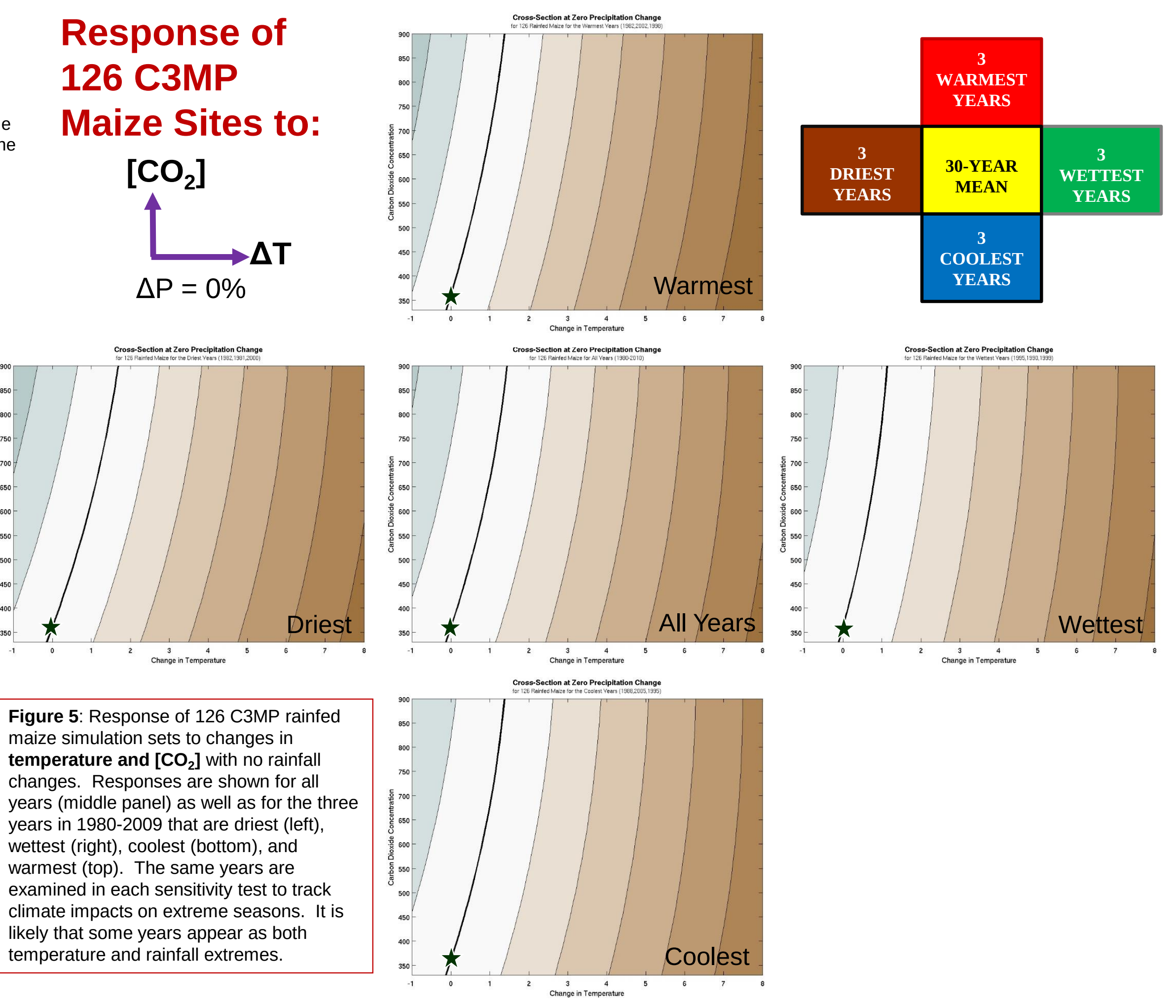


Figure 5: Response of 126 C3MP rainfed maize simulation sets to changes in **temperature and [CO$_2$]** with no rainfall changes. Responses are shown for all years (middle panel) as well as for the three years in 1980-2009 that are driest (left), wettest (right), coolest (bottom), and warmest (top). The same years are examined in each sensitivity test to track climate impacts on extreme seasons. It is likely that some years appear as both temperature and rainfall extremes.

- **Methodology: The C3MP emulator approach may also be applied to sensitivity test metrics beyond the 30-year mean yield. In the above plots we have first examined the 1980-2009 climate data for each simulation set to identify the 3 years that are warmest, coolest, driest, and wettest. These represent extreme years from the historical record. As sensitivity tests were created by imposing mean changes on historical data, these same extremes exist in each sensitivity test, allowing us to track these extreme years' yields across the entire CTW sensitivity space. By fitting an emulator to each set of extreme years we are therefore able to create impacts response surfaces for different types of years, as shown in Figures 4 and 5.**

- **Figure 4 represents the response of extreme years at 126 rainfed maize simulation sets to mean changes in temperature and precipitation. The full 30-year response surface (center) is also shown for reference.**

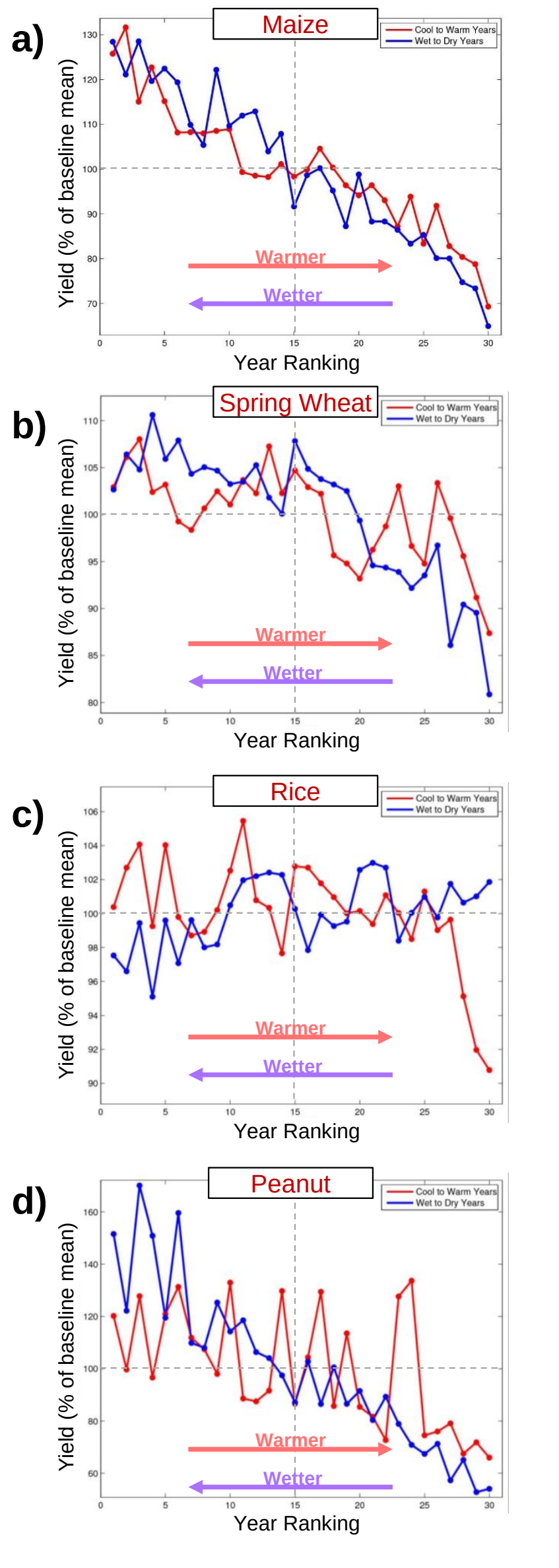
- **Results indicate that mean climate change will not affect all years equally, with years that tend to be warm and dry more dramatically affected by climate than the average year. Cool and wet years tend to have a muted response to mean climate change. Together, these responses indicate that climate changes toward warmer and drier conditions will reduce mean yield but also increase yield variability, with the most detrimental impacts occurring when future hot or dry extremes occur on top of a climate that is already trending in that direction.**

- **Figure 5 represents the response of extreme years at 126 rainfed maize simulation sets to mean changes in temperature and [CO$_2$]. The full 30-year response surface (center) is also presented for reference.**

- **Although somewhat subtle, results indicate that dry years tend to benefit more from increased CO$_2$ concentrations than do the average year. This is consistent with the experimentally-observed increase in water-use efficiency from improved stomatal gas exchanges in elevated [CO$_2$] environments. A similar benefit is seen in the warmest years' response to increased CO$_2$, as there is likely a strong correlation between hot and dry years and both heat waves and droughts increase evapotranspiration demand and resulting water stress.**

5. More Variable Climate Affects Mean Yields

- **Recent observations and modeling studies have suggested a link between climate change and an increase in variability in major agricultural regions (e.g., Francis and Vavrus, 2012). Even beyond the effects of mean climate change and interactions between climate change and extreme event impacts on crop yields, the potential of climate change to affect mean yields simply by increasing climate variability is a different dimension of impact that we explore here. As farmers weigh mean climate heavily in their selection of cultivars and management practices, anomalous years are hypothesized to produce lower yields and therefore more variable climate would reduce yields over a long period.**



- **Methodology: We examine C3MP results to see if average climate conditions really produce the highest yields with reductions in the most extreme years (as determined by ranking the 1980-2009 seasons according to rainfall and temperature).**

Rainfed Maize Response to Extremes (Fig. 6a)

- **Maize models simulate lower yields for hotter and wetter conditions, but cool and wet extremes are the best years. This may come from maize generally being grown in areas where frost during the growing season does not occur, or from shortcomings in model simulation of frost and water logging damages.**

Rainfed Spring Wheat Response to Extremes (Fig. 6b)

- **Yield in cool and wet extremes is not much different than average yields, but strong impact when hot and dry. Models may be missing frosts and water logging.**

Rainfed Rice Response to Extremes (Fig. 6c)

- **Most C3MP rice results use paddy management, so higher rainfall can be problematic due to leaching of nitrogen. Dry extremes do not seem damaging. Cool conditions are not much different than average, but warm extremes can have a large impact.**

Rainfed Peanut Response to Extremes (Fig. 6d)

- **Peanut models show a strong response to precipitation, with dry and warm conditions leading to the lowest yields. Extremely wet seasons are favorable despite known problems from pod rot when soil is saturated.**

Figure 6: Average %yield anomalies (across all C3MP simulation sets) depending on ranking of growing seasons by temperature (red line) and precipitation (blue line) for (a) maize (126 simulation sets); (b) spring wheat (53 simulation sets); (c) rice (48 simulation sets); and (d) peanut (16 simulation sets). Hypothesis of increased variability leading to decreased mean yields requires non-linearity in these responses, particularly if extremes have lower yields (on average).

6. Conclusions

The Coordinated Climate-Crop Modeling Project (C3MP) has produced a very interesting archive of 1137 simulation sets from modeled farm systems around the world. This provides an unprecedented look at climate sensitivity and uncertainties that stand in the way of a universal response function. C3MP results can be used to investigate the various ways in which mean climate change interacts with climate variability and results in impacts on agriculture.

Mean climate changes are the most studied factor in assessing impacts on agriculture, and C3MP results indicate a substantial sensitivity to changes in mean temperature, rainfall, and [CO$_2$]. The 126-member ensemble of maize simulation sets show a strong negative response to warming temperatures and drier conditions, with a benefit from elevated [CO$_2$] that is fitting for a C4 crop. Responses are non-linear and suggest that biophysical thresholds may increasingly come into play as the climate warms. Similar findings for other crops are also being evaluated by Mavromatis et al. (in prep.).

Warm and dry years are most sensitive to both the beneficial and detrimental impacts of climate change, as these are more readily pushed near the heat and water stress thresholds that reduce yields in the future. In this sense climate change will be felt in the agricultural sector most acutely when heat waves and droughts occur on top of a changing baseline of warmer and drier conditions. Preliminary evaluations also indicate that growing seasons with extreme climates have lower average yields than those that experience a typical growing season's climate, suggesting that an increase in climate variability alone would be enough to reduce mean yields over an extended period of time. Simulations likely underestimate this effect as damages from wet and cool conditions appear to be lower than expected.

7. Next Steps

Results presented here are in preparation for submission to a journal later this year. This study also suggests additional work to further understand the questions raised here:

- **Historical analysis of interannual yield distributions, with particular emphasis on non-linearities in temperature and precipitation response that may suggest anomalous years tend to have lower yields than the average year.**
- **This research will also have implications for indicator insurance programs, which often target a better balance through management of this interannual yield distribution.**

C3MP analyses are designed to enable rapid assessment of new climate scenarios in order to identify key sites that merit further study.

We are therefore planning intercomparisons and/or assessments with the following:
- **AgMIP's Regional Integrated Assessment sites in Africa and South Asia**
- **Results from the AgMIP Global Gridded Crop Model Intercomparison (which also plans to run C3MP-based tests on a global grid)**
- **C3MP response functions for integrated assessment models (IAMs) and economic models.**
- **Links to AgMIP's Coordinated Global and Regional Assessment**
- **Results from the Coordinated Regional climate Downscaling Experiment (CORDEX), which provides downscaled scenarios**
- **AgMIP crop model intercomparison team outputs and field trials**

8. Join us!

C3MP is strengthened by each additional participating scientist and contributed simulation set. We encourage crop modelers to test new sites with the C3MP sensitivity tests in order to gauge core model responses and contribute to the common archive of C3MP sites.

- **It is not too late to participate! We continue to accept results, although each published paper freezes its archive and therefore earlier submissions are likely to appear in more publications.**

- **Growth in the C3MP archive and network will increase the robustness of analyses and increase the potential for collaborations in the AgMIP community and beyond.**

- **There is currently a great amount of data in the C3MP archive and we are eager for more researchers to evaluate it. We have developed several strong paper ideas, and are willing to share the analyses and initial outlines with interested researchers and students who may have more time to pursue these ideas all the way to publication.**

For more information, visit www.agmip.org/c3mp or contact the C3MP Coordination Team at c3mp@agmip.org

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