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LETTER

Projected changes in cold hardiness zones and suitable overwinter ranges of perennial crops over the United States

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Abstract

Average annual absolute minimum temperatures (TN_n) provide a means of delineating agriculturally relevant climate zones and are used to define cold hardiness zones (CHZ) by the United States Department of Agriculture. Projected changes in TN_n, mean winter minimum temperatures, and CHZs over the conterminous United States (CONUS) were assessed using an ensemble of statistically downscaled daily climate model output through the mid 21st century (2041–2070). Warming of TN_n is on average ~40% greater than that of mean winter minimum temperatures across CONUS with an average climate velocity of 21.4 km decade^{-1} resulting in widespread shifts in CHZs. These changes enable a geographic expansion of thermally suitable areas for the cultivation of cold-intolerant perennial agriculture including almond, kiwi, and orange crops. Beyond these crops, warming of TN_n has broad implications for food security and biotic interactions.

Introduction

A number of studies have highlighted the importance of both mean and extreme minimum temperatures to ecological systems. For example, monthly average minimum temperatures have been used for habitat mapping (e.g. Ledig *et al* 2010), crop yield assessment (e.g. Lobell and Field 2007), and pest monitoring (e.g. Trần *et al* 2007, Paradis *et al* 2008). While the distribution of species may not be directly linked to mean annual or monthly temperatures, extreme minimum temperatures have established links to the overwinter survival rates of insects (e.g. Bale 1996, Stahl *et al* 2006) and plants (Alden and Hermann 1971, Vetaas 2002). Consequently, extreme minimum temperatures provide constraints on the potential geographic range of natural and cultivated species (e.g. Woodward *et al* 2004), and can impact crop yields (e.g. Porter and Gawith 1999, Gu *et al* 2008).

Cold damage to plants may occur at a range of minimum temperatures ($T_{\min}$) depending on species sensitivity and phenological stage (Sakai and Larcher 1987, Larcher 2005). Given the challenges in generalizing plant cold tolerance, the United States Department of Agriculture (USDA) developed cold hardiness zones (CHZ) based on annual minimum $T_{\min}$ (TN_n) averaged over a climatological period. These zones provide guidance for where plants might survive through winter temperatures and are presently used to establish nursery crop insurance standards. A map of CHZs was first published by the USDA in 1960, and was updated in 1990 (Cathey 1990) and again in 2012 (Daly *et al* 2012). Although other measures of delineating horticulturally relevant climate zones exist, we focus on the USDA hardiness zones because of their ubiquity over the United States (McKenney *et al* 2007).

Under climate change scenarios, mean winter temperatures (e.g. Maloney *et al* 2014) and extreme minimum temperatures are projected to warm (e.g. Kharin *et al* 2013, Sillmann *et al* 2013, Wuebbles *et al* 2014). Given the importance of cold extremes to species survival and distribution, increased temperatures may allow for the geographic expansion of plants, pests and invasive species into areas where they had previously been thermally limited (e.g. Battisti *et al* 2005, Weiss and Overpeck 2005, Walther *et al* 2009). Additionally, annual $T_{\min}$ cold extremes are of interest to a variety of civil sectors including electricity, transportation and infrastructure (e.g. Amato *et al* 2005, Larsen *et al* 2008).

Improved understanding of projected changes in temperature extremes—including TN_n—have implications for informing climate adaptation approaches for crop cultivation, identifying areas at risk for invasive species expansions, and tracking potential changes in electricity and infrastructure needs. Increases in TN_n under climate change will result in significant redistribution of biologically relevant thermoclines and subsequent species (e.g. Diffenbaugh *et al* 2008). Observed warming in annual average $T_{\min}$ across the conterminous United States (CONUS) has resulted in poleward and altitudinal shifts in thermoclines, with spatially varying climate velocity—that is the speed and direction that a given property migrates with climate change (e.g. Dobrowski *et al* 2013). Previous studies have examined changes in the coldest minimum temperatures over the observational record (e.g. Alexander *et al* 2006, Brown *et al* 2008, Abatzoglou *et al* 2014), and those projected over the 21st century using climate models (Diffenbaugh *et al* 2008, Sillmann *et al* 2013, Abatzoglou and Barbero 2014). Further, studies have shown larger warming of TN_n relative to maximum $T_{\min}$ in observations (Alexander *et al* 2006), and in modeling studies (e.g. Kharin *et al* 2013, Sillmann *et al* 2013). The warming of these cold extremes in mid- and high-latitude locations has been connected to the reduction in snow and sea ice (e.g. Kharin and Zwiers 2005, Kharin *et al* 2013), as well to the diminished variance in cold-season temperatures resulting from Arctic amplification (e.g. Screen 2014).

We build on these aforementioned studies by examining TN_n and CHZ projections using an ensemble of global climate model output downscaled to a spatial resolution congruent with contemporary agroclimatic information, evaluating projected changes in TN_n relative to mean winter (December–February) $T_{\min}$ ($\mathrm{TN}_{\overline{\mathrm{DJF}}}$), and calculating the climate velocity of CHZs, TN_n and $\mathrm{TN}_{\overline{\mathrm{DJF}}}$. Further, we complement previous work by examining the impact of projected changes in TN_n on thermally suitable areas for the cultivation of three high market-value perennial fruit and nut crops: Nonpareil almond, Hayward kiwi, and Navel orange.

Data and methods

We obtained daily $T_{\min}$ data from twenty global climate models (GCMs) participating in the fifth phase of the Climate Model Intercomparison Project (CMIP5) (Taylor *et al* 2012) that were statistically downscaled over CONUS using Multivariate Adaptive Constructed Analogs (MACA) method (Abatzoglou and Brown 2012) for both historical (1950–2005) and future (2006–2099) experiments. Downscaled data were trained using the gridded surface meteorological dataset of Abatzoglou (2013) at a 1/24th degree resolution grid that ensures that quantiles of the downscaled historical GCM period adhere to those of the observed record (1979–2012). The gridded dataset of Abatzoglou (2013) is a hybrid product that bias correct data from the North American Land Data Assimilation System (NLDAS2; Mitchell *et al* 2004) with monthly data from the Parameter Regression on Independent Slopes Model (PRISM; Daly *et al* 1994), and exhibits nominal biases for temperature extremes such as TN_n when compared to *in situ* weather stations (i.e., coldest 1% of daily TN had a mean bias of +0.5 °C compared to data from Global Historical Climate Network stations). MACA uses an analog approach for mapping GCM fields to observed fields and applies an equidistant quantile mapping bias correction procedure (Li *et al* 2010, Pierce *et al* 2015) that preserves the differences between future and historical daily temperatures from GCM simulations across quantiles, including TN_n and other extreme values.

Dynamical downscaling using regional climate models (RCM) is arguably better suited for assessing climate extremes modulated by mesoscale land-surface phenomena (e.g., snow-albedo feedback). However, the restricted availability of RCM output from multiple GCMs and the additional statistical bias correction procedures needed for local assessment limited our analysis to the statistically downscaled products. We conduct a complementary analysis to facilitate a comparison between statistically downscaled products used in our analysis and dynamically downscaled results from two RCMs (CanCM4 and RCM4) using a common GCM ensemble member from the second generation Canadian Earth System Model (CanESM2) forced with RCP 8.5 as part of the CORDEX project (Giorgi *et al* 2009).

We constrained our analysis to model simulations for the historical period (1971–2000) and mid 21st century period (2041–2070). We chose to assess mid-century projections in TN_n, $\mathrm{TN}_{\overline{\mathrm{DJF}}}$, and CHZs because of the limited ability for developing meaningful management strategies relevant to end-of-century projections. We primarily focus on future experiments run under Representative Concentration Pathway 8.5 (RCP 8.5) given that inter-model variability exceeds inter-scenario variability for these time horizons (Kharin *et al* 2007, 2013), and emissions trajectories to date have more closely followed RCP 8.5 (Peters *et al* 2013).

TN_n for each winter-centric year was calculated from November–March, along with $\mathrm{TN}_{\overline{\mathrm{DJF}}}$. We calculated 30 year averages of TN_n and $\mathrm{TN}_{\overline{\mathrm{DJF}}}$ for each model for both the historic and mid 21st century time periods and considered both multi-model ensemble averages, as well as the ensemble 25th and 75th percentiles to assess intermodel variability. The climate velocities of multimodel mean TN_n and $\mathrm{TN}_{\overline{\mathrm{DJF}}}$ between historical and mid 21st century were calculated using a distance-based velocity algorithm (Hamann *et al* 2015). This algorithm determines the shortest distance between locations with analog climates and divides by the number of years between the two climate periods to provide the climate velocity in units of km yr^{-1}. We calculated both forward (i.e. current-to-future) and backward (future-to-current) velocities of the ensemble average temperature and report the minimum of the two velocities as a conservative estimate.

The multi-model mean of 30 year average TN_n values were also used to define CHZs. Hardiness zones range from −51.1 °C to 21.1 °C with each zone spanning 5.6 °C and being comprised of half-zones A and B, each covering a 2.8 °C range. Projected changes in CHZs and the velocity of CHZ shifts were calculated. While CHZ projections may be useful for assessing climate change impacts on crop cultivation, we utilize minimum temperature thresholds ($\mathrm{TN}_{\mathrm{CROP}}$) for dormancy as a means of examining how projected changes in TN_n may expand thermally suitable areas for crop survival. We chose to examine the impacts of projected changes in TN_n on Nonpareil almonds, Hayward kiwis, and Navel oranges because of their relatively high market value. These cultivars also provide examples across a range of hardiness threshold temperatures, from −25 °C for Nonpareil almonds (Janick and Moore 1996), to −12 °C for Hayward kiwifruit (Strik 2005), to −4.4 °C for Navel oranges (Fake and Norton 2012). Using the multi-model mean TN_n for both the historical and mid-century periods, we calculated the percent area over CONUS with TN_n values above $\mathrm{TN}_{\mathrm{CROP}}$. Additionally, to provide a more conservative measure of potential changes in crop cultivation area, we assessed the percent suitable land area where at least 80% of the models showed $\mathrm{TN}_n > \mathrm{TN}_{\mathrm{CROP}}$.

Results

Ensemble average projected increases in $\mathrm{TN}_{\overline{\mathrm{DJF}}}$ range from 1.7 °C in the southeastern US to more than 5 °C in the Upper Midwest and northern Great Plains (figure 1(a)). While the spatial pattern of warming for $\mathrm{TN}_{\overline{\mathrm{DJF}}}$ resembled that seen in TN_n, the magnitude of warming of the latter was more acute across a majority of CONUS (figure 1(b)). The ensemble average TN_n warming ranged from 1.8 °C to more than 7 °C warming, yielding a 40% greater increase compared to $\mathrm{TN}_{\overline{\mathrm{DJF}}}$ when averaged over CONUS. This results in an additional 2 °C of warming of TN_n over $\mathrm{TN}_{\overline{\mathrm{DJF}}}$ across a broad region of the Midwestern US, Great Lakes and interior northwestern US (figure 1(c)). This asymmetric warming was found for all downscaled GCMs across much of the northern half of the United States from the Great Plains to the Atlantic Ocean, as well as for much of the Intermountain West. Conversely, fewer GCMs showed differential warming across portions of the southern United States, the Rocky Mountains, and portions of the Southwest including California and Arizona (figure S1). Intermodel variability, represented by 25th and 75th percentiles of projected increases in TN_n and $\mathrm{TN}_{\overline{\mathrm{DJF}}}$ across models (figure S2), was largest over the northern US and the northern Rocky Mountains of Idaho and Montana, for $\mathrm{TN}_{\overline{\mathrm{DJF}}}$ and TN_n, respectively.

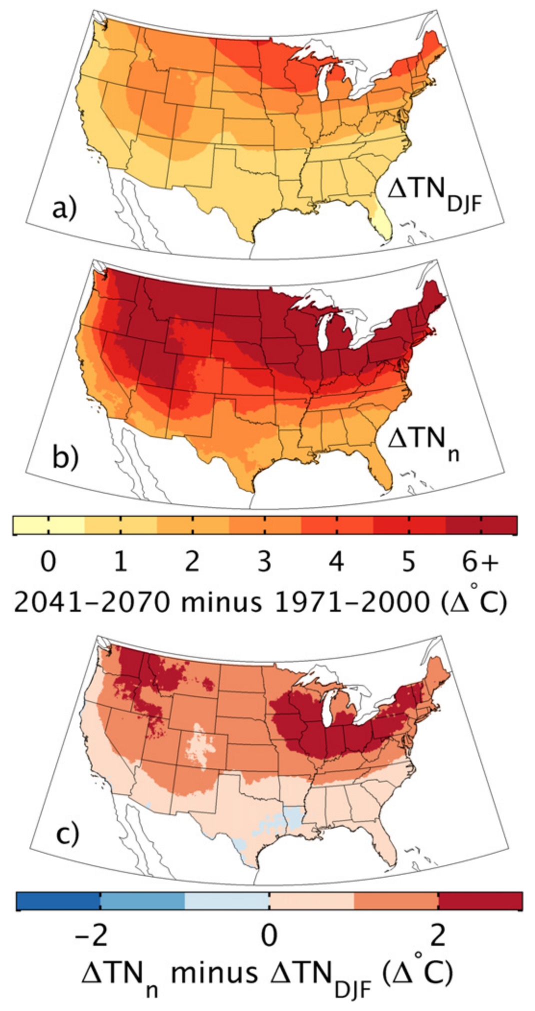

Figure 1. Projected ensemble averages of (a) mid-century warming in $\mathrm{TN}_{\overline{\mathrm{DJF}}}$ for RCP 8.5 over CONUS, (b) mid-century warming in average TN_n, and (c) the difference in warming of TN_n and warming of $\mathrm{TN}_{\overline{\mathrm{DJF}}}$.

The velocity of TN_n also varied spatially (figure 2(a)). The mean (median) estimate of the speed of TN_n over CONUS was 21.4 km decade^{-1} (16.2 km decade^{-1}), albeit with substantial spatial heterogeneity as seen in prior assessments of climate velocity (e.g., Loarie *et al* 2009, Dobrowski *et al* 2013). The fastest speed of TN_n was found over the northern Great Plains and Midwestern US due to large increases in TN_n coupled with a weak spatial gradient in TN_n, while slow speeds were found along the West Coast, in the Southwest, and in coastal Florida. By comparison, the velocity of projected $\mathrm{TN}_{\overline{\mathrm{DJF}}}$ was less than TN_n, with a mean (median) of 15.6 km decade^{-1} (12 km decade^{-1}) and with similar spatial patterns (figure 2(b)).

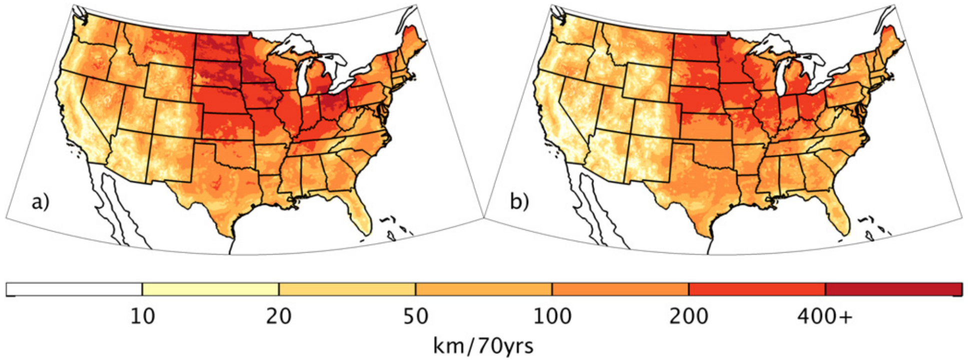

Figure 2. Estimated climate velocity of TN_n (a) and $\mathrm{TN}_{\overline{\mathrm{DJF}}}$ (b), defined as the minimum of the forward and backward looking calculations.

As an artifact of the spatial bounds of our data, forward-looking climate velocities have no analog climates within CONUS for parts of the Northern Plains and more localized areas in the Rocky Mountains and the Northeast (figure S3). Backward-looking velocities show analog climates over 95% of locations and differ from forward-looking velocities, particularly over the topographically complex Western US.

As CHZs are calculated from average TN_n, those locations showing the largest warming of TN_n also exhibited the largest projected increases in CHZs (e.g. from zone 5 to 6). CHZs of downscaled GCM data from historical runs (figure 3(a)) were similar to published CHZs from observational records (e.g. Daly *et al* 2012). A comparison of ensemble mean TN_n downscaled from historical runs and TN_n calculated using daily PRISM data from 1981 to 2010 showed absolute biases <1.5 °C over CONUS, with a mean bias of +0.1 °C, suggesting reasonable agreement. Mid-century CHZ projections showed northward and upward shifts in existing zones (figure 3(b)), with a mean (median) shift over CONUS of ~93 km (~56 km) by the mid 21st century. Nearly all (98%) of CONUS exhibited an increase in CHZ (i.e. toward warmer absolute minimum temperature) using the multi-model mean, and no location saw a decrease in CHZ. Similar changes in CHZ were projected by the mid 21st century using RCP 4.5 forcing (figure S4).

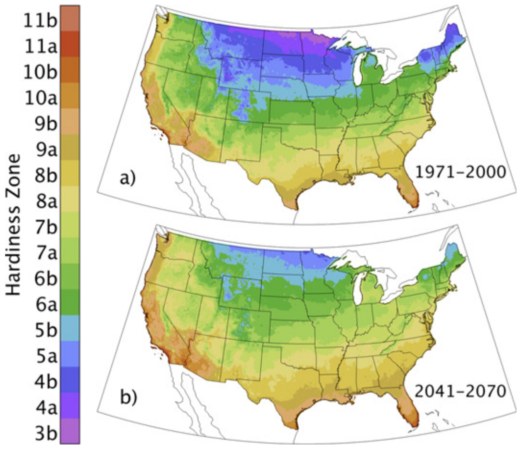

Figure 3. (a) Cold hardiness zones as defined by the multi-model mean of TN_n averaged over (a) 1971–2000, and (b) 2041–2070 for experiment RCP8.5.

Warming TN_n (and consequent shifting CHZs) resulted in an increase in land area with sufficiently warm temperatures for overwinter survival of crops. Over the historical period, approximately 24% and 5% of CONUS had sufficiently warm TN_n for overwinter survival of oranges and kiwifruit, respectively (figures 4(a) and (c)). Mid 21st century projections of TN_n would enable an expansion of land with suitable overwinter temperatures to approximately 37% and 9% of CONUS for kiwifruit and oranges, respectively; the extent of $\mathrm{TN}_{\mathrm{CROP}}$ for oranges expanded northward along coastal areas and kiwi expanded northward from its historical range (figures 4(b) and (d)). The majority (~74%) of CONUS showed multi-model mean $\mathrm{TN}_n > \mathrm{TN}_{\mathrm{CROP}}$ for almonds over the historical period (figure 4(e)), expanding into the north central plains and covering ~93% of CONUS by the mid 21st century (figure 4(f)). A more conservative approach, where at least 80% of the models have $\mathrm{TN}_n > \mathrm{TN}_{\mathrm{CROP}}$, shows comparable results: the percent land area suitable for crop survival over the historical (future) period was ~73% (~90%) for almonds, ~23% (~32%) for kiwi, and ~5% (~8%) for oranges.

Similar patterns of warming are evident across the statistically and dynamically downscaled data, however changes in TN_n and $\mathrm{TN}_{\overline{\mathrm{DJF}}}$ are more heterogeneous in the dynamically downscaled outputs (figure S5). The spatial correlation of changes in TN_n ($\mathrm{TN}_{\overline{\mathrm{DJF}}}$) between the downscaled data and the RCMs were 0.80 (0.87) for RCM4, and 0.83 (0.88) for RCA4. The raw GCM output, statistically downscaled data, and both RCMs show amplified warming of the TN_n versus $\mathrm{TN}_{\overline{\mathrm{DJF}}}$ over the majority of CONUS. Whereas the RCMs highlight heterogeneous warming in the topographically complex western United States, the inter-RCM variability is quite large.

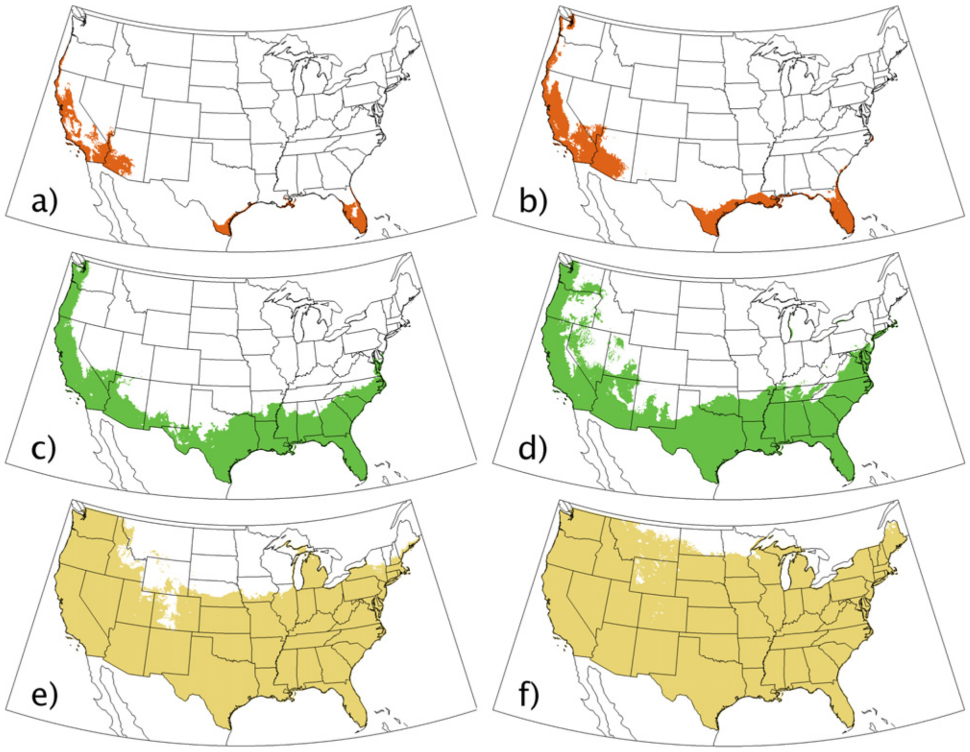

Figure 4. Shaded areas are those where the ensemble average $TN_n > TN_{CROP}$ for: (a) oranges over the period 1971–2000, (b) oranges over the period 2041–2070, (c) kiwifruit over the period 1971–2000, (d) kiwifruit over the period 2041–2070, (e) almonds over the period 1971–2000, (f) almonds over the period 2041–2070.

Discussion and conclusions

The mechanisms responsible for the amplified warming of TN_n are likely a function of Arctic amplification and land-atmosphere interactions. The Arctic and interior Canada are primary air mass source regions for cold air outbreaks over CONUS that typically result in TN_n. Observed amplification in warming rates over high latitude landmasses and the poles versus the mid-latitudes has contributed to an increase in the temperature of cold air masses that have impacted CONUS over the second half of the 20th century (Walsh *et al* 2001, Hankes and Walsh 2011). Huybers *et al* (2014) showed a pattern of decreased variance of the coldest 5% of TN in DJF with warming $TN_{\overline{DJF}}$ on an interannual basis in observations, which supports the amplified warming of TN_n. Continued amplified warming rates of source regions for cold air outbreaks likely contribute to the larger warming rate of TN_n versus $TN_{\overline{DJF}}$. While changes in atmospheric circulation with climate change have been hypothesized to increase the potential for cold air outbreaks (e.g. Francis and Vavrus 2012), decreases in temperature variance as a result of climate change would reduce the potential for cold air outbreaks (e.g. Schneider *et al* 2015, Screen 2014). Changes in snow cover and depth can also increase warming rates as the high albedo and thermal emissivity of snow cover helps promote exceptionally cold temperatures. Consequently, projected declines in snowfall (Lute *et al* 2015) and snow depth (e.g. Salathé *et al* 2008) may locally alter the radiative balance and contribute to differential rates of warming (e.g. Dyer and Mote 2006). However, Abatzoglou and Barbero (2014) and Gao *et al* (2015) noted that extreme cold air outbreaks including all-time record low temperatures may occur under a warmer climate, though with reduced duration and spatial extent.

Climate velocity may shape the distribution of ecological zones and resident species (Loarie *et al* 2009). As TN_n has a direct link to species viability, we suggest that the climate velocity of such metrics is important for changes in range shifts in agricultural and natural ecosystems. While their methodology for calculating climate velocities differs from that used here, Dobrowski *et al* (2013) showed similar patterns in the velocity of mean $T_{\min}$ over the 20th century, though our mean projected velocities of TN_n are greater than the average velocity of mean $T_{\min}$ in that study. The greater velocity of TN_n versus $TN_{\overline{DJF}}$ suggests a hastened rate of change that may be important for planning and adaptation efforts, and in fact the velocity of change may be more important for some adaptation efforts than the magnitude of the change itself.

It is important to note the uncertainty in the projection of extremes in GCM data and associated statistical downscaling that may not fully capture the mesoscale land-surface feedbacks that can modify warming of temperature extremes. Statistically and dynamically downscaled products for a common GCM ensemble member generally show similar patterns in TN_n and $TN_{\overline{DJF}}$, but localized magnitudes differ. The heterogeneity exhibited in the dynamically downscaled products (e.g. over the western US) likely highlight regions where snow-albedo feedbacks are captured by RCMs (e.g. Salathé *et al* 2008, Pepin *et al* 2015). In this respect, RCMs may help to unveil changes occurring at local scales that are not adequately resolved using statistical approaches. However, the influence of snow-albedo feedbacks is contingent upon accurately simulating snowcover changes. The differences in magnitude and spatial heterogeneity of the change in TN_n and $TN_{\overline{DJF}}$ between the RCMs examined here indicate the challenges in refining the magnitude of change at local scales. Likewise, the lack of ensemble GCM-RCM combinations and the potential for GCM biases to propagate into RCM simulations currently limit a comprehensive analysis suitable for research of this sort. However, coordinated experiments such as CORDEX (Giorgi *et al* 2009) can better elucidate uncertainty that arises through downscaling approaches as well as highlight value-added downscaling from RCMs on changes in TN_n that may help refine our results.

The increase in TN_n and subsequent shifts in CHZs projected for mid-century periods supports previous work on changing thermal suitability envelopes. For example, the analysis of Lobell *et al* (2006) on perennial crops over California showed favorability for future crop development at higher latitudes or elevations. Similarly, Olesen *et al* (2007) project an expansion in thermal suitability zones for maize production over Europe during the 21st century. While our analysis does not consider other factors (e.g. heat tolerance thresholds, chilling hour requirements, water availability, competing land use) that govern where crops can be cultivated, warming of TN_n may provide opportunities for crop production in regions that are currently thermally limited by cold extremes. However, there are many caveats to the potential for crop expansion with respect to warming TN_n. For the perennials examined here that are either early blooming or highly sensitive to frost damage, commercial cultivation occurs almost exclusively in areas where TN_n is much warmer than TN_{CROP} and there are few studies providing thorough examination of threshold temperatures for cold hardiness (Janick and Moore 1996). It should be noted that the TN_{CROP} values used in this study are temperatures that would severely damage or kill crops during overwinter dormancy; during other phenological stages, crops may be at higher risk for damage from less extreme cold temperatures. Further, while these threshold temperatures may be tolerated during dormancy for a few hours, many hours below TN_{CROP} would result in increased damage or mortality (Fake and Norton 2012). Additionally, tolerance may decrease on nights with little wind when radiative heat loss can cool plant tissues below the ambient air temperature (Johnson 2011).

Warming TN_n and projected shifts in CHZs have implications for agricultural and natural vegetation, land management, the energy sector and infrastructure. In addition to cultivated crops, native and invasive species and pests may also see geographic expansion, resulting in additional challenges for agricultural land managers as well as those managing forests, rangelands and other natural resources (e.g. Noss 2001). Moreover, an increase in TN_n may also have economic impacts. Provided that the greatest electrical demands for heating occur during the coldest temperatures, the anticipated reductions in heating demand assessed from projected changes in $TN_{\overline{DJF}}$ may be augmented further with greater rates of warming of TN_n (Scott and Huang 2007, Mideksa and Kallbekken 2010). In addition to lowered heating costs, further economic impacts of warming TN_n include the reduced cost of transportation infrastructure repairs as warmer T_{min} extremes reduce thermal stress on asphalt and damage from frost heaves (e.g. Mills and Andrey 2002).

The differential warming exhibited between changes in mean and extreme minimum winter temperatures highlights the importance of assessing both means and extremes in understanding potential impacts of climate change. Through utilizing daily projections to illustrate results with direct implications for climate change impacts, we show the benefit in revisiting previous studies whose analyses were limited temporally and spatially by previously unavailable downscaled daily data, and suggest that for applied purposes statistically downscaled products may be preferable to RCMs for multi-member ensemble studies. Finally, although the caveats presented above highlight the need for additional research to more fully account for the role of climatological factors governing crop survival, our results show promise for geographic expansion of thermally limited cultivars under climate change.

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References

Abatzoglou J T 2013 Development of gridded surface meteorological data for ecological applications and modelling *Int. J. Climatol.* **33** 121–31

Abatzoglou J T and Barbero R 2014 Observed and projected changes in absolute temperature records across the contiguous United States *Geophys. Res. Lett.* **41** 6501–8

Abatzoglou J T and Brown T J 2012 A comparison of statistical downscaling methods suited for wildfire applications *Int. J. Climatol.* **32** 772–80

Abatzoglou J T, Rupp D E and Mote P W 2014 Seasonal climate variability and change in the Pacific Northwest of the United States *J. Clim.* **27** 2125–42

Alden J and Hermann R K 1971 Aspects of the cold-hardiness mechanism in plants *Bot. Rev.* **37** 37–142

Alexander L V, Zhang X, Peterson T C, Caesar J, Gleason B, Klein Tank A M G and Vazquez-Aguirre J L 2006 Global observed changes in daily climate extremes of temperature and precipitation *J. Geophys. Res.: Atmos.* (*1984–2012*) **111** D05109

Amato A D, Ruth M, Kirshen P and Horwitz J 2005 Regional energy demand responses to climate change: methodology and application to the Commonwealth of Massachusetts *Clim. Change* **71** 175–201

Bale J S 1996 Insect cold hardiness: a matter of life and death *Eur. J. Entomology* **93** 369–82

Battisti A, Stastny M, Netherer S, Robinet C, Schopf A, Roques A and Larsson S 2005 Expansion of geographic range in the pine processionary moth caused by increased winter temperatures *Ecol. Appl.* **15** 2084–96

Brown S J, Caesar J and Ferro C A 2008 Global changes in extreme daily temperature since 1950 *J. Geophys. Res.: Atmos.* (*1984–2012*) **113** D05115

Cathey Henry M 1990 *USDA Plant Hardiness Zone Map*

Daly C, Neilson R P and Phillips D L 1994 A statistical-topographic model for mapping climatological precipitation over mountainous terrain *J. Appl. Meteorol.* **33** 140–58

Daly C, Widrlechner M P, Halbleib M D, Smith J I and Gibson W P 2012 Development of a new USDA plant hardiness zone map for the United States *J. Appl. Meteorol. Climatol.* **51** 242–64

Diffenbaugh N S, Krupke C H, White M A and Alexander C E 2008 Global warming presents new challenges for maize pest management *Environ. Res. Lett.* **3** 044007

Dobrowski S Z, Abatzoglou J, Swanson A K, Greenberg J A, Mynsberge A R, Holden Z A and Schwartz M K 2013 The climate velocity of the contiguous United States during the 20th century *Glob. Change Biol.* **19** 241–51

Dyer J L and Mote T L 2006 Spatial variability and trends in observed snow depth over North America *Geophys. Res. Lett.* **33** L16503

Fake C and Norton M 2012 Avoiding cold damage to home citrus *Merced County Cooperative Extension* (http://cemerced.ucanr.edu/files/134971.pdf)

Francis J A and Vavrus S J 2012 Evidence linking Arctic amplification to extreme weather in mid-latitudes *Geophys. Res. Lett.* **39** L06801

Gao Y, Leung L R, Lu J and Masato G 2015 Persistent cold air outbreaks over North America in a warming climate *Environ. Res. Lett.* **10** 044001

Giorgi F, Jones C and Asrar G R 2009 Addressing climate information needs at the regional level: the CORDEX framework *World Meteorol. Organ.* (*WMO*) *Bull.* **58** 175

Gu L, Hanson P J, Mac Post W, Kaiser D P, Yang B, Nemani R and Meyers T 2008 The 2007 Eastern US spring freeze: increased cold damage in a warming world? *BioScience* **58** 253–62

Hamann A, Roberts D R, Barber Q E, Carroll C and Nielsen S E 2015 Velocity of climate change algorithms for guiding conservation and management *Glob. Change Biol.* **21** 997–1004

Hankes I E and Walsh J E 2011 Characteristics of extreme cold air masses over the North American sub-Arctic *J. Geophys. Res.: Atmos.* (*1984–2012*) **116** D11102

Huybers P, McKinnon K A, Rhines A and Tingley M 2014 US daily temperatures: the meaning of extremes in the context of nonnormality *J. Clim.* **27** 7368–84

Janick J and Moore J N 1996 *Fruit Breeding, Nuts* vol 3 (New York: Wiley)

Johnson W 2011 Understanding how cold temperatures affect citrus trees *Texas A&M AgriLife Extension Aggie Horticulture Hort Update* (http://aggie-horticulture.tamu.edu/newsletters/hortupdate/2011/mar/citrus_freeze.html)

Kharin V V and Zwiers F W 2005 Estimating extremes in transient climate change simulations *J. Clim.* **18** 1156–73

Kharin V V, Zwiers F W, Zhang X and Hegerl G C 2007 Changes in temperature and precipitation extremes in the IPCC ensemble of global coupled model simulations *J. Clim.* **20** 1419–44

Kharin V V, Zwiers F W, Zhang X and Wehner M 2013 Changes in temperature and precipitation extremes in the CMIP5 ensemble *Clim. Change* **119** 345–57

Larcher W 2005 Climatic constraints drive the evolution of low temperature resistance in woody plants *J. Agric. Meteorol.* **61** 189–202

Larsen P H, Goldsmith S, Smith O, Wilson M L, Strzepek K, Chinowsky P and Saylor B 2008 Estimating future costs for Alaska public infrastructure at risk from climate change *Glob. Environ. Change* **18** 442–57

Ledig F T, Rehfeldt G E, Sáenz-Romero C and Flores-López C 2010 Projections of suitable habitat for rare species under global warming scenarios *Am. J. Bot.* **97** 970–87

Li H, Sheffield J and Wood E F 2010 Bias correction of monthly precipitation and temperature fields from intergovernmental panel on climate change AR4 models using equidistant quantile matching *J. Geophys. Res.: Atmos.* **115** D10101

Loarie S R, Duffy P B, Hamilton H, Asner G P, Field C B and Ackerly D D 2009 The velocity of climate change *Nature* **462** 1052–5

Lobell D B and Field C B 2007 Global scale climate–crop yield relationships and the impacts of recent warming *Environ. Res. Lett.* **2** 014002

Lobell D B, Field C B, Cahill K N and Bonfils C 2006 Impacts of future climate change on California perennial crop yields: model projections with climate and crop uncertainties *Agric. Forest Meteorol.* **141** 208–18

Lute A C, Abatzoglou J T and Hegewisch K C 2015 Projected changes in snowfall extremes and interannual variability of snowfall in the western United States *Water Resour. Res.* **51** 960–72

Maloney E D, Camargo S J, Chang E, Colle B, Fu R, Geil K L and Kinter J 2014 North American climate in cmip5 experiments: III. Assessment of twenty-first-century projections *J. Clim.* **27** 2230–70

McKenney D W, Pedlar J H, Lawrence K, Campbell K and Hutchinson M F 2007 Beyond traditional hardiness zones: using climate envelopes to map plant range limits *BioScience* **57** 929–37

Mideksa T K and Kallbekken S 2010 The impact of climate change on the electricity market: a review *Energy Policy* **38** 3579–85

Mills B and Andrey J 2002 Climate change and transportation: potential interactions and impacts *The Potential Impacts of Climate Change on Transportation* [US] DOT Center for Climate Change and Environmental Forecasting (http://climate. volpe. dot. gov/workshop1002/mills. doc) pp 77–88

Mitchell K E, Lohmann D, Houser P R, Wood E F, Schaake J C, Robock A and Bailey A A 2004 The multi-institution North American Land Data Assimilation System (NLDAS): utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system *J. Geophys. Res.* **109** D07S90

Noss R F 2001 Beyond Kyoto: forest management in a time of rapid climate change *Conservation Biol.* **15** 578–90

Olesen J E, Carter T R, Diaz-Ambrona C H, Fronzek S, Heidmann T, Hickler T and Sykes M T 2007 Uncertainties in projected impacts of climate change on European agriculture and terrestrial ecosystems based on scenarios from regional climate models *Clim. Change* **81** 123–43

Paradis A, Elkinton J, Hayhoe K and Buonaccorsi J 2008 Role of winter temperature and climate change on the survival and future range expansion of the hemlock woolly adelgid (Adelges tsugae) in eastern North America *Mitigation Adaptation Strateg. Glob. Change* **13** 541–54

Pepin N, Bradley R S, Diaz H F, Baraer M, Caceres E B, Forsythe N and Yang D Q 2015 Elevation-dependent warming in mountain regions of the world *Nat. Clim. Change* **5** 424–30

Peters G P, Andrew R M, Boden T, Canadell J G, Ciais P, Le Quéré C and Wilson C 2013 The challenge to keep global warming below 2 °C *Nat. Clim. Change* **3** 4–6

Pierce D W, Cayan D R, Maurer E P, Abatzoglou J T and Hegewisch K C 2015 Improved bias correction techniques for simulations of climate change *J. Hydrometeorology* **16** 2421–42

Porter J R and Gawith M 1999 Temperatures and the growth and development of wheat: a review *Eur. J. Agronomy* **10** 23–36

Sakai A and Larcher W 1987 *Frost Survival of Plants: Responses and Adaptation to Freezing Stress* (Berlin: Springer)

Salathé E P Jr, Steed R, Mass C F and Zahn P H 2008 A high-resolution climate model for the US Pacific Northwest: mesoscale feedbacks and local responses to climate change *J. Clim.* **21** 5708–26

Schneider T, Bischoff T and Płotka H 2015 Physics of changes in synoptic midlatitude temperature variability *J. Clim.* **28** 2312–31

Scott M J and Huang Y J 2007 Effects of climate change on energy use in the United States *Effects of Climate Change on Energy Production and Use in the United States. A Report by the U.S. Climate Change Science Program and the subcommittee on Global change Research, Washington, DC* pp 8–44

Screen J A 2014 Arctic amplification decreases temperature variance in northern mid-to high-latitudes *Nat. Clim. Change* **4** 577–82

Sillmann J, Kharin V V, Zwiers F W, Zhang X and Bronaugh D 2013 Climate extremes indices in the CMIP5 multimodel ensemble: II. Future climate projections *J. Geophys. Res.: Atmos.* **118** 2473–93

Stahl K, Moore R D and McKendry I G 2006 Climatology of winter cold spells in relation to mountain pine beetle mortality in British Columbia, Canada *Clim. Res.* **32** 13–23

Strik B 2005 Growing kiwifruit *Oregon State University Extension Catalog* (http://catalog.extension.oregonstate.edu/pnw507)

Taylor K E, Stouffer R J and Meehl G A 2012 An overview of CMIP5 and the experiment design *Bull. Am. Meteorol. Soc.* **93** 485–98

Trần J K, Ylioja T, Billings R F, Régnière J and Ayres M P 2007 Impact of minimum winter temperatures on the population dynamics of Dendroctonus frontalis *Ecological Appl.* **17** 882–99

Vetaas O R 2002 Realized and potential climate niches: a comparison of four Rhododendron tree species *J. Biogeography* **29** 545–54

Walsh J E, Phillips A S, Portis D H and Chapman W L 2001 Extreme cold outbreaks in the United States and Europe, 1948–99 *J. Clim.* **14** 2642–58

Walther G R, Roques A, Hulme P E, Sykes M T, Pyšek P, Kühn I and Czucz B 2009 Alien species in a warmer world: risks and opportunities *Trends Ecology Evol.* **24** 686–93

Weiss J L and Overpeck J T 2005 Is the Sonoran Desert losing its cool? *Glob. Change Biol.* **11** 2065–77

Woodward F I, Lomas M R and Kelly C K 2004 Global climate and the distribution of plant biomes. *Phil. Trans. R. Soc.* B **359** 1465–76

Wuebbles D, Meehl G, Hayhoe K, Karl T R, Kunkel K, Santer B and Sun L 2014 CMIP5 climate model analyses: climate extremes in the United States *Bull. Am. Meteorol. Soc.* **95** 571–83