

## Impacts of Day Versus Night Temperatures on Spring Wheat Yields: A Comparison of Empirical and CERES Model Predictions in Three Locations

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### ABSTRACT

Trends in recent temperature observations and model projections of the future are characterized by greater warming of daily minimum ( $t_{min}$ ) relative to maximum ( $t_{max}$ ) temperatures. To aid understanding of how  $t_{min}$  and  $t_{max}$  differentially affect crop yields, we analyzed variations of regional spring wheat yields and temperatures for three irrigated sites in western North America that were characterized by low correlations between  $t_{min}$  and  $t_{max}$ . The crop model CERES-Wheat v3.5 was evaluated in each site and used to project future response to temperature changes.  $T_{min}$  and  $t_{max}$  exhibited distinct historical correlations with yields, with CERES successfully capturing the observed relationships in each region. In the Yaqui Valley of Mexico, historical yields were strongly correlated with  $t_{min}$  but not  $t_{max}$ . However, CERES projections of response to increased  $t_{min}$  or  $t_{max}$  (holding other variables constant) were similar ( $\sim 6\% \text{ } ^\circ\text{C}^{-1}$ ), indicating that the apparent historical importance of  $t_{min}$  mainly results from covariation between temperatures and solar radiation and not greater direct effects of  $t_{min}$  on yields. In the San Luis-Mexicali Valley of Mexico and in the Imperial Valley of California, the opposite was observed: historical yield correlations with  $t_{min}$  and  $t_{max}$  were similar, but projected responses to  $t_{max}$  were roughly three times larger than  $t_{min}$ . The latter is explained by opposing effects of  $t_{min}$  and  $t_{max}$  on grain filling rates in CERES, with higher  $t_{min}$  increasing harvest indices. This model mechanism was not clearly supported by historical data and remains an area of uncertainty for projecting yield responses to climate change.

A POTENTIALLY IMPORTANT TRAIT of anthropogenic climate change is asymmetric warming between day and night. On a global average, daily minimum temperature ( $t_{min}$ ) has risen more than twice as fast as daily maximum temperature ( $t_{max}$ ) over the past century (Easterling et al., 1997), and most models simulate a further reduction in the diurnal temperature range ( $\text{DTR} = t_{max} - t_{min}$ ) in the next century (Dai et al., 2001).

For several reasons, the response of crop yields to temperature change may depend on the relative warming of  $t_{min}$  and  $t_{max}$  (Peters et al., 1971; Ziska and Manalo, 1996; Stone, 2001; Peng et al., 2004). Processes such as photosynthesis and transpiration are concentrated in daylight hours and therefore should be more responsive to  $t_{max}$ , whereas processes such as respiration occur throughout day and night. Crop development rates and the duration of critical phases such as grain filling may also be differentially sensitive to  $t_{min}$  and  $t_{max}$ . In ad-

dition, impacts of extreme hot or cold temperatures, such as winterkill in wheat or spikelet sterility in rice, depend on changes in daily extremes (Ziska and Manalo, 1996; Porter and Gawith, 1999).

Models capable of simulating the crop yield response to temperature and other environmental factors are useful tools to anticipate the impacts of climate change and to develop appropriate responses. Commonly used models of the major cereal crops, such as the models included in the DSSAT software (Jones et al., 2003), consider the effect of temperature on rates of several processes affecting crop yields. These processes include vernalization, crop phasic development, leaf appearance and expansion rates, photosynthesis and respiration, evapotranspiration, and grain filling (Ritchie and NeSmith, 1991; Wilkens and Singh, 2001).

Several studies have used crop models to investigate the impacts of asymmetric warming on rainfed crops in the USA. Rosenzweig and Tubiello (1996) compared the effects of  $t_{min}$  and  $t_{max}$  on winter wheat in the central USA using CERES-Wheat and found that, for identical changes in average temperatures, increasing  $t_{min}$  more than  $t_{max}$  resulted in higher simulated yields than when increasing both by equal amounts. This disparity was attributed to reduced winterkill in experiments with greater  $t_{min}$  increases. Dhakhwa and Campbell (1998), using the EPIC model for maize, soybean, and wheat in the Southeastern USA, similarly report greater simulated yields for scenarios of greater nighttime warming than for scenarios of equal day–night warming. In their case, the main mechanism responsible was reduced water stress in the asymmetric warming scenario, where lower daytime temperatures led to reduced evaporative losses.

Whether these models properly represent the separate effects of  $t_{min}$  and  $t_{max}$  has not been specifically addressed. This is primarily because historical interannual variations in growing season  $t_{min}$  are highly correlated with  $t_{max}$  in most regions. Thus, “validation” of the model by comparing yield simulations with historical records does little to elucidate the model’s ability to capture separately the responses to  $t_{min}$  and  $t_{max}$ .

However, there are some growing regions in the world for which  $t_{min}$  and  $t_{max}$  are poorly correlated historically. These provide a unique opportunity to develop understanding of  $t_{min}$  and  $t_{max}$  effects. Specifically, there are several regions where interannual correlations be-

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tween  $t_{min}$  and  $t_{max}$  for 1981 through 2002 are not significant at  $p = 0.05$  (Fig. 1). This is displayed for four different months for the  $0.5^\circ$  by  $0.5^\circ$  grid cells within the Climate Research Unit climate database (Mitchell and Jones, 2005). Although the mechanisms behind these correlations are beyond the scope of this paper, it is interesting to note that for most of the major cropping regions (e.g., Indo-Gangetic Plains, U.S. Corn Belt, Europe, and China), the correlations are typically greater than 0.8 in this dataset.

Recently, two empirical studies within regions of low correlation between  $t_{min}$  and  $t_{max}$  have suggested, in contrast to the modeling studies discussed previously (albeit in different systems), that warming of  $t_{min}$  is more harmful to yields than  $t_{max}$ . For rice in the Philippines (Peng et al., 2004) and wheat in Mexico (Lobell et al., 2005), historical yields were shown to be strongly and negatively correlated with  $t_{min}$  but very weakly correlated with  $t_{max}$ . Sheehy et al. (2006) suggested that the results of Peng et al. (2004) could be largely explained by a negative correlation between  $t_{min}$  and ra-

diation, and thus a direct effect of  $t_{min}$  on yields was not required to explain the results.

Here we examine the mechanisms behind the results reported in Lobell et al. (2005) for spring wheat in Northwest Mexico. The region of analysis has been expanded to include the Imperial Valley of California and two sites in Mexico. Specific goals were to (i) analyze the empirical relationships between  $t_{min}$ ,  $t_{max}$ , radiation, and yields in the three sites; (ii) test the ability of CERES-Wheat to reproduce these empirical relationships; (iii) use CERES-Wheat to simulate the effect of changing  $t_{min}$  or  $t_{max}$  while holding other climatic variables constant; and (iv) compare estimates of climate change impacts from CERES to those from multiple regression models based on historical data. The latter objective provides a measure of how well past empirical relationships can be used to estimate impacts of future climate change.

## MATERIALS AND METHODS

### Site Description and Data Sources

This study was conducted with data from three sites (Fig. 2). The Yaqui Valley (YV;  $27.4^\circ$  N,  $109.9^\circ$  W) is in the state of Sonora, Mexico. The San Luis/Mexicali Valley (SV;  $32.5^\circ$  N,  $114.8^\circ$  W) spans the border of Sonora and Baja California, Mexico. The Imperial Valley (IV;  $33.0^\circ$  N,  $115.4^\circ$  W) is at the southernmost edge of Imperial County, California. Total spring wheat production in 2002 was 1.08, 0.49, and 0.13 million t in YV, SV, and IV, respectively. Wheat is typically planted in late fall or early winter (November–January) and harvested in late spring (April–June). All regions have been irrigated throughout the study period (post-1980) and are heavily fertilized ( $>200$  kg N ha $^{-1}$ ) and thus achieve yields that commonly approach genetic potential. As a result, temperature and radiation

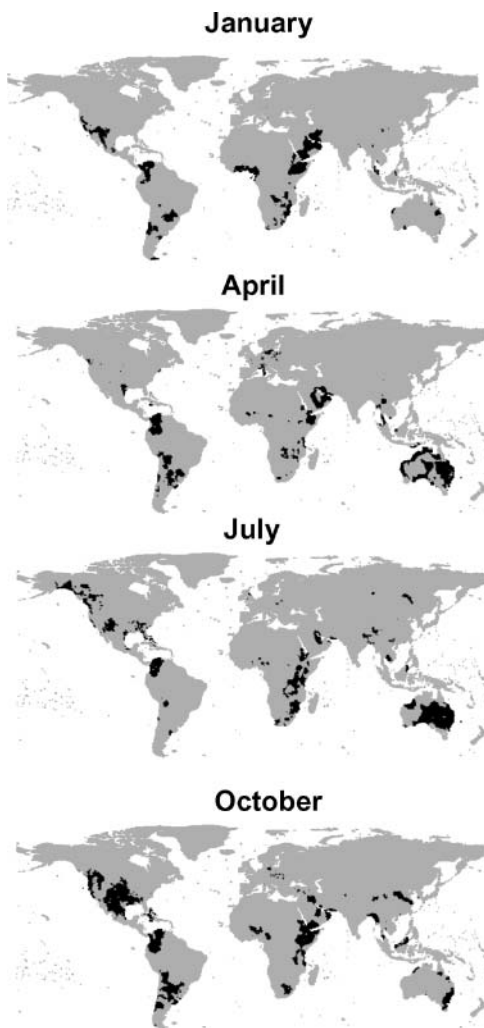


Fig. 1. Areas with nonsignificant ( $p > 0.05$ ) correlation b/w daily minimum temperature and daily maximum temperature for 1981–2002 in Climate Research Unit dataset (shown in black) for four different months.

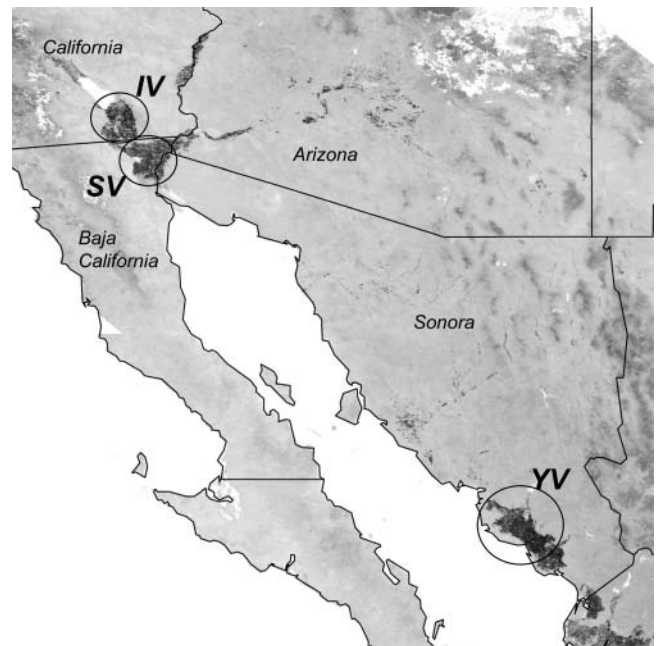


Fig. 2. Study site locations shown on an enhanced vegetation index from the Moderate Resolution Imaging Spectroradiometer image from March 2006. Dark pixels indicate higher values of enhanced vegetative index corresponding to dense vegetation, which are mostly wheat crops in this region at this time of year.

**Table 1. Study time period and growing season averages and correlations of climate variables for each site.**

Site	Years	Jan.–Apr. averages‡			Correlation		
		tmin	tmax	Rad	tmin – tmax	tmin – rad	tmax – rad
YV	1980–2004	9.7	27.3	20.9	0.09	–0.39†	0.66*
SV	1988–2004	8.5	24.9	18.8	0.40	–0.34	–0.25
IV	1985–2005	6.4	24.9	18.4	0.16	0.07	0.46*

\* Significant at  $p = 0.05$ .† Significant at  $p = 0.10$ .

‡ rad, solar radiation; tmax, daily maximum temperature; tmin, daily minimum temperature.

variations are among the major controls on average yields (Fischer, 1985).

Regional crop yield records for YV and SV were obtained from Mexican government records (Secretaría de Agricultura, 2005), and IV wheat yields were taken from USDA census records (National Agriculture Statistics Service, 2006). In YV, tmin, tmax, and daily precipitation have been measured since 1979 at an experimental station near the center of the Valley (27.4° N, 109.9° W). Solar radiation (rad) has been measured continuously only since 1998 but was extrapolated by Lobell et al. (2005) back to 1979 based on the model of Bristow and Campbell (1984). This model is based on clear sky transmissivity and DTR and performed well in the post-1998 period. Specifically, for the January–April growing season, the bias and RMSE of model predictions were  $-0.4 \text{ W m}^{-2}$  and  $2.3 \text{ W m}^{-2}$ , respectively, with a model  $R^2$  of 0.82. For SV, daily measurements since 1987 from a nearby station in Yuma, AZ (32.7° N,  $-114.7^\circ$  W) were used (<http://ag.arizona.edu/azmet>) due to the lack of long-term station data from within the Valley. For IV, daily data since 1985 measured at the Calipatria/Mulberry Station (33.0° N,  $-115.4^\circ$  W) were obtained from CIMIS ([www.cimis.water.ca.gov](http://www.cimis.water.ca.gov)). Daily values of  $ET_0$  were also available at all sites, modeled from pan evaporation (YV) or based on modified Penman equations (SV and IV).

All three sites were characterized by relatively low correlations between tmin and tmax, which allowed us to evaluate the potentially unique effects of each (Table 1). Correlations between temperatures and rad are more variable between regions. In YV, rad is negatively correlated with tmin and positively correlated with tmax, whereas tmin and tmax are negatively correlated with rad in SV and positively correlated with rad in IV. Most of these correlations were not statistically significant at  $p = 0.05$  (two-sided  $t$  test), with the exceptions of rad and tmax in YV and IV.

### CERES-Wheat

This study used CERES-Wheat version 3.5. CERES is a commonly used model for a variety of applications, including climate change impact assessments (e.g., Rosenzweig and Parry, 1994). Some of the processes discussed in this article are explicitly dependent on tmin and tmax in CERES v3.5, including crop development, photosynthesis, and grain filling

(Table 2, Fig. 3). For example, degree-day calculations in CERES v3.5 include a cap at 15°C, so that temperatures warmer than this do not affect development rates. Because daytime temperatures in all three sites are nearly always above this threshold, development rates in CERES for these sites are controlled mainly by tmin and not tmax. This sensitivity to tmin is reflected in significantly faster development for reduced DTR at a given average temperature.

Another important difference is the effect on grain filling rates. For most situations ( $t_{\text{mean}} > 10$ ), decreases in DTR increase modeled grain filling rates. Thus, tmin and tmax have opposing effects, with increases in tmin increasing grain filling rates and increases in tmax decreasing them. Simulated photosynthesis rates are also somewhat sensitive to DTR, with reduced DTR leading to higher rates for most values of average temperature.

As with nearly all process-based models, the use of CERES requires that one first calibrate several model parameters (Table 3). Here, crop parameters for YV were taken from Bell and Fischer (1994) and for SV from Lobell et al. (2005). The parameters for SV were also used in IV because the two regions are close and because data for an independent calibration of IV were not available. Crop growth was simulated without water or nutrient stress because crops in these regions were irrigated and heavily fertilized.

## RESULTS AND DISCUSSION

### Yaqui Valley

Historical relationships between January–April climatic averages and yields (Fig. 4, Table 4) indicate a roughly 10% decline in yields for each degree increase in tmin. Daily maximum temperature had an apparently negligible effect on yields, whereas yields increased roughly 10% per  $\text{MJ d}^{-2}$  of rad. CERES produced remarkably similar relationships between weather and simulated yields for 1980–2004 (Fig. 4). Average yields in CERES were higher than average reported yields because processes that cause yield losses in farmers' fields, such as disease, pest damage, or less-than-perfect harvest efficiency, were neglected in these simulations. However, the percent reductions in yield for tmin, tmax, and rad were nearly identical to those observed (Table 4).

The reduction of yield in CERES with increased tmin was associated with a shortening of growing season, with strong positive correlations between simulated yields and days to anthesis and days to maturity (Table 5). The length of the growing season simulated by CERES v3.5 is mainly sensitive to tmin because tmax values exceed the upper limit to degree-day accumulation as defined in CERES v3.5 (see Fig. 3).

These results suggested at first glance that tmin was much more important than tmax for wheat production

**Table 2. Main processes and equations in CERES-Wheat v3.5 that are explicitly dependent on minimum and maximum daily temperatures.**

Process	Equation
Crop development	Thermal time accumulation for hour $i$ : $TH_i = 0.5 \times (t_{\text{max}} + t_{\text{min}}) + 0.5 \times (t_{\text{max}} - t_{\text{min}}) \times \sin(i \times /12) - T_{\text{base}}$ $TH_i = \max(0, \min[TH_i, T_{\text{opt}} - T_{\text{base}}])/24$ ( $T_{\text{base}} = 0^\circ\text{C}$ ; $T_{\text{opt}} = 15^\circ\text{C}$ )
Photosynthesis	Phot. Reduction Factor = $1.0 - 0.0025 \times (0.25 \times t_{\text{min}} + 0.75 \times t_{\text{max}} - 18.0)^2$
Grain filling	$\text{Rate} = \begin{cases} 0.65 + 0.0787 - 0.00328 * (t_{\text{max}} - t_{\text{min}}) * (t_{\text{mean}} - 10)^{0.8} & \text{if } t_{\text{mean}} \geq 10 \\ 0.065 * t_{\text{mean}} & \text{if } t_{\text{mean}} < 10 \end{cases}$



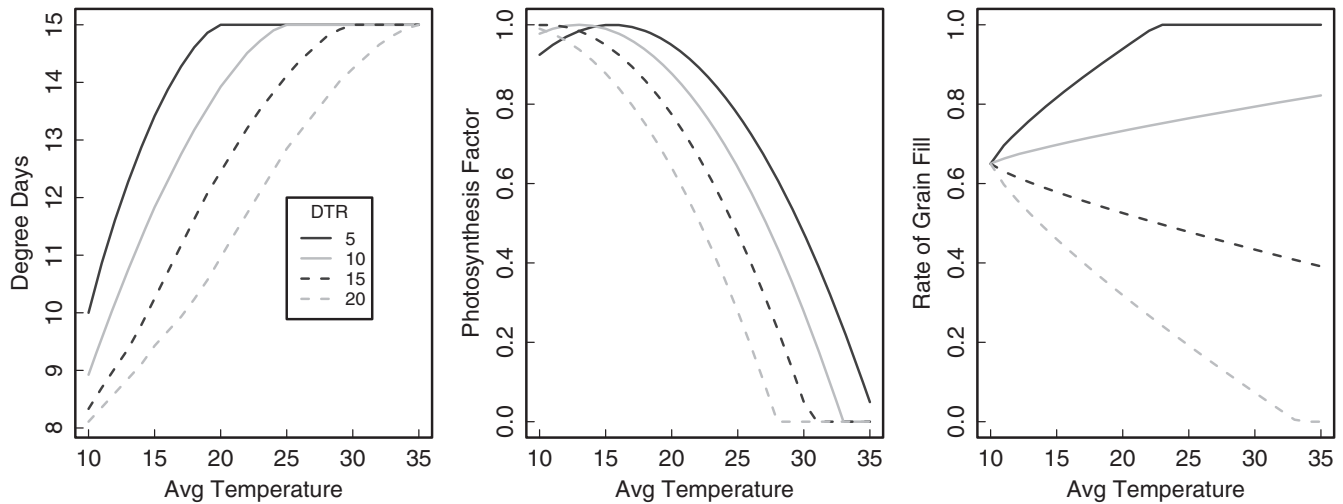


Fig. 3. The response of (a) degree day, (b) photosynthesis rate, and (c) grain filling rate calculations in CERES v3.5 to changes in average temperature and diurnal temperature range. Equations are shown in Table 2.

in YV. However, when CERES was used to simulate yields for a 1°C increase in  $t_{min}$  or  $t_{max}$ , average yields decreased by approximately 6% in both cases (Fig. 5). Thus, the model's sensitivity to  $t_{min}$  and  $t_{max}$  were similar despite the fact that the historical correlations with yields (observed and simulated) were different. This apparent paradox was explained by the fact that  $rad$  and  $t_{max}$  have been positively correlated, so that negative effects of higher  $t_{max}$  have historically been canceled by positive effects of increased solar radiation. Conversely, years with lower  $t_{min}$  tend to occur with higher  $rad$ , so that positive effects of reduced  $t_{min}$  have been augmented by greater radiation. Overall, these results were consistent with Sheehy et al. (2006), who concluded that high empirical correlations between  $t_{min}$  and yields for the data of Peng et al. (2004) could be attributed to effects of solar radiation.

One of the main differences between  $t_{min}$  and  $t_{max}$  in CERES involved the effect on grain filling rates and therefore harvest index (HI) (the fraction of biomass in grain yield). As a measure of the importance of this mechanism, the temperature sensitivities of biomass and yield were compared. Average biomass response to  $t_{min}$  ( $-7.1\% \text{ } ^\circ\text{C}^{-1}$ ) was slightly greater than to  $t_{max}$  ( $-6.4\% \text{ } ^\circ\text{C}^{-1}$ ), whereas yield sensitivity to  $t_{min}$  ( $-5.8\% \text{ } ^\circ\text{C}^{-1}$ ) was slightly lower than to  $t_{max}$  ( $-6.1\% \text{ } ^\circ\text{C}^{-1}$ ) (Fig. 5).

Table 3. Value of CERES-Wheat v3.5 model parameters used in each site.

Parameter	Description	YV†	SV	IV
P1V	modifies vernalization requirement	0.5	0.5	0.5
P1D	modifies photoperiod sensitivity	3.5	4.2	4.2
P5	modifies grain filling duration	7.0	2.0	2.0
G1	modifies kernel number	5.0	4.0	4.0
G2	modifies kernel filling rate under optimum conditions	2.0	2.0	2.0
G3	modifies stem weight	4.4	4.4	4.4
PHINT	defines the phyllochron interval, the interval in thermal time (degree days) between successive leaf tip appearances	60	75	75

† IV, Imperial Valley, California; SV, San Luis and Mexicali Valleys, Mexico; YV, Yaqui Valley, Mexico.

Thus, the effect of DTR on grain filling rates was apparent but was quantitatively not important in this region.

### San Luis/Mexicali Valley

Historical relationships between weather and yields in SV revealed similar effects of  $t_{min}$  and  $t_{max}$  (Fig. 6). The empirical effects of  $t_{min}$  ( $-8.0\% \text{ } ^\circ\text{C}^{-1}$ ) and  $t_{max}$  ( $-10.1\% \text{ } ^\circ\text{C}^{-1}$ ) were well reproduced by CERES simulations (Table 4). The empirical effect of solar radiation ( $8.8\% \text{ MJ}^{-1}$ ) was also successfully modeled by CERES ( $9.8\% \text{ MJ}^{-1}$ ). Thus, similar to the case of YV, CERES was able to capture historical yield variations and their correlation with climatic variables. Unlike YV, where the empirical effect of  $t_{min}$  dominated  $t_{max}$ , the effects of each were apparently similar in SV. Correlations between CERES variables indicated that yield reductions were less associated with days to maturity than for YV (Table 5). Yield variations in SV were also only weakly associated with changes in HI, which reflected changes in grain filling rates ( $r = 0.54$ ). Thus, of the three processes in Fig. 3, variations in photosynthesis rates seemed to be most important for yields in SV, rather than crop

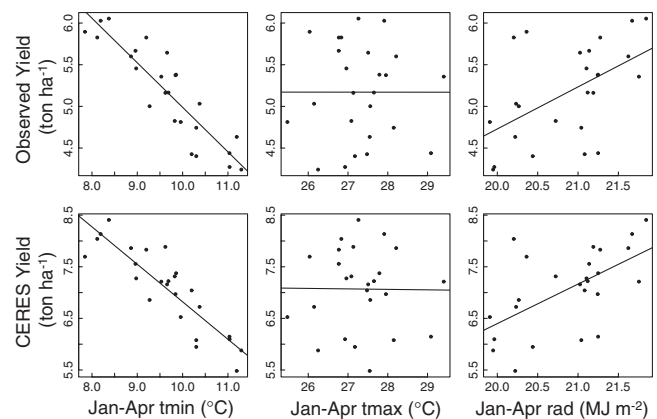


Fig. 4. January–April average daily minimum temperature ( $t_{min}$ ), daily maximum temperature ( $t_{max}$ ), and solar radiation ( $rad$ ) vs. observed (top) and CERES-simulated (bottom) yields in YV.

**Table 4. Slope of regressions between yield and growing season (Jan.–Apr.) temperatures and solar radiation for observations and CERES simulations for historical period. Slopes are given in absolute values and as percentage of average yields.**

Site†	Observations‡			CERES				
	Avg. yield	$\partial Y/\partial t_{min}$	$\partial Y/\partial t_{max}$	$\partial Y/\partial rad$	Avg. yield	$\partial Y/\partial t_{min}$	$\partial Y/\partial t_{max}$	$\partial Y/\partial rad$
YV								
t ha <sup>-1</sup>	5.17	-0.53***	0.00	0.50**	7.07	-0.73***	-0.00	0.77**
%		-10.3	0.0	9.8		-10.2	-0.0	10.8
SV								
t ha <sup>-1</sup>	5.71	-0.46	-0.57*	0.50**	7.04	-0.58	-0.63*	0.69***
%		-8.0	-10.1	8.8		-8.2	-9.0	9.8
IV								
t ha <sup>-1</sup>	6.62	-0.16	-0.33***	-0.14	7.35	-0.01	-0.54***	-0.08
%		-2.6	-5.0	-2.0		-0.2	-7.4	-1.1

\* Significant at  $p = 0.05$ .\*\* Significant at  $p = 0.01$ .\*\*\* Significant at  $p = 0.001$ .

† IV, Imperial Valley, California; SV, San Luis and Mexicali Valleys, Mexico; YV, Yaqui Valley, Mexico.

‡ tmax, daily maximum temperature; tmin, daily minimum temperature; rad, solar radiation.

development or grain filling rates. Because CERES was run without water or nutrient stress, simulated yield responses to temperatures did not involve changes in vapor pressure deficits or water stress.

Although historical correlations with tmin and tmax were similar, the CERES-simulated yield sensitivities to a 1°C increase in tmin ( $-1.8\% \text{ } ^\circ\text{C}^{-1}$ ) vs. tmax ( $-5.1\% \text{ } ^\circ\text{C}^{-1}$ ) suggested that yields in this region are more than twice as sensitive to tmax than to tmin (Fig. 7). This occurred despite nearly identical effects of tmin and tmax on biomass, indicating that simulated response of HI explained the greater impact of tmax. An important question, therefore, is how well the grain filling process was simulated in CERES.

### Imperial Valley

Historical relationships between temperatures and yields were slightly weaker in IV than in the other regions (Fig. 8, Table 4). The empirical yield response to tmin and tmax were  $-2.6\% \text{ } ^\circ\text{C}^{-1}$  and  $-5.0\% \text{ } ^\circ\text{C}^{-1}$ , respectively, and the effect of radiation was  $-2.0\% \text{ MJ}^{-1}$ . The weaker temperature effects and negative radiation effect were the result of a positive correlation between temperatures and radiation (Table 1). In particular, negative effects of temperature were partially canceled by the greater radiation levels that tended to occur in warmer years. Conversely, positive effects of radiation were overwhelmed by negative effects of increased temperatures.

CERES simulations agreed well with historical relationships, although the effect of tmin was slightly underpredicted ( $-0.2\% \text{ } ^\circ\text{C}^{-1}$ ), and that of tmax slightly

overpredicted ( $-7.4\% \text{ } ^\circ\text{C}^{-1}$ ). Yield variations in CERES were most closely associated with changes in HI (Table 5). The simulated response to changes in tmin or tmax while holding other variables constant (Fig. 9) indicated much larger effects of tmax than tmin. Yield decreases for tmax ( $-5.4\% \text{ } ^\circ\text{C}^{-1}$ ) were more than three times greater than those for tmin ( $-1.6\% \text{ } ^\circ\text{C}^{-1}$ ), suggesting that changes in DTR can be important. However, as in SV, these results depended almost entirely on a simulated effect of DTR on HI because biomass responses to tmin and tmax were nearly identical.

To determine whether the increased model sensitivity to DTR in SV and IV relative to YV was due to differences in climatic conditions or model parameters, the analysis for YV was repeated using the crop coefficients from SV. The results indicated a larger disparity between tmin and tmax effects on yields for this case (not shown) and thus demonstrated that differences in crop parameter values were responsible for the greater sensitivity to DTR. In particular, increasing P1D and PHINT and decreasing G1 each resulted in an increased difference between yield sensitivities to tmin and tmax.

### CERES Variations in Harvest Index

Harvest index is a diagnostic variable in CERES, determined only after final biomass and grain yields have been computed. There is therefore no single equation used to compute HI that can be evaluated directly. Instead, HI combines the effects of several model variables, including grain number, the temperature-dependent grain filling rate (Table 2), the genetic coefficient G2

**Table 5. Average simulated values of selected CERES variables and correlation coefficient with simulated yields. All correlations above 0.5 are significant at  $p < 0.05$ .**

Site†	Days to anthesis	Days to maturity	Grain weight	Grain no.	Biomass	Harvest index
	days		mg	grains m <sup>-2</sup>	t m <sup>-2</sup>	
YV						
Mean	75	127	43.9	16 118	12.1	0.58
Correlation with yield	0.76	0.86	-0.21	0.96	0.97	0.00
SV						
Mean	115	158	37.6	18 670	17.6	0.40
Correlation with yield	0.04	0.38	0.66	0.97	0.89	0.54
IV						
Mean	110	154	36.2	20 291	18.5	0.40
Correlation with yield	0.05	0.25	0.65	0.93	0.74	0.82

† IV, Imperial Valley, California; SV, San Luis and Mexicali Valleys, Mexico; YV, Yaqui Valley, Mexico.

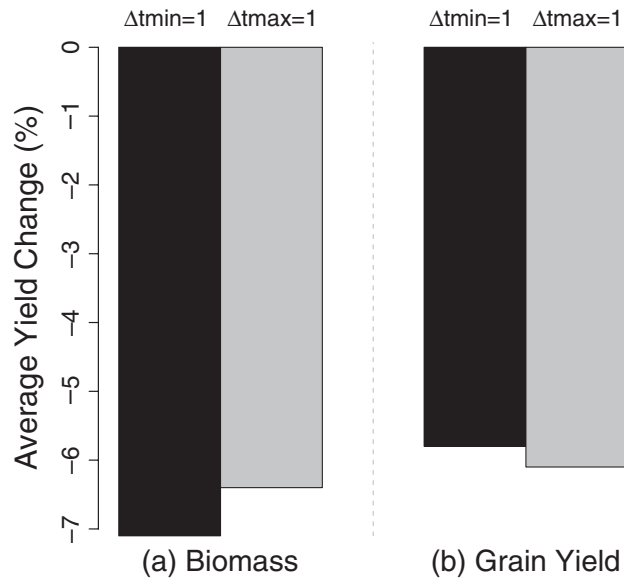


Fig. 5. CERES-simulated biomass (a) and yield (b) response to 1°C increase in daily minimum temperature ( $t_{min}$ ) or daily maximum temperature ( $t_{max}$ ) in Yaqui Valley, Mexico.

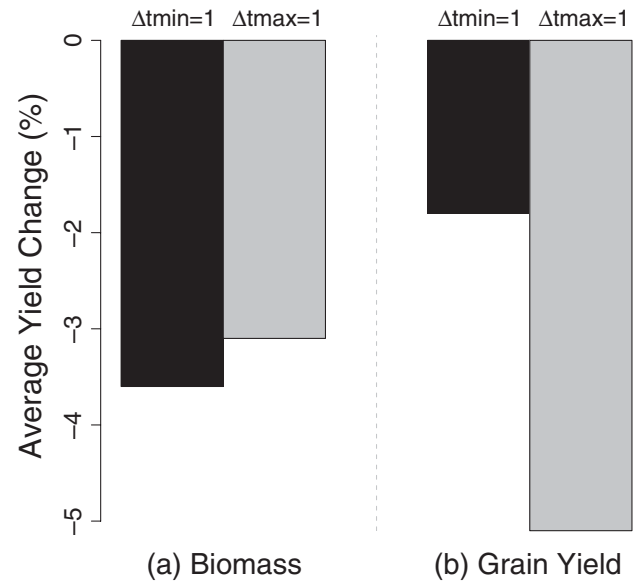


Fig. 7. CERES-simulated biomass (a) and yield (b) response to 1°C increase in daily minimum temperature ( $t_{min}$ ) or daily maximum temperature ( $t_{max}$ ) in San Luis and Mexicali Valleys, Mexico.

(Table 3), and photosynthesis rates during grain filling. To evaluate the simulation of HI in CERES, historical yields were compared with CERES-simulated values of yield and biomass (Table 6). In cases where actual yields were more highly correlated with simulated yields than biomass (YV and IV), this indicated that variations in HI simulated by CERES helped to improve model

agreement with observations compared with the use of a constant HI. This improvement thus provided some support of the treatment of HI in CERES. In contrast, in SV, agreement with historical yields was higher for simulated biomass than yields, indicating that simulation of HI changes decreased model performance at this site.

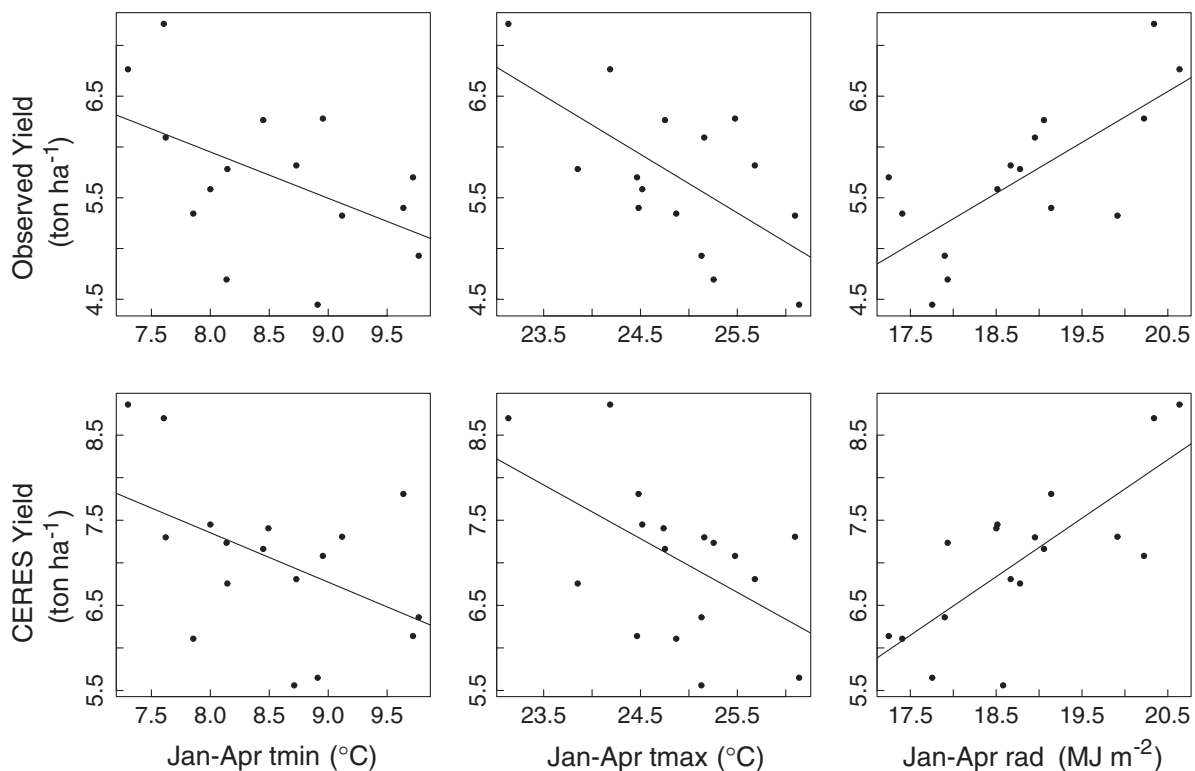


Fig. 6. January–April average daily minimum temperature ( $t_{min}$ ), daily maximum temperature ( $t_{max}$ ), and solar radiation (rad) vs. observed (top) and CERES-simulated (bottom) yields in San Luis and Mexicali Valleys, Mexico.

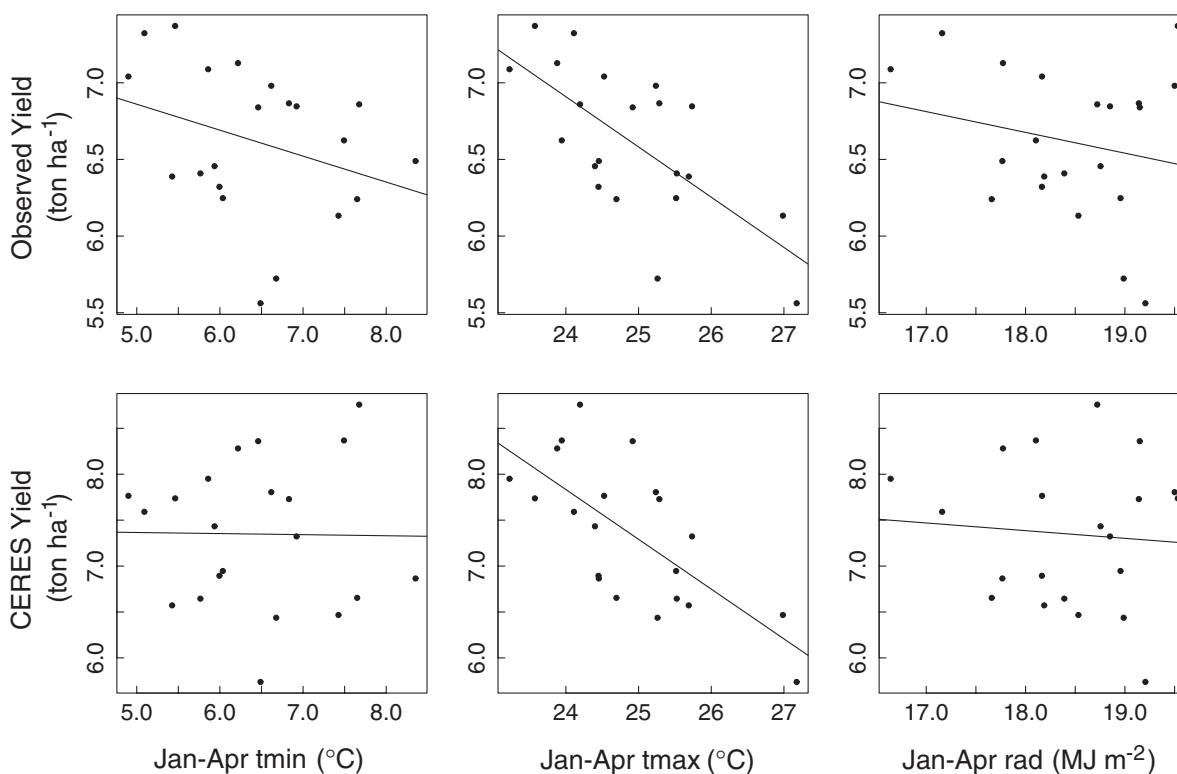


Fig. 8. January–April average daily minimum temperature (*tmin*), daily maximum temperature (*tmax*), and solar radiation (*rad*) vs. observed (top) and CERES-simulated (bottom) yields in Imperial Valley, California.

The statistical significance of model improvements when using simulated yields instead of biomass was tested by computing the *F* statistic:

$$F = \text{RSS}_2 / \text{RSS}_1 \quad [1]$$

where  $\text{RSS}_1$  is the residual sum of square errors for a linear model with observed yields as the response variable

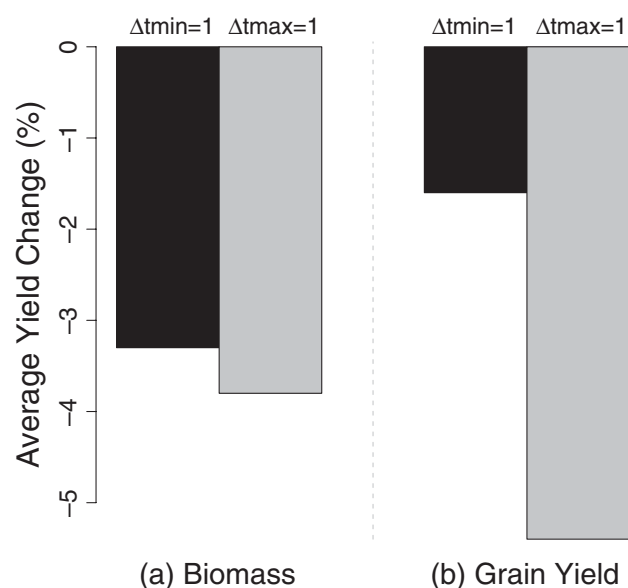


Fig. 9. CERES-simulated biomass (a) and yield (b) response to 1°C increase in daily minimum temperature (*tmin*) or daily maximum temperature (*tmax*) in Imperial Valley, California.

and CERES simulated yields as the predictor variable, and  $\text{RSS}_2$  is the corresponding value for a model with CERES simulated biomass as the predictor variable. The *p* values of the *F* statistic were higher than 0.1 in all three sites. Thus, although observations in two of the three sites suggest that CERES treatment of HI improved model performance, this improvement was not statistically significant at  $p = 0.10$ .

A recent synthesis of CERES modeling studies (Timsina and Humphreys, 2006) showed that predictions of grain yield across several studies were slightly better than for biomass yield (RMSE = 13% vs. 16%). However, the evaluation of biomass yields was based on just two studies, one of which used CERES-Wheat version 2.1 (Hundal and Kaur, 1997). Wilkens and Singh (2001) questioned the temperature response of grain filling rates in CERES, given the expectation that lower night temperatures should reduce night respiration and therefore enhance grain filling. Overall, it seems that CERES simulations of HI are critical for projecting response to changes in DTR and that this aspect of model performance requires further testing.

Table 6.  $R^2$  between observed yields and CERES yields or biomass and statistical significance of improvement when using simulated yields instead of biomass.

Site†	Yields	Biomass	<i>F</i> statistic	<i>p</i> value
YV	0.75	0.68	1.26	0.29
SV	0.50	0.63	0.74	0.72
IV	0.63	0.49	1.38	0.11

† IV, Imperial Valley, California; SV, San Luis and Mexicali Valleys, Mexico; YV, Yaqui Valley, Mexico.

## Empirical Versus CERES Model Predictions of Climate Change Impacts

In all three sites, the empirical effect of  $t_{min}$  and  $t_{max}$  inferred from historical yield variations differed from the responses simulated by CERES when changing one variable while holding all others constant. Indeed, an often-cited strength of process-based models is their ability to simulate yields for combinations of temperatures and radiation that have not previously been observed. However, in cases where process models cannot be used (e.g., because of lack of data required for model calibration), purely empirical (i.e., statistical) models can provide a simple and potentially useful alternative. For comparison with CERES predictions of yield response to temperature increases, we computed multiple linear regression models of yield response, with January–April average  $t_{min}$ ,  $t_{max}$ , and  $rad$  comprising the three predictor variables. The models are summarized in Table 7. For all models, interaction terms and a term for  $ET_0$  were considered but did not significantly improve model  $R^2$  and were therefore not used.

The difference between empirical and CERES model predictions for a  $1^\circ\text{C}$  increase in average temperature was less than 3% in all three sites for the case of symmetric warming, with  $t_{min}$  and  $t_{max}$  increased by  $1^\circ\text{C}$  (Table 8). In SV and IV, even for extreme scenarios where all of the warming occurred at night or day, the differences in model predictions were less than 2%. The greatest differences were observed for asymmetric warming in YV, with the regression model predicting a 5% greater yield response than CERES when warming occurred only at night and an 8% smaller response when warming occurred only during daytime. Thus, the differences between empirical and CERES model predictions can indeed be substantial (e.g., 4% vs. 12% yield loss for  $2^\circ\text{C}$ ), but in most cases the models agreed well.

## CONCLUSIONS

The high correlation in most regions between growing season  $t_{min}$  and  $t_{max}$  presents a challenge to understanding the unique effects of each on crop growth and yields. However, improved understanding of the temperature response is needed to better quantify and reduce uncertainties in climate change impact assessments because anthropogenic climate change is characterized by greater increases in  $t_{min}$  than  $t_{max}$ . Here we ana-

**Table 7. Summary of linear regression models of yield for each region, using Jan.–Apr. average daily minimum temperature ( $t_{min}$ ), daily maximum temperature ( $t_{max}$ ), and solar radiation ( $rad$ ) as predictor variables.**

Site†	Model coefficients				Model $R^2$
	Intercept	$T_{min}$	$T_{max}$	Rad	
YV	5.51*	-0.45***	-0.10	0.32*	0.85***
SV	9.25	-0.11	-0.40*	0.40**	0.76***
IV	14.26***	-0.11	-0.34**	0.09	0.52**

\* Significant at  $p = 0.05$ .

\*\* Significant at  $p = 0.01$ .

\*\*\* Significant at  $p = 0.001$ .

† IV, Imperial Valley, California; SV, San Luis and Mexicali Valleys, Mexico; YV, Yaqui Valley, Mexico.

**Table 8. Modeled impact of  $1^\circ\text{C}$  temperature increase using empirical and CERES models.**

Site†	Temperature scenario	Simulated avg. yield change (%)		
		Empirical model‡	CERES	Difference
YV	$\Delta t_{min} = 1, \Delta t_{max} = 1$	-10.4 (-13.5, -7.0)	-12.0	1.6
	$\Delta t_{min} = 2, \Delta t_{max} = 0$	-17.0 (-23.2, -11.6)	-11.7	-5.3
	$\Delta t_{min} = 0, \Delta t_{max} = 2$	-4.0 (-9.4, 1.3)	-12.2	7.8
SV	$\Delta t_{min} = 1, \Delta t_{max} = 1$	-9.1 (-15.3, -0.6)	-6.9	-2.2
	$\Delta t_{min} = 2, \Delta t_{max} = 0$	-4.2 (-16.2, 7.7)	-3.6	-0.6
	$\Delta t_{min} = 0, \Delta t_{max} = 2$	-12.0 (-23.4, 1.0)	-10.3	-1.7
IV	$\Delta t_{min} = 1, \Delta t_{max} = 1$	-6.6 (-11.2, -3.2)	-7.0	0.4
	$\Delta t_{min} = 2, \Delta t_{max} = 0$	-2.9 (-6.5, 1.6)	-3.2	0.3
	$\Delta t_{min} = 0, \Delta t_{max} = 2$	-10.1 (-16.6, -4.0)	-10.8	0.7

† IV, Imperial Valley, California; SV, San Luis and Mexicali Valleys, Mexico; YV, Yaqui Valley, Mexico.

‡ Empirical models are summarized in Table 6. Confidence intervals for empirical models (shown in parentheses) were estimated by repeating regression for 100 bootstrap samples of historical data.

lyzed historical time series of regional yields for three sites where historical correlations between  $t_{min}$  and  $t_{max}$  were uncommonly low.

The CERES model successfully simulated historical yield variations and their correlations with  $t_{min}$ ,  $t_{max}$ , and solar radiation. The model thus seems to be a useful tool to assess the impact of change in these climatic variables at these sites.

Historical correlations between yields and  $t_{min}$  (or  $t_{max}$ ) were often at odds with the modeled sensitivity to  $t_{min}$  (or  $t_{max}$ ), with the latter measured as the average change in CERES-simulated yields when holding all other variables constant. This finding reflected the important role of covariation of  $t_{min}$  and  $t_{max}$  with each other and especially with solar radiation in historical temperature–yield relationships.

CERES sensitivities of simulated yields to  $t_{min}$  were substantially different than for  $t_{max}$  in two of the three sites, with  $t_{max}$  increases resulting in  $\approx 3$  times greater yield losses than similar increases in  $t_{min}$ . In contrast, biomass sensitivities were similar for  $t_{min}$  and  $t_{max}$ , indicating that simulated changes in HI explain the difference in model sensitivities. Further testing of HI simulations in CERES is therefore critical to improved understanding of  $t_{min}$  and  $t_{max}$  effects on wheat yields.

Predictions of average yield response to climate change using multiple regression models based on historical data differed from CERES predictions by less than 3% for most sites. Thus, although correlations between individual temperature variables and yields may differ with CERES model sensitivities, multiple regression models that include solar radiation agree well with CERES predictions. Process-based models such as CERES offer distinct advantages, such as an ability to simulate adaptation responses or effects of rising  $\text{CO}_2$ . However, in the absence of calibrated process-based models, empirical models can provide a useful means to assess climate change impacts.

For the regions studied here, the effects of higher temperatures were consistently negative. Modeled sensitivities for symmetric warming ranged from  $-10\% \text{ }^\circ\text{C}^{-1}$  at the warmest site (YV) to  $-7\% \text{ }^\circ\text{C}^{-1}$  at the coolest site (IV). Maintaining current yields in the face of 1 to  $4^\circ\text{C}$  temperature increases expected over the next 50 yr



(Ruosteenoja et al., 2003) therefore represents a considerable challenge to the farmers of these regions. Crop breeders will also be challenged to generate new varieties that maintain or improve current yields in a future warmer climate.

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